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"Urban Energy planning: integrating dynamic building simulation tool with energy system simulation models for studying building stock energy savings"

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Index

Abstract

In the last years, high attention is posed in climate change issues and in the energy measures able to stop them; global goals are stipulated to reduce green house gas emission. The transition to a low-carbon society requires several changes in energy systems, in future is expected a higher role for electricity in transport and heating sector, an increase in fuel prices, a higher integration of renewable energy sources and lower energy consumption. The start of this process is recognized in the necessity to reduce the energy consumption, in particular the focus is posed on the built environment, being one of the major energy consumer sectors. Each nation has realized energy policies based on energy efficiency trough national energy action plans. Action plans provide a general analysis on possible interventions at national, regional or urban level to achieve energy efficiency goals. Urban planning is actually performed considering separately buildings energy consumption and energy investments related to it and change on power plant production; usually, energy efficiency interventions are applied to single buildings or single generation plant, without possibility to analyze the impact of this change in the urban energy system. Current practices don't allow to consider together depth analysis on buildings retrofit and relate change in energy system. Understanding the implication of energy savings measures for the urban energy system require the integration of different tools to study both buildings or power plant at single level and possible change at urban level. Under this assumption, this thesis provides a methodology to analyze urban energy system trough an energy planning tool, with the integration of building simulation tool, to investigate the relation between buildings savings and change in energy system at urban level, to help the energy planning of future investments, with a focus on buildings savings correlate to new investments on district heating. The methodology presents reference buildings simulation with dynamic simulation software to analyze possible buildings retrofit options and, with a study on building distribution trough census data, their effects on heat demand at city level. The interaction of building saving with the urban energy system is studied with an energy planning tool, to investigate the impact on heat supply and possible change of it, to find the best scenario in terms of green house gas emission, primary energy supply and costs. The method is applied to a case study, and results underline the synergy between buildings retrofit and change in power production, specially on the necessity to correlate buildings energy savings with district heating expansion. The best scenario provides the integration of heat pumps in the actual heat production, together with the decommission of existing natural gas power plants, underlining the

importance on future energy investments for reach energy savings goals. Despite the methodology is affected by some uncertainties, it provides an aid to the existing practices for the future urban energy planning and several actions can be made in future analysis to improve the method.

1. *Introduction*

In the last years, several actions have been made for contrasting climate change. According to the IEA [1], it's necessary to limit global warming well below 2 °C beyond pre-industrial levels in 2050 for made reversible the change. However, the process will be irreversible with catastrophic consequence for the planet.

1.1. Toward a low-carbon energy system

The European Union, in 2009, decided to plan a reduction in green house gas (GHG) emissions to be at least 80% below 1990 levels by 2050. To achieve this goal, the European Climatic Foundation redact a study for analyzing the feasibility of this target, in term of economic, environmental and social sustainably: "Roadmap 2050: a practical guide to a prosperous, low-carbon Europe" [2] has been the result, with 3 different volumes. For achieving 80% GHG emission reduction, a change in energy system is needed, take in care that a decarbonised energy system must be secure and competitive compared to the actual system. Major changes in particular will regard to carbon price, technology and networks. For a future decarbonised energy system, the first step will be an energy efficiency increase, especially in building patrimony: in addition to a concrete and relevant energy savings achievable trough envelope improvement and efficiency systems, buildings can be an important field of energy production. For example, roof of buildings is considered a relevant area for solar system installations in future scenario in which the increasing of renewable energy sources (RES) production is forecasted.

In low-carbon societies both transport sector and heating (and cooling) sector will be satisfied by electricity, this will imply an increment in the electricity demand. An increment in the energy demand means an increasing price, for this reason a change in power production must be realized in 2030, or will be impossible contain and assimilate prices [2]. RES production is another focus point for 2050, it's important an increment of RES in the production mix: future electricity needs can be satisfied by several renewable sources like wind power or solar production. A more integrated RES production enhance a supply security, the diversification in mix production allows to be less dependent on few technology and in few fuels, that means a lower dependence from other nations and prevent risk connected to this. For achieve the aim of GHG reduction, RES integration and electricity demand increasing require a change in power plant production. Existing power

plant must operate to the end of their economic life before to be substituted, for this reasons them must be integrated with CCS (carbon capture and storage) systems, that allows a big gas emission reduction. To conclude, a grid expansion must be realized to afford this new demand and mix production.
All of this changes imply a relevant increase in capital costs, for this reason important is engaging the users: society must be prepared for higher energy prices, it's important that they understand that GHG reduction is a commune interest, for health and for the future of the planet. A low-carbon society is a aim that all people must pursue, is a social duty.
For pursue this aim, actions previously described must be coordinated together with a systematic approach, in particular in urban areas, that are relevant consumption hubs, it is important to plan energy interventions. The aim of recent researches is understand how support the energy transition at urban level.

1.2. European trend and energy policies

European nations must work together for reach GHG emission reduction, interaction and cooperation are the key. With a grid expansion, nations could share power sources, electricity produce from renewable sources like wind in north country could be used to supply electrical demand of other base-fuels nations, in the same way nations with more stabile technology could guarantee network stability for countries supplied by intermittence resource.
European Union alone can't contrast climate change, and its decarbonisation measures will be useless if there will not be a global policy that allows a change in energy systems. This means that in future price of fossil fuels must increase to permit industry convenience in clean energy, and all previous analysis needed an increment in average carbon price to drive industries towards gas emission reduction policies.
In the last years, carbon price has been lower than price predicted for 2020 from (ETC), the actual average price is provide to be beyond 18 €/t_{CO2} in 2020, far from 20-30 €/t_{co2} expected from previously study [1]. This gap must be covered from common energy policies because carbon price can influence future investments and future for clean energy. Future scenario whit a high carbon price contribute to decarbonisation system, with new investment drive in low-carbon system, high-carbon supply is retired, electricity price

increase thanks to high energy efficiency, transport and heating are electrified, markets take into account gas emission reduction.

EU Emission Trading System (EU ETS) is the mayor carbon market in the world, give a price for each tone of CO_2 emitted by industry permit to bring gas emission reduction aim and climate policy on the attention of company. Buy credits from emission-saving project allow investments in clean technology and low-carbon solutions. [3]

How previously underlined, in GHG emission reduction high influence is attributed to supply power generation (mix generation), but also in energy consumption. A lower energy consumption can drive the transition to a variegate mix production. In this transition, natural gas covers a fundamental role: in short-term it can substitute other fossil fuels, like oil and coal, in existing building heat systems and in power plants, in long-term scenario can be used for stabilize the production covered from renewable intermittence energy sources. Furthermore, associated with CCS system, also in low-carbon society natural gas power plant can be affordable.[2]

In 2014, European Commission has set new goals in energy policies for 2020 to 2030 period. [4] This framework propose a gas emission reduction 40% beyond 1990 levels, and 27% of power production satisfied by renewable sources. In terms of energy savings, for reached previously goals, energy savings must increase to 25%. However, in 2016 a review has been proposed for fix energy savings to 30% in 2030 in order to boost GHG emission reduction goal. The suggestion is still in negotiation, but results derived from the actual normative are satisfactory, however after an initial decreasing of energy consumption in period 2007-2014, in last two years energy consumption has increased, due to lower fuels price and colder winters [5]. It's important that this increasing doesn't mean a change on future trend, because linear trends for energy savings currently are below predicted trends for reach 2020 goals. In 2017, nations must deliver new national energy action plan for the 2017-2020 period about energy efficiency and new policies for buildings retrofit. High energy savings are due to energy efficiency, and major energy policies regard building sector.

National energy action plan provide guidelines and energy polices to be implemented by the nation for reach GHG savings goal. For example, Italy Action Plan for Energy efficiency (PAE) [6] provide an exhaustive explication of energy policies and initiative adopt in the country for comply to same requirements of EPDB Recast [7], as "Certificati Bianchi" (TEE), fiscal detraction, “Conto termico”, “Fondo strutturale”, information campaigns, measures promoted by regions. Instead, high efficiency cogeneration and district heating expansion are relate to regional action plan; in turn, regions can delegate feasibility study to cities. It’s a hierarchical system, from urban level to national level energy plans must be develop and work together in harmonic way. The necessity to integrate energy policies of different sectors and to explore the synergy between regional energy plan and urban energy plan are developed in the “ Strategia Energetica Nazionale” (SEN), [8] in which is proposed an approach based on the individuation of interventions and application areas respect to the current approaches based on the definition of sectorial energy targets (each sector is considered separately from others).

1.3. The role of building space heating and benefit of DH expansion

Directive 2010/31/EU [7] on the energy performance of buildings wants to reduce the gap between member nations in building energy savings, take in care different climatic condition, indoor climate environment and cost-effectiveness. It’s give information about methodology calculation, minimum requirement for energy performance of new buildings and existing buildings, energy certifications of buildings and independent control system for energy performance certificates.

Energy consumption of building sector is 40% of total European energy use, this means an associated CO_2 emission of 36%.

Space heating counts for 80% of heating consumption in colder climate [9] and heat losses are the cause of this consumption for a relevant part. Major parts of buildings in Europe were built without energy efficiency regulation, and individual heating systems are boiler with energy efficiency lower than 60%. For this reason, energy saving measures covered a fundamental role in building environment, starting from renovation and insulation of building envelope and improvement of energy systems efficiency.

The importance of heat savings in building is well trade in literature, but Hansen et al. [10] underline the importance to find a balance between saving heat and supplying heat: in their study, Energy system approach found that heat saving must be between 30% and 50% respect to actual level. Over that level, costs for savings heat are bigger than costs for supplying heat.

Heat supply is usually provide from boiler in individual houses, but in a future with heating covered by electricity, finding a synergy between heating and electricity production can provide lower cost. District heating (DH) provides 9% of EU's heating [9], it can integrate renewable electricity, thanks to heat pumps and several heat sources.

In [11] Connolly et al analyzed a potential 100% renewable scenario for European Union, following several steps, that can be summarized in 1. Starting point, 2.General Consensus, 3. Individual Heating, 4. Individual and Network Heating and 5.Renewable Electrofuels. In this progress to a 100% renewable society, a big role is attributed to the building sector. Heat savings in buildings are connected to the choice of better individual heating, that is recognized in heat pumps. After that, the advantage to connect individual heating with a network heating is well analyzed, finding that in a urban area district heating is more energy efficient, whit lower gas emission and costs.

District Heating (DH) system present several advantages, like explicate in [12], thanks to the possibility of integrate different heat technologies: boilers, heat pumps, geothermal and solar energy, waste heat industry and all heat loads present in the country. They conclude saying that *"The future EU trend is towards sustainable DH development which will be feasible by reducing the consumption of conventional fuels, by increasing share of RE, by improving energy efficiency and by reducing the impact of the systems on the environment and the human health."*[12]

Connolly and Co. in [13] analyze the proposed scenario from EU Energy Efficiency (EU EE scenario) in Energy Roadmap 2050, in this future scenario isn't forecast the expansion of district heating. District heating can be considerate an energy efficiency measures, but its expansion is strictly connect to a heat densities. Conclusions of the study show that a future expansion of DH in Europe provide the same consumption as predicted in EU EE scenario, but with a reduction of total cost of 15%. Furthermore, DH provides a more realistic scenario, with lower emphasis on heat building saving measures and a higher penetration of different energy sources.

1.4. Thesis aim

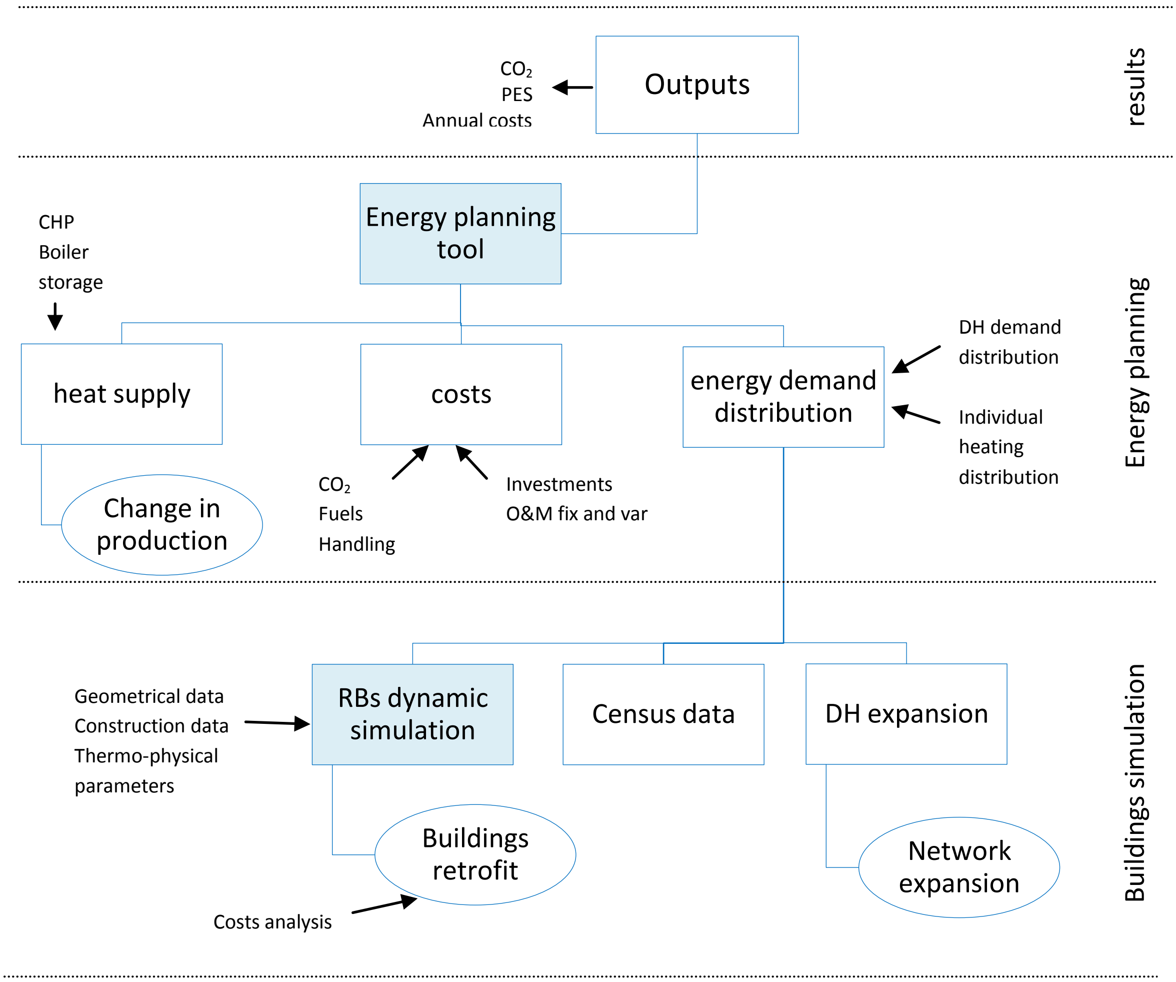
An energy action plan is necessary to pursue national requirements, and a big attention must be concentrate both on building energy savings and on supply sides. Understanding which possible actions can be done in each country, in each city, for apply EU directive need an analysis pursued in several field. The integration between energy demand and energy supply is difficult, several studies are needed to correlate the demand with the supply specially at urban level. The problematic is related to different scales: the energy demand is estimated at buildings level, while energy supply is usual referred to regional scale. The first aim of this thesis is to integrate two different tools that are used for different scales (one for building level and one for regional/national level) and understand if it’s possible apply them to analyze demand and supply to urban level. The aim of this thesis is to analyze a methodology for linking building energy saving measures with a planning on heat production, with a focus on possible DH network expansion at urban level. The scope is to study several energy efficiency scenarios, with building energy interventions and change in heat production, to find the best solution in terms of GHG emission reduction, primary energy savings and costs.

Energy scenarios and different heat supply strategies are analyzed with an energy planning software based on simulation (EnergyPLAN), that provide as results costs, primary energy consumption and GHG emission of an energy system, well explained in chapter 2.1. In part 2.2 building retrofits are studied with a dynamic simulation software, EnergyPlus, together with DesignBuilder, a graphic interface. Building simulations are used as input data for EnergyPLAN, to analyze the impact of buildings savings on the urban energy system and possible demand-supply synergies.

The methodology is applied to a case study in chapter 3 and results are commented in paragraph 3.4. Discussion as well as major key points and limitations with the application of this method are provided in chapter 4, while chapter 5 conclude the thesis with conclusions and tips for further analysis.

2. *Methodology*

The methodology describes in the following sections provides the integration between a buildings simulation tool and an energy planning tool to analyze the urban energy system and to forecast possible interventions in terms of energy efficiency to urban level. Buildings energy demand is analyzed trough reference buildings simulation, while census data are used to study buildings urban distribution to find the total urban energy demand. The total demand is used as input data in energy planning tool together with energy supply data to analyze the entire energy system in terms of CO_2, PES and annual costs (outputs). The interaction between buildings simulation tool and energy planning tool provide a complete analysis in terms of energy demand and supply for a urban level. In the following scheme the methodology is summarized: white rectangles represent input and output data, blue rectangles represent simulation tools application while possible change and interventions on buildings, DH and heat supply are represented in white circle.



Scheme of the methodology

2.1. *Energy Planning methodologies*

Global goals for a low-carbon society required a higher integration on renewable energy sources. Integrate renewable energy in existing energy system and forecast their implementation require a computer tool for the analysis. Connolly et al. [14] analyze tools create for energy analysis (energy tools) used in different researches and provide comparison between them. They define seven different tools types to describe existing energy tools:

1. *" A simulation tool simulates the operation of a given energy-system to supply a given set of energy demands.*
2. *A scenario tool usually combines a series of years into a long-term scenario.*
3. *An equilibrium tool seeks to explain the behavior of supply, demand and prices in a whole economy or part of an economy with many markets.*
4. *A top-down tool is a macroeconomic tool using general macroeconomic data to determine growth in energy prices and demands.*
5. *A bottom-up tool identifies and analyses the specific energy technologies and thereby identifies investment options and alternatives.*
6. *Operation optimization tools optimize the operation of a given energy system.*
7. *Investment optimization tools optimize the investments in an energy-system."* [13]

In conclusion, they describe 37 tools including information about their availability and number of downloads, the different types of analysis that they can compute, the type of tools and energy-sectors consider from tools.

One of them is EnergyPLAN, developed and expanded at Aalborg University, Denmark. It's a free available software, and it is a Bottom-up simulation tool (to generate explorative scenarios). The considered Energy-sectors are the heat sector, electricity sector and transport sector, the tool is able to simulate a 100% renewable-energy system at national or regional level, whit a timeframe scenario of 1 years and hourly time-step simulation.

EnergyPLAN is a deterministic model (with the same input, it will always come to the same results) with the aim of analyze optimal energy system design for a national system evaluating synergies between different sectors [15]. The purpose of the tool is to help the design of alternatives based on the integration of renewable energy technologies. The study underlines the importance of separate energy tool between detailed hour-by-hour simulation or aggregated annual calculation, and between national or regional system level or single project level. Simulations based on aggregate data are more detailed and require more time for collect input data, but if the aim is to integrate renewable sources that present a flexible and intermittence demand, a simulation hour-by-hour is necessary. All of energy tools have the aim of design possible energy scenarios, in term of both technical optimization of sources as investment strategies. EnergyPLAN is able to perform both economic analysis as technical operation simulation of the entirely energy sectors, and supports the choice of different regulation strategies.

2.1.1. EnergyPLAN

"The main purpose of this model is to assist the design of national or regional energy planning strategies on the basis of technical and economic analyses of the consequences of implementing different energy systems and investments." [15]

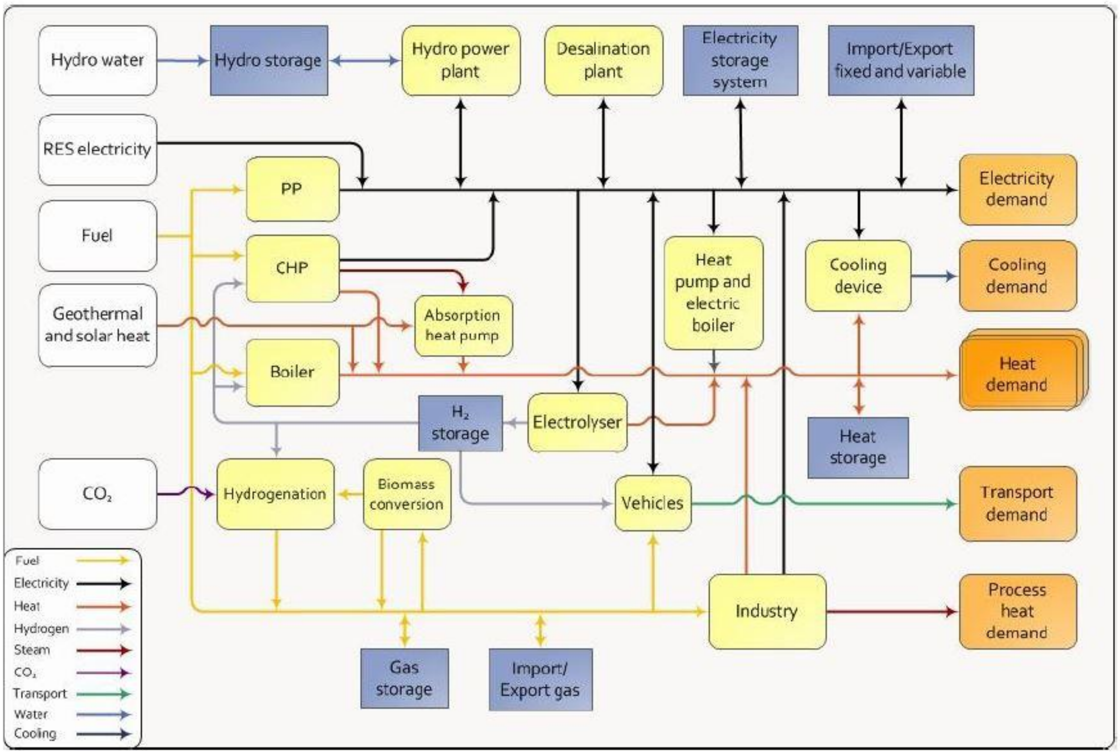


Figure 2.1. EnergyPLAN tool start page [16]

EnergyPLAN is an input/output software. Input data are divide into energy demand and energy supply. Energy demand is separate into electrical demand, heat demand (with focus on district heating demand), transport and industry. Input data require are annual consumption in TWh/year and a hourly distribution. It's possible chose from hourly distribution present in database or a new hourly distribution can be create. The model help to change easily the distribution, for example after a reduction in the electricity demand due to energy saving measures. District heating demand is divided into three groups, in relation to the typology of heat supply.

Input data for supply system are divided into electrical supply, heat and electrical supply, heat supply and fuel distribution. In electrical supply are including several renewable energy sources, correlated with their capacity, energy efficiency and hourly distributions. Heat and electrical supply is divided into three groups:

Group 1. District heating demand is supply by boilers. Input data needed are boiler capacity MW_{th} and their efficiency.

Group 2. DH demand is supply by small combined heat and power plant (CHP),input data are thermal capacity and electrical capacity, together with relative thermal efficiency and electrical efficiency.

Group 3. DH is supply by large CHP based on thermal extraction plant. For simulate this CHP, data needed regard both input data for electrical configuration as input data for cogeneration configuration.

Solar thermal plant, geothermal plant and heat pumps are considered for heat only supply. For each typology of energy sources, capacities and energy efficiencies are related to average values.

Fuel distribution field regard a fuels division based on annual average consumption. Distribution is done by relative number, and all types of fuels increasing or decreasing accordingly. Types of fuel considered are: oil, natural gas, coal, biomass.

After definition of demand and supply fields, it's possible provide element for energy balance. Heat balance is done with thermal storage, data required are thermal capacity and number of storage daily, thanks to this is possible define daily, monthly, seasonal storage. Electrical balance regards grid transmission, with minimum and maximum value allowed.

In conclusion is possible indicate costs, separate in investment costs, fixed and variable O&M, CO_2 price, percentage of interest rate, fuels prices, fuel handling costs, additional costs and several taxes.

Outputs depend on type of analysis, there are two possibility:

- Technical analysis: input data used for the analysis are demand and supply data, to find the optimal technical solution for the energy system described. Outputs consists in annual balance, CO_2 emission and fuel consumptions. In technical analysis two technical simulation are possible:

  Strategy 1- Meeting heat demand. In this regulation, only heat balance is considered.

  Strategy 2-Meeting both heat and electricity demands, heat and electrical balance are considered.
- Economic analysis: input data are costs and taxes, and major distribution is electricity market price. In this case, economy profit is relevant, and simulation provide the optimal configuration for business profit.

Also a feasibility analysis is provided, costs input data are considered without include taxes, and outputs is total costs divided into investment costs, fixed costs, electricity exchange and payment.

EnergyPLAN require a choice between technical and economic analysis, but in technical analysis is also include feasibility study with correlated outputs.

Demand and supply input data can be used for simulating a reference scenario, similar to a real situation, or for simulating a future scenario with change in technology supply for integrate renewable sources or reduction in consumptions.

The model can make an analysis of different energy system based on fossil fuel, nuclear energy or renewable energy.

EnergyPLAN provides several advantages: it’s a free download tool; on the web page is possible find documentations, guides and tutorials to help users; input data are easily to find; it has a user-friendly interface; it’s possible analyze an entire energy systems, demand and supply are divided into sectors. Furthermore, different analysis can be made thanks to the possibility to perform a technical analysis or an economic analysis: a technical optimization study can be integrate with an economic analysis that provide also information about the energy policies followed in the society analyzed.

2.1.2. Using EnergyPLAN for energy planning of national/regional/urban level

EnergyPLAN can be used to simulate a 100% renewable energy system, or to analyzed only a specific energy sector. For understand how it is used, Østergaard [17] collect and divide journal articles applying EnergyPLAN model, showing an increasing of tool application from 2003 to 2014. In major applications, the model is applied to country or state level, with 76 articles about different nations (95 total articles considered). Only 13 articles present a local area, as regions, municipalities, islands or towns. The tool is mostly used for analyzing the integration of renewable energy sources in energy-system, which are the integration limits of RES or what amount can be integrated.

Examples on analysis made at national levels are many, the study of Connolly [11] quote on introduction regard a European level simulation. Also in Heat Roadmap 2050 project, EnergyPLAN has been used for simulate same European country. In Stratego [18] Italy is analyzed and several scenario are performed with the model, a reference scenario (2010) is compared to a 2050 reference scenario (what will happen without change to energy system) and to a 2050 Heat Roadmap scenario (the aim is reach energy efficiency and gas emission reduction hypothesized for 2050). Thanks to EnergyPLAN is possible to quantify the impact deriving from future energy efficiency measures in terms of primary energy, CO2 emission and annual total costs. Examples of results are shown in the following figures.

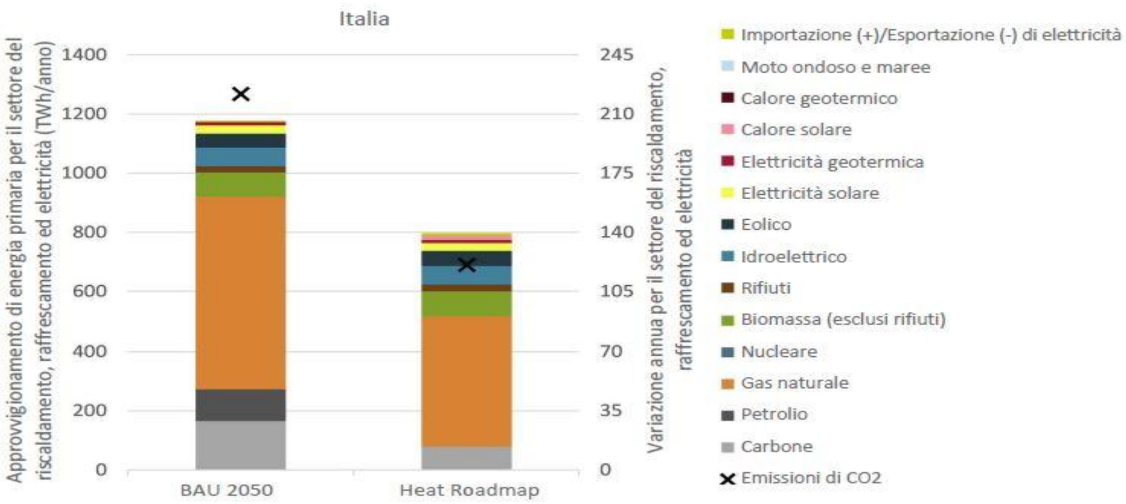


Figure 2.2. Primary Energy sources and CO2 emissions for Italy in Stratego study [18]

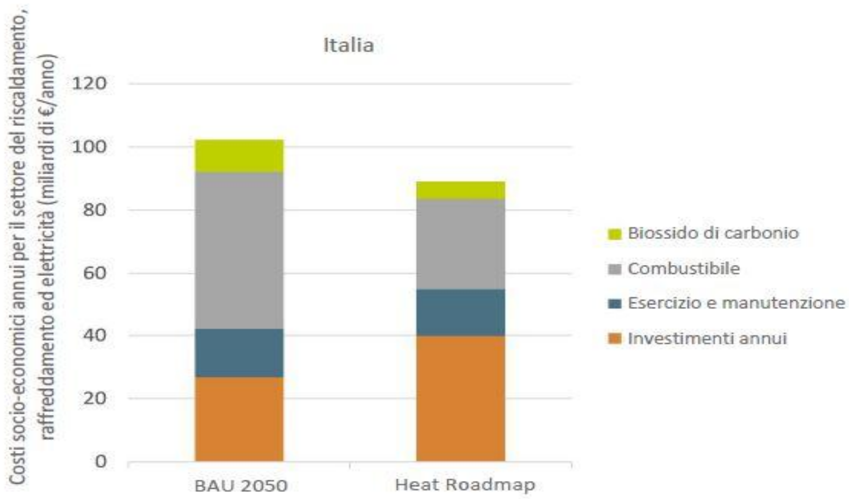


Figure 2.3. total costs for heating sector, cooling sector and electricity sector for Italy in Stratego [18]

At regional level, an energy system model for Hong Kong was developed in [19]. The aim of this study is to create with a EnergyPLAN a reference scenario from Hong Kong that could be compared with two other scenario, Gov 2020, scenario that analyzed government decision of substitute coal-production by an increase of nuclear power, and RE 2020 scenario, an alternative scenario in which coal is substituted by renewable sources, without a nuclear increasing. Reference scenario simulate with EnergyPLAN is compared with real data about electricity demand and production, CO2 emissions, find that simulation agree with actual data. As results, same goals for gas emission reduction and coal power reduction are obtained with each scenario, but obviously a high penetration of renewable sources is better than nuclear energy, above all because after Fukushima accident, Hong Kong government decide to change their nuclear policy.

Urban area present in very few articles, city level is analyzed in [20] for an Italian city, Corinaldo. Focus of the study is the integration of micro-combined heat and power systems for the building sector. Energy demand is well defined in each sector, and several renewable generation capacity are introduced to pursue a energy saving and gas reduction emission for the city. The problem of grid transmission capacity due to an high integration of renewable sources is taken in care, a further attention is posed on the gradually integration of different technologies for CHP: authors underline that is not possible analyze together different technologies because EnergyPLAN considers only aggregate heat demand and also aggregate supply, only average values can be insert.

Recently researches are interested on urban applications of this tool, but it is not clear if EnergyPLAN is adapted for detailed analysis like that require by urban scale. For this reason, the focus of this thesis is to understand and to explore which are benefits and limits of its application to a urban scale, and which type of results can be obtained.

2.1.3. DH studies with EnergyPLAN

The aim of this thesis is simulate possible building retrofit and to analyze the energy savings impact on the energy system, focusing on heat demand and consequent heat production by using EnergyPLAN. In the introduction, the importance of consider and expand district heating is well explained in [21] where Lund et al. consider the possible expansion of DH in future Danish energy system. Several alternative options are provided for heating house system, like individual heat pumps, individual electric heating, micro CHP units and several possible connections to DH. Results show that district heating solutions are the cheapest options, and cost of district heating network expansion are not relevant compare with total costs. The study don't take in care important technologies as geothermal heating, solar thermal heating or biogas production that district heating can help to integrate, like shown in figure 2.4.

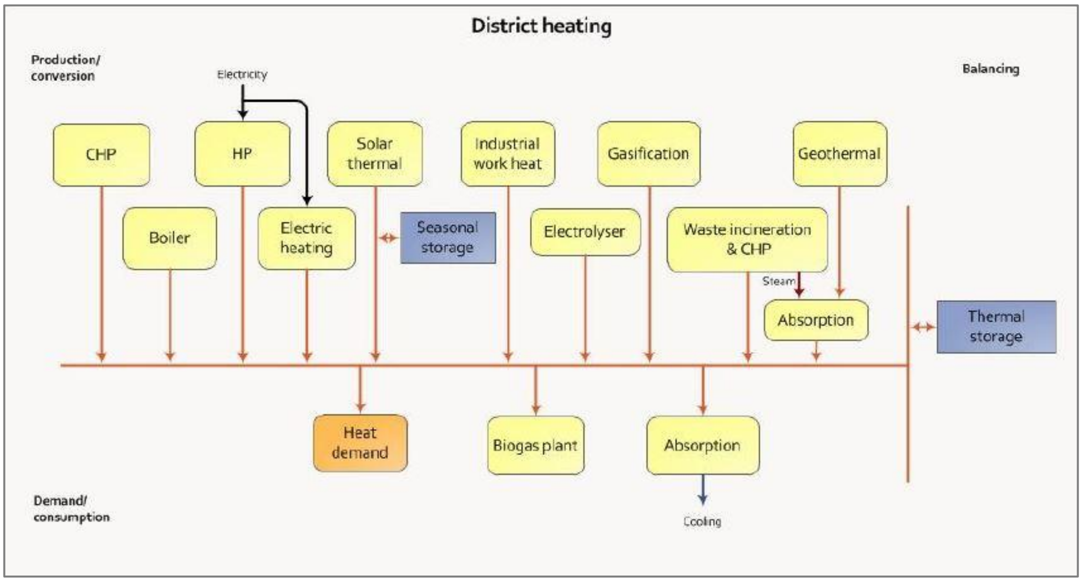


Figure2. 4. District heating interactions in EnergyPLAN tool. [16]

An example of the integration of district heating with a renewable heat source is provide In [22]. The role of geothermal energy in combination with an absorption heat pump is provide for Frederikshavn, a city of Denmark. Results show that without geothermal energy, the heat production of district heating is covered by boilers with higher consumption of fuel and higher emissions. Integrating an absorption heat pump which use low-thermal heat extract by a geothermal plant boilers production decrease and also fuel use. Thanks to the possibility of interaction of several energy sources, EnergyPLAN tool is used in articles and papers for analyzed the expansion of district heating related to a decreasing of heat demand in residential sector due to energy efficiency measures. EnergyPLAN can be used for perform different types of analysis as shown, but it request an aggregate heat demand for district heating and also for individual heating. Analyze heat consumption of building sector for the area of study to create heat load distribution to use as input data for the tool, and consequent change in the distribution due to energy savings measures, is the problem that this thesis want to stress.

2.1.4. Buildings heat savings with EnergyPLAN

In literature, this problem is trade in different ways. Energy savings measures in the building sector implies a percentage decrease of heat demand. The percentage is determined from previous literature or study, as in [21], or from the analysis of a standard building case, in which future energy efficiency standard are applied, as in [20]. EnergyPLAN is able to adapt the hourly distribution provide for the basic scenario to follow the demand variation. A more precise and extend analysis is done with heat atlas methodology, that is used to quantifies and located heat demand in building sector. In Denmark [23] a heat atlas is provide for each single buildings so the net heat demand is calculated for each building using net floor area, and each building is divided for type, age class and construction period. The heat atlas is designed as a geographical database using geographical information systems (GIS). The use of a generic heat demand models, which calculate heat demand on the basis of specific heat demand as a function of building use, age and floor area is a source of uncertainty, as underline by Möller and Lund. In [24] heat atlas methodology is used for asses a heat demand to building stock of the town of Frederikshavn, and empirical data of specific heat saving potential are use to assess the potential energy saving of buildings. Also in this case, the total amount of heat demand of the city and its hourly distribution are provided from registered data, and reduction of 20% of heat demand has been supposed. How underline by Petrović in [25], a detailed heat atlas has been defined for Frederikshavn, but they have predefined a heat demand reduction and did not analyzed heat saving in detail.

A difference approach for attribute heat saving potentials of the built environment is used in Stratego project. As explain in [26], heat demand distribution in absence of real data is construct considering heating degree days (HDD) of nation. If outside temperature is 15°C, indoor building temperature is almost 17-18°C, and if outside temperature is below 15°C, also indoor temperature decrease, for this reason outside temperature is used for estimate the heat demand. HDD are calculated based on the difference between set-point temperature (15 °C) and outside temperature, the difference reflect the heat that is request at that time. The methodology is applied each hour, considering that if outside temperature is above set-point temperature, HDD are set to zero. Of course, this methodology is strongly dependent of set-point temperature choice. Energy demand of buildings is analyzed with BEAM tool [27], that require more input detail for simulate building stock: age groups, reference building geometries, thermal quality of building envelopes (with reference u-values or u-values required for energy efficiency policies) and climate data, with in output annual heat demand for building. In this case, hourly distribution don't depend on real data, and energy savings is more detailed thanks to the introduction of reference u-values and geometric data.

Two different approaches are used in literature for analyzed energy saving potentials of building sector and use the results as input data for EnergyPLAN simulation. In the first case, heat atlas provide a georeferenced heat consumption of each building, and hourly distribution is obtained from real data. In the second case, a reference building is simulate take in care climate data and building envelope, and hourly distribution is constructed from HDD methodology.

Each analysis provides a separation between hourly distribution and heat building demand. In this way it's impossible provide regulation measure that can ensure an energy savings, but this will be study in deep in chapter 3.

For stipulate a urban energy planning, it's necessary know which are the high-energy-density areas, which buildings require energy savings interventions, but these information can't be obtained by EnergyPLAN, for reach this type of detail a dynamic simulation software must be integrated for study the built environment and possible energy savings measures relate to it. A dynamic simulation software provides also the possibility to analyze building heat hourly distribution, as explained in the following section.

2.2. *Reference buildings and dynamic buildings simulation*

In the previous sections, the problem of attributing energy savings potentials to the built environment is emphasized. In literature, different models are used to evaluate energy consumption of urban level. As described in [28], urban energy models can be divided in:

1. Top-down and bottom-up approach. Top-down approach uses a total energy consumption of a sector, so it can't attribute a energy consumption to each building. On other hand, bottom-up approach considers energy consumption of each single building and the entire building stock consumption is construct as the sum of single building demand. They are used for define annual total energy demand.
2. Micro-simulation, each building of a city is simulated and is part of the total urban energy demand. Building energy simulation (BES) are used for simulate a stand-alone building (e.g with EnergyPlus tool), but this type of approach doesn't allow the interaction of the building with the urban structure. Urban building energy simulation (UBEM) are made to take in care urban surrounding, and city energy simulation (CEM) are use to simulate a large number of buildings.

An alternative approach, called GIS-based simulation, is used to attribute energy consumption of each building of a city trough a Geographical Information System (GIS), and also geometrical data can be extracted by it.

The bottom-up approach is chosen for this study, because the disaggregation of the heat demand is required for analyze in depth buildings energy savings at urban scale. Starting from buildings level several energy efficiency interventions can be analyzed, and summing all the single building consumption, the aggregate demand can be performed, as request by EnergyPLAN.

2.2.1. Building stock energy consumption

Jarre et al. [29] used information about energy building consumption and relative data analysis to help the Public Administration of Turin to decide future retrofitting interventions in public buildings. In general analysis they collect data about monthly consumption and expense of both gas and electricity, about geometry, and then evaluate specific energy consumption referred to gross heated volume and related expense for each building. Buildings are divided into category of use, energy consumption and energy cost, and in detailed analysis only five of that buildings are analyzed. A software has been programming to analyze energy consumption to identify bad controls that can cause an increment in energy consumption, consequently hypotheses regard low-costs intervention are made, whit relative percentage energy saving. The aim of the study is to identify low-cost interventions for energy savings of public buildings starting from available consumption data.

A method to determine the Statistical Distribution of Buildings according to primary Energy use for heating (E-SDOB) starting from Census data is proposed by Fracastoro et al. [30]. Primary energy consumption of a region area is calculated starting from statistical data about building typologies and their number, using sources like census, literature, energy statistics, while European standards are use to attribute energy consumption for each building, with a time period equal to a month: defined the geometry in terms of floor area and building envelope surface, construction data as u-values and thermal plant efficiency are define considering standard UNI. Starting from census data, 72 building typologies are identified for represent building stocks and primary energy consumption is calculated for each of them. A reference value is than found for stocks analyzed, and at each buildings typologies is attributed a class of the energy performance scale (A to G). E-SDOB can help to understand which buildings can be subjected to specific retrofit measures, and their distribution on the territory.

The building stock of Finland and its energy saving potentials is analyzed trough an MS Excel base modeling tool called REMA by Tuominen et al. [31]. REMA is use to forecast the development of energy consumption in a building stock, using input data about energetic properties of building coming from a dynamic simulation tool IDA-ICE. The built environment is divided into 4 building types (detached houses, apartment buildings, commercial building and holiday homes), also divided into age groups. Representative buildings of different types and ages are simulated with dynamic software to attribute them an energy consumption, then the energy consumption is modeled with REMA take in care the future development of the building stock (for example, a reduction in energy consumption). As output, REMA calculate a linear development of energy consumption or in CO2 emission at a determined time.

A GIS approach is proposed in [32], in which geometrical data with statistical analysis are use to identify Reference Buildings at urban level. Trough GIS at each building is possible attribute geometrical parameters (floor area, perimeter, gross volume) and a Reference Building with its specific parameters (envelope material and thermo-physical characteristic) and all census variable, with the creation of a GIS building database. After that, energy demand is associated to Reference Buildings trough real energy consumption data or using energy simulation software. The same approach is followed in [33], but the bottom-up approach used for attribute building energy consumption is than correct with a urban energy models with top-down data.

A similar study has made by Caputo et al. [34], four building archetyping with different number of floor, form factor and size and seven construction age classes are identify and simulate with EnergyPlus tool. At each building of the city is attributed a building archetype with the calculated energy consumption and a GIS database is created in order to stabilize building energy performance and possible energy savings potential. In this case, several energy savings measures are applied to archetypes and simulated with dynamic software, than GIS database is updated with new simulated data. GIS approach allows to evaluate also which part of the city present higher energy density and where interventions must be concentrate.

These models are an implemented version of the usual bottom-up approach, they consider in a simplified way each building of a city, but neglect real urban built dynamics.

A completely different model to attribute energy consumption to single building in a city is proposed from Monsalvete et al. [35]. A modular physical building model is developed in INSEL8 and is connected with urban geometry data models in the CityGML. This process can be done easily thanks to the separation of building model into different blocks. A urban energy simulation platform, called SimStadt, has been create to calculate thermal energy demand of the city. CityGML is the base of the platform, a 3D model of each building of the city is create with different level of accuracy, and thanks to the platform, geometric data, building physics properties and weather data are connect to each 3D building models. After, 3D models is match to a physical model thank to the blocks separation and dynamic energy simulation is performed with INSEL.

In this thesis, building level is analyzed trough dynamic simulation of reference buildings, and census data are use to provide a building distribution at city level. As from bottom-up approach, total energy consumption is calculated summing reference building energy consumptions.

2.2.2. Reference Building approach and TABULA project

To analyze the built environment is necessary referring to the concept of "reference building". A Reference Building is defined as "*buildings characterized by and representative of their functionality and geographic location, including indoor and outdoor climate conditions.*" in Directive 2010/31/EC [7]. RBs must be representative of the built environment of a nation or a city, but simulate a RB is complex because require a lot of data usually difficult to find, especially for performed an accurate dynamic simulation with a dynamic software, as explain by Corgnati et al. in [36]. The data needed for simulate a RB can be summarize:

1. Form, regard building type
2. Envelope, construction material and thermo-physical properties
3. System, regard every energy system present in the building.
4. Operation, parameters that influence building usage and are define trough time schedule (e.g. electrical system or occupancy).

An international project called Typology Approach for Building Stock Energy Assessment (TABULA) has been develop for three years (2009-2012), with the aim to define an European building typologies in order to estimate the energy demand of residential building stock at national level [37]. Building typologies are classified for construction period, type and shape of building for different climatic zone. Three different methodologies are applied for define building type:

- "Real Example Building"(ReEx), if statistical data are not available reference building is choice by a group of experts.
- "Real Average Building" (ReAv), building with characteristics similar to a sample of buildings is choice following statistical analysis.
- "Synthetical Average Building" (SyAv) building type is identified as an archetype, a virtual building with properties characterizing a sample of building.

Eight construction period are identify: class I (up to 1900), class II (1901-1920), class III (1921-1945), class IV (1946-1960), class V (1961-1975), class VI (1976-1990), class VII (1991-2005), class VIII (after 2005).

Four “Building Size Classes”: single-family house (SF), Terraced house (TH), Multi-Family house (MF), apartment block (AB).

For Italian nation, middle climatic zone is chosen.

Construction material and thermo-physical properties are attribute to each construction period trough experience and scientific literature, also for energy systems.

In TABULA report is possible find information about geometrical data, number of floor and apartments, heated volume and floor area, typologies and efficiency of energy system, u-values of each construction material considerate [38].

Energy calculations are done with a steady-state calculation following European standards and national standard. In the same ways, two levels of energy savings potentials are provide with the relative additional level of insulation required.

Figure 2.5. shows the Italian building matrix presented in TABULA project. Multi-family house and apartment block from class I to class VII are chosen as “Real Building Example”, the rest of buildings are archetypes.

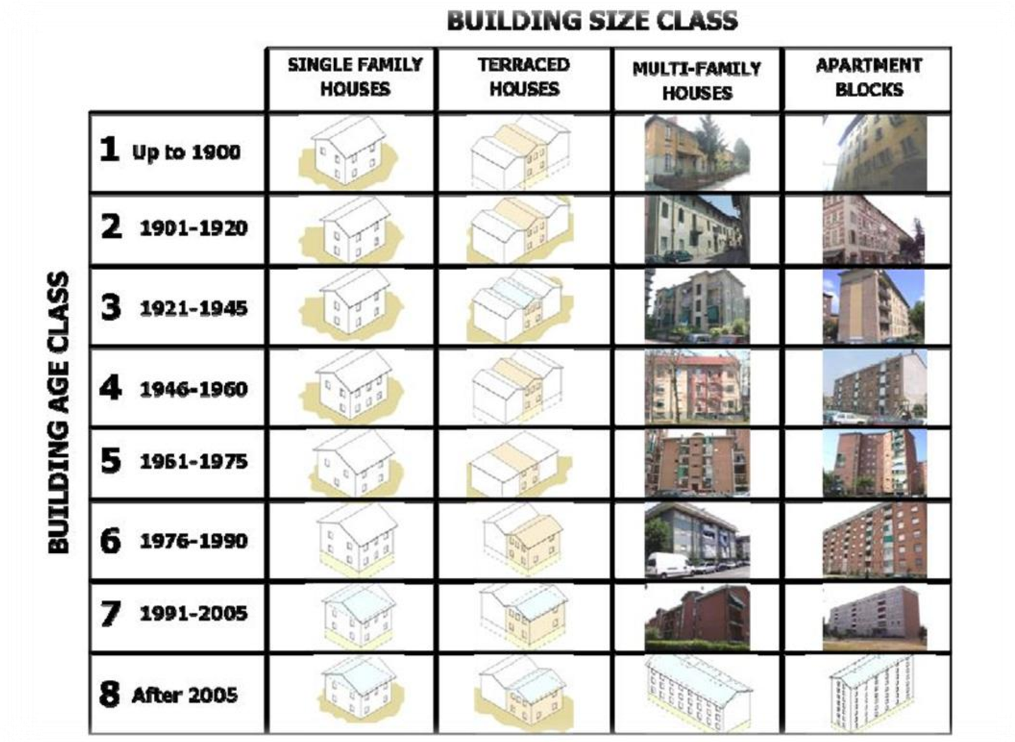


Figure 2.5. Italian building Matrix of TABULA [37]

Major information can be found on the website of the project, TABULA WebTool [39], in which TABULA project of each country is proposed. Following TABULA data, Reference Building can be simulated for each nation and each city, how explain in the case study. After RBs simulation with dynamic software to analyze its energy consumption, it's necessary find the frequency of building typologies in the city to create the total energy consumption. Census data provide from ISTAT are use, match together with a census map for estimate the building distribution at urban level. Census data give information, for each census sector, about number of buildings, subdivided into four building typologies (Apartment Block - AB, Multi Family - MF, Terraced House -TH, Single House - SH) and the nine construction periods of census data are merged into 3 construction periods (pre 1980, post 1980, post 2006). In the same way, gross heated volume, net heated volume and gross heated surface are provided. Thanks to census data, a frequency of building distribution of each census sector is well known, and at each building can be associated a RB, with its energy consumption. Summing together each buildings consumption, a total energy demand of the urban system can be obtained.

2.3. *Methodology application*

The aim of this methodology is to analyze the urban level in terms of energy demand and energy supply, to help the urban energy planning to forecast the best future energy efficiency investments. This is done connecting an energy planning tool (able to consider the aggregate energy demand of different sectors and the relative energy system production) with a tool for studying building energy savings.

Building simulation with a dynamic software give the possibility to analyze the effective impact of energy savings measures on building, for example inserting a insulation material on wall or improve efficiency of energy system the change on heat consumption of building can be studied.

Census data of a city provide buildings distribution at urban level, and each single building simulation can be connected to this spatial distribution to create the total heat consumption of a city. Change in building consumption due to energy interventions can be analyze for the entire built environment and this variation in energy demand influence the production of thermal plants. Thanks to the energy planning tool, the impact of building saving on heat production can be studied together, at the same time it's possible analyze how change in heat supply can be integrated on the urban system.

EnergyPLAN is chosen because provides several advantage, first of all is a free-download tool with exhaustive guides and documentations easily findable on the web page. Aggregate data input are a source of uncertainty (as explain in chapter 4.) because require average values but at the same time they are easily to find.

The tool allow to analyze the entire energy system and the interaction between different sectors as transports, electricity and heat, in this way change in transport, for example the transition from fuels to electricity vehicles, can be analyze in relation with its impact on the electricity system.

The possibility to study these interactions with a single tool provide several advantage, specially for urban energy planning, in which these relations must be take in care and study in deep. The methodology applied in this thesis is a resource to analyze in deep buildings energy savings and their effects on the urban energy system.

3. *Case Study*

The methodology previously described has been applied to a case study: the city of Turin. Turin is a city situated in northern Italy, whit 2706 heating degree day (HDD). According to previous literature, heating volume of residential building is almost 139 Mm3 [40]. The district heating (DH) presents in the city is one of the most expanse in Europe, with 550 km of pipes line and 60.3 Mm3 connected to it. The heat production is satisfied for the 98% by three different cogenerating thermal plants administrated by IREN Energia [41], with a total of 1200 MW electrical power installed and 740 MW thermal power in cogenerating configuration. In table 1 data for the three power plant are assumed.

Table 1. Power plants of Turin [41]

	MW_{th}	MW_{el}	η_{el}	η_{cog}
Moncalieri 2GT	260	400	0.58	0.90
Moncalieri 3GT	260	400	0.57	0.87
Torino Nord	220	400	0.56	0.85

The remaining heat need is satisfied by natural gas boiler, with a thermal power installed of 1000 MW. Three thermal storages are distributed in the city, with a total capacity of 430 MW.

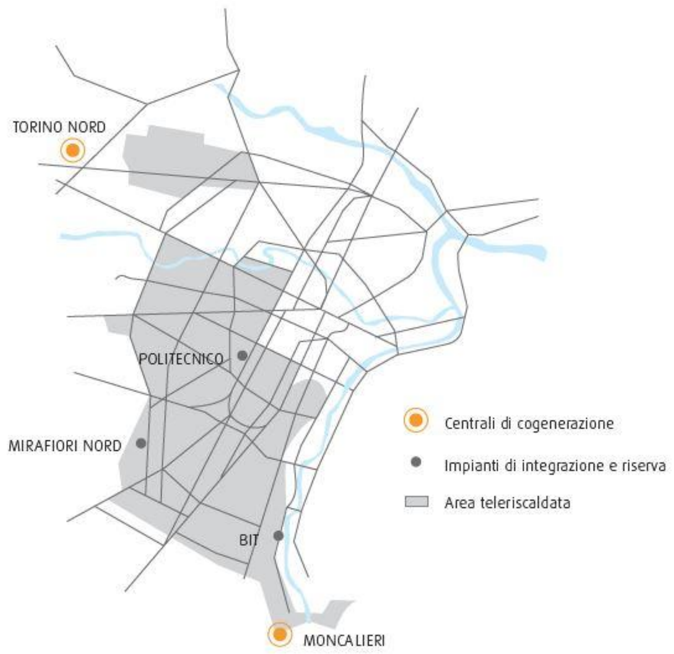


Figure 3.1. district heating of Turin [41]

In section 3.1. a reference scenario is simulated in EnergyPLAN to analyze total heat consumption and production of the city, in terms of primary energy supply, total costs and CO_2 emissions. Then, in 3.2. Reference Buildings (RBs) are simulated with a dynamic software, and possible building retrofit options are applied to the models thus created in 3.3. Thanks to census data, buildings distribution of the city is investigated and reference buildings data are attributed to volumes of interest in order to create heat load profile of the city in section 3.4. RBs simulations results are used as input data for future scenario in EnergyPLAN, considering also possible change on supply side (chapter 3.5) and relative costs (chapter 3.6). In section 3.7. the methodology and its application outputs are commented.

3.1. *Base scenario with EnergyPLAN for Turin.*

A base scenario is created with EnergyPLAN, with the aim to analyze heat consumption and heat supply of the city. Focus of this scenario is on heat consumption of the district heating, and heat supply from cogenerating heat and power plants. Real data of heat consumption of district heating are provided by IREN, manager of district heating, for year 2014. Hourly distribution is created (considering 366 days with a total of 8784 hours/year), and total annual heat consumption is 1.99 TWh/year. In 2014 district heating supplied heat to 57 Mm3.

District heating consumption is attributed to group 2 in EnergyPLAN (see section 2.1.), and heat supply is attributed to CHP in group 2 with a thermal power of 74 MW and electrical power of 1022 MW. In Table 2 data used for heat supply are summarized, considering the necessity of aggregate the production as request from the tool. A thermal power of 1000 MW is considered from natural gas boiler with an energy efficiency of 0.90 and 0.430 GWh are considered for daily thermal storage. CHP and boilers are fuelled by natural gas.

Table 2. Input data for EnergyPLAN simulation of heat supply

	MW_{th}	MW_{el}	η_{el}	η_{th}
CHP group 2	740	1022	0.449	0.361
Boilers group 2	1000			0.90
Thermal Storage group 2	430			

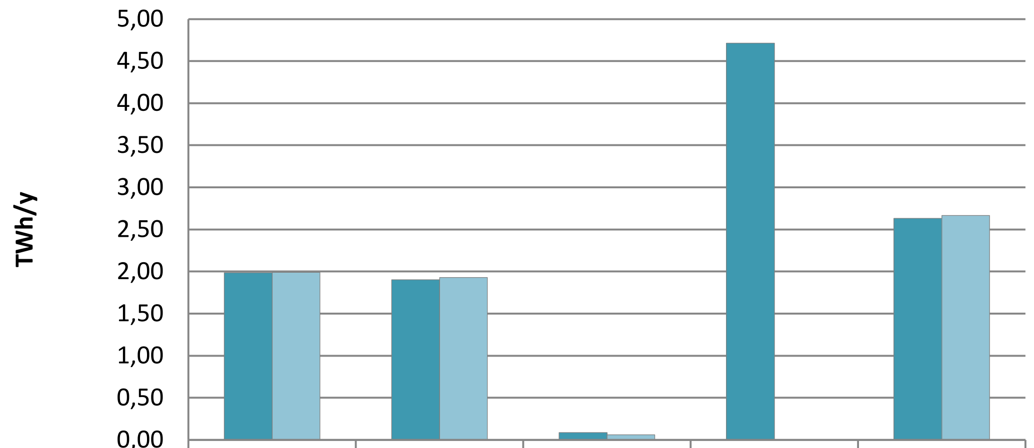
The analysis is performed in group 2 because the main activity of CHP plants in Turin is to produced heat: for 99% of time they work in cogenerating configuration, so it is reasonable to don't considered the contribution of the electricity configuration.

First simulation is done without considering individual heating, in this way simulation outputs are compared with real data and the accuracy of the simulation is analyzed.

Technical simulation with strategy 1 (Heat only balance) is chosen, because electrical consumption and production are not taken in care in this study.

Outputs provide a heat production divided in 1.93 TWh/y from CHP and 0.06 TWh/y from boilers. Fuel consumption is 5.41 TWh/y of natural gas, with 1.093 Mt of CO_2 emissions.

Results are compared with real data as shown in Figure 3.2.



	consumption	CHP heat	boiler	storage	CHP el
Real data	1,99	1,90	0,09	4,72	2,63
EnergyPLAN	1,99	1,93	0,06	0,00	2,67

Figure 3.2 Real data vs EnergyPLAN simulation of heat production

EnergyPLAN simulation increase CHP production of 1.26 %, and decrease boiler production of almost 28%. This high difference in boiler production is due to the different use of thermal storage made from the tool respect to the real situation. In the real configuration, thermal storages are used to contain excess heat produced from CHP during night to cover morning heat peak demand, as show in Figure 3.3. for a day in January.

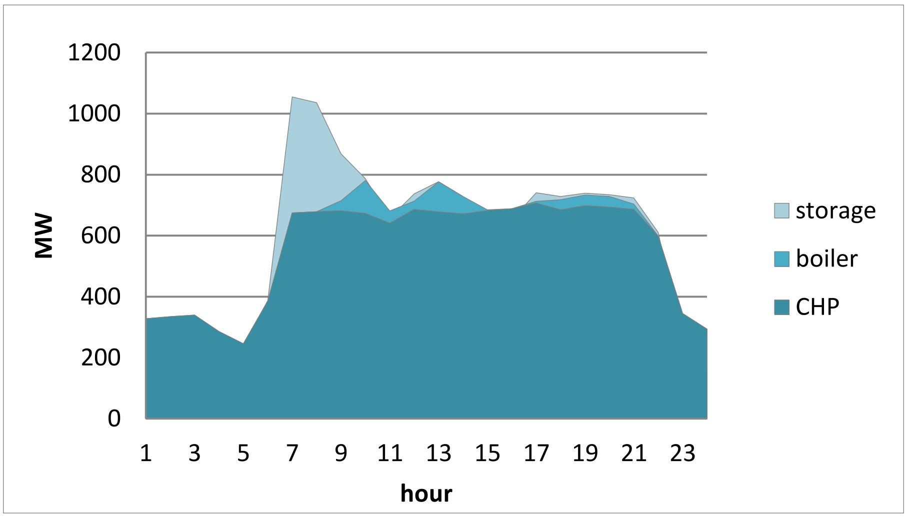


Figure 3.3. Real heat production in a typical day of January

Thermal storage in EnergyPLAN is used to allocate CHP heat excess in order to permit a major production of electricity from CHP. Strategy 1 does not consider electrical balance, so thermal storage are not used.

The differences in terms of CO_2 emission and PES is summarized in table 3, EnergyPLAN simulation produce for both 1% more than real data, so the simulation is considered accurate.

Table 3. Difference outputs real data vs EnergyPLAN

	CO_2 (Mt)	Fuel (TWh/y)
Real data	1.085	5.37
EnergyPLAN	1.093	5.41
%	+ 0.75%	+0.73 %

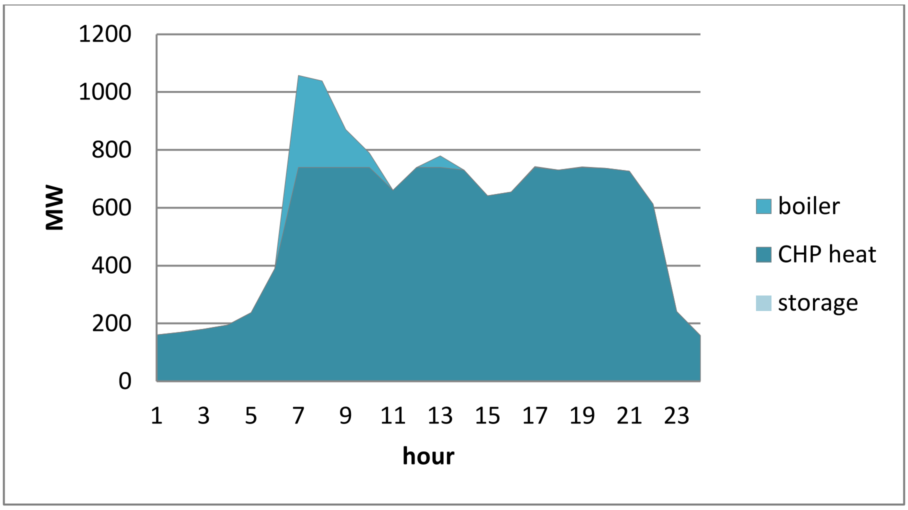


Figure 3.4. EnergyPLAN heat production in a day in January

3.2. Dynamic simulation of reference buildings

Turin has 36158 residential and occupied buildings according to census data, subdivided into nine construction periods, that have been reduced to eight classes in Figure 3.5 to be comparable with the eight age classes assumed by TABULA project.

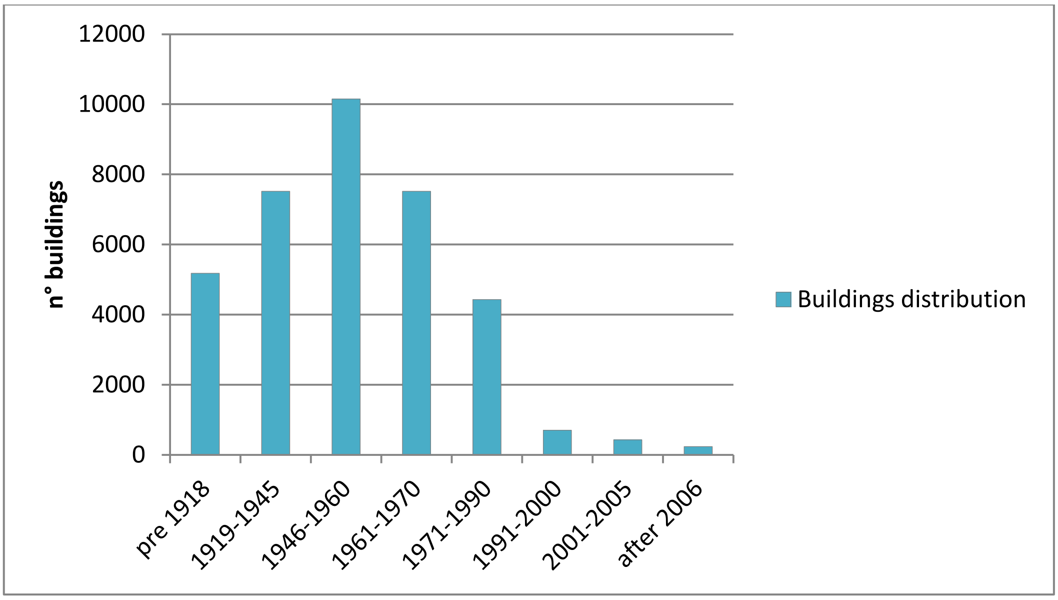


Figure 3.4. Turin Buildings distribution for construction period.

In Turin almost 96% of buildings was built before 1980, and 40% of them are apartment block (AB) and 28% are multi-family house (MF) (Figure 3.6)

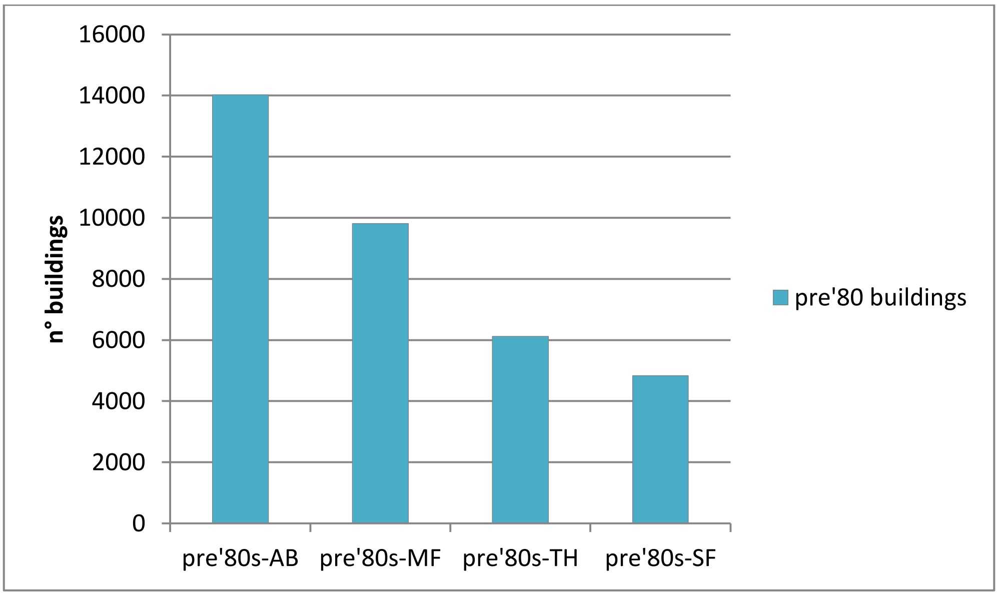


Figure 3.5 pre'80 buildings distribution for building type

For this reason, Reference Buildings choice for this study are apartment block, for three age: AB class IV, AB class V, AB class VI. The three classes are chosen according to their sampling number in the city.

It's also important to underline that district heating is connected to buildings with a heated volume higher than 2500 m^3 [42], so it's correct to assume that building types connected to DH in Turin are AB and MF.

TABULA project is used to analyze the city of Turin: the age classes used to analyze the buildings distribution of the city are chosen according to TABULA, and several information about RBs representative of the classes chosen are extrapolated from the project.

A matrix with 32 different type of building is presented in [42], and a schedule for each RB presents data about: heated volume, floor area, number of apartments, number of floors, surface to volume ratio (S/V), construction material with total u-values, energy systems with their energy efficiency and heat consumption result from steady-state calculation. Other information derive by author assumptions.

This data together with information find in TABULA WebTool [39], are the basis for the following Reference Building simulations.

Stratigraphies are hypothesized for roof, floor and walls (two types of wall are simulated for each RB). A lower insulation is performed, as request in TABULA (U ≈0.8 W/m^2K), and material data and thermo-physical properties are taken from UNI 10355 and UNI 10351 [43], while for resistances the reference norm is UNI 6946 [44].

All structures neighboring with non heated zone, as suggested in UNI 6946, provide a superficial resistance equal to the internal superficial resistance for each side. (see Appendix 6.1.)

A building layout is created starting from available data of floor area, gross volume of building and compactness (S/V).

RBs simulations are performed by DesignBuilder software, a graphic interface based on EnergyPlus, a dynamic simulation tool.

Heat energy requirement is calculated following TABULA indications and procedures reported in UNI 11300-part 1 [45], in this way simulations results can be compared to TABULA results.

Assumptions:

- Calculation related to heated floor
- Air exchange 0.3 vol/h
- Frame factor 0.8
- Total internal gain for heated floor as indicating (paragraph 13.1.1)
- Absorption factor of opaque component as norm (paragraph 14.2)
- Thermal bridge related to UNI 14683:2008 [46]
- Unique thermal zone for each flat
- Internal partitions considered adiabatic.
- Heating 24 h and internal set-point temperature equal to 20 °C

It's important to note that energy systems are not taken in care in this simulations, only heat needed is calculated. This is because the aim of this process is to use results (hourly heat demand) as input data for EnergyPLAN: information about energy systems typology and relative energy efficiencies will be also insert as input data in the tool.

3.3.1. Evaluation adapted to users

Energy analysis performed under previously assumptions is called "standard" evaluation, and it is compared to TABULA results. After that dynamic simulation of RBs is considered accurate and reliable respect to TABULA results (the difference in energy consumption between the two models is in the order of 1% for each RBs), it's necessary relax assumptions made in previous simulation to create a real heat needed of building, taking in care occupants behavior, intermittency of heating and operating schedules of electrical equipments. In literature several studies consider the influence of occupant behavior on the heat consumption. There is a relationship between occupant behavior and hourly profile of thermostat set point and set-back for heating, as underlined in [47]. The study analyzes three different RBs (also defined following TABULA data and simulated with EnergyPlus) with three different occupant behavior scenarios, and results show that occupant behavior influences heat consumption and can alter the effect of energy savings measures. A similar analysis is done by Barthelmes et al. [48], occupant behavior influences largely the building energy use, the study expresses the need for more reference models related to human behavior in different building typologies.

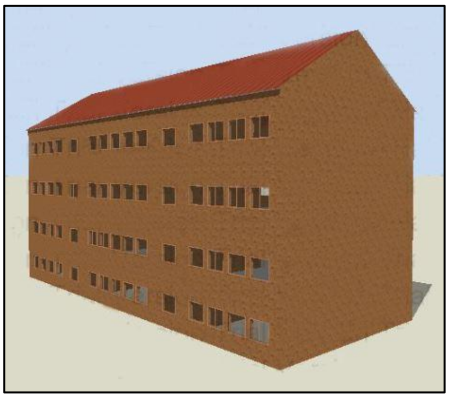
In this thesis this argument is not stressed, since the aim is to use reference building to simulate all the built environment in the city, then it's not possible made depth hypothesizes on occupant behavior. Internal gains as internal light, electrical equipment and people are aggregated with a single operating schedule, called "internal gain schedule". Hourly profile of the schedule is extrapolated from UNI 11300 part 1, this is done in order to have a reliable hourly profile, because information are too few to create a more complex hourly profile. (see Appendix 6.2.)

Furthermore, operating of heating must be reported to real case. It has been supposed that heating starts on 5:00 am and stops on 9:00 pm, with a set point temperature of 20 °C and set-back of 16 °C. With the aim to compare simulated heat consumption with real data provided by district heating supplier, hourly heat operating of RB is stressed to be the same of district heating load profile. This assumption will be analyzed in depth in discussion section (chapter 4.)

In the following pages it is possible to see Reference Buildings data used and simulations results.

AB, 1945-1960

Geometric data			
Parameter	Symbol	Unit	
Gross heated volume	V	m^3	5949
Net floor area	A_n	m^2	1763
Shape factor	S/V	m^{-1}	0.46
N° apartments	-	-	24
N° floors	-	-	4
Gross heated surface	S	m^2	2746
Gross heated floor	A_l	m^2	1595
Windows area	W	m^2	217
Reference floor area	A_{ref}	m^2	1478



Construction data						
roof	walls		Lower floor	Upper floor	Window	
U(W/m²K)	U_1(W/m²K)	U_2(W/m2K)	U(W/m²K)	U(W/m²K)	U(W/m²K)	$g_{,gl}$
1,8	1,15	2,6	1,65	1,3	4,9	0,85

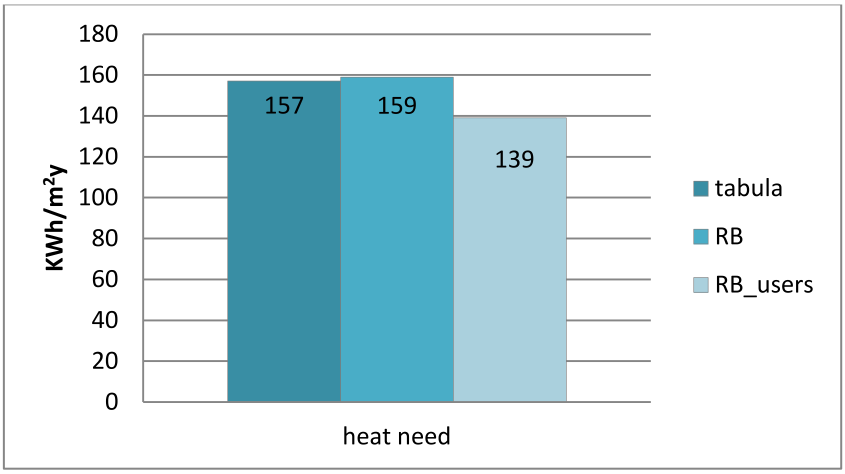
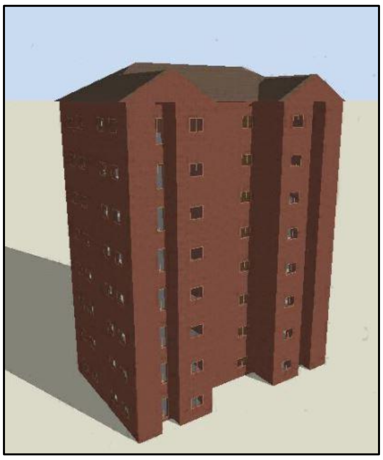


Figure 3.7. Heat need for AB 1945-1960

Standard simulation overestimates heat need of 1% respect to TABULA, and simulation adapt to users provide a heat need reduction of 13% with respect to standard simulation. Heating need for reference building AB 1945-1960 is 139 kWh/m²y.

AB, 1961-1975

Geometric data			
Parameter	Symbol	Unit	
Gross heated volume	V	m^3	9438
Net floor area	A_n	m^2	2869
Shape factor	S/V	m^{-1}	0.46
N° apartments	-	-	40
N° floors	-	-	8
Gross heated surface	S	m^2	4346
Gross heated floor	A_l	m^2	2483
Windows area	W	m^2	321
Reference floor area	A_{ref}	m^2	2159



Construction data						
roof	walls		Lower floor	Upper floor	Windows	
U(W/m²K)	U_1(W/m²K)	U_2(W/m²K)	U(W/m²K)	U(W/m²K)	U(W/m²K)	g,gl
2.20	1,10	1.13	1,65	1,56	4,9	0,85

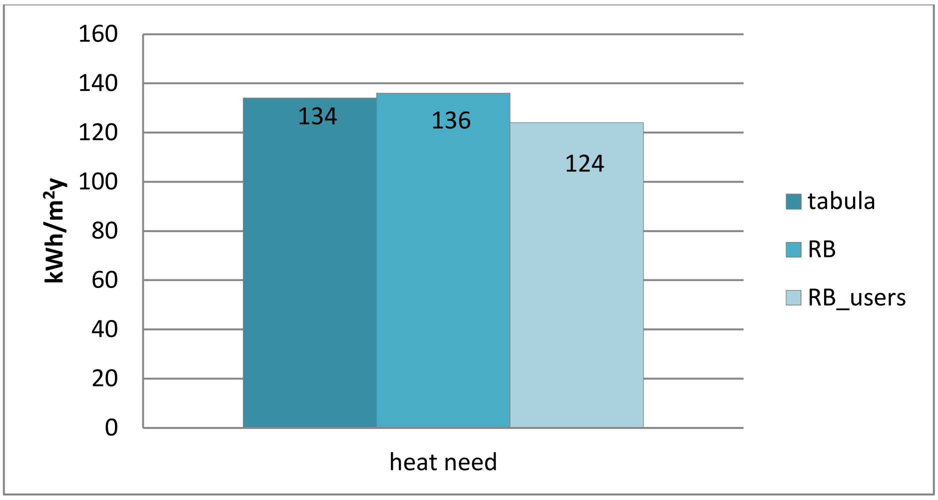


Figure 3.8. Heat nee of AB 1961-1975

Standard simulation overestimates heat need of 1% respect to TABULA, and simulation adapt to users provide a heat need reduction of 9% with respect to standard simulation. Heating need for reference building AB 1961-1975 is 124 kWh/m^2y.

AB, 1976-1990

Geometric data			
Parameter	Symbol	Unit	
Gross heated volume	V	m^3	12685
Net floor area	A_n	m^2	4123
Shape factor	S/V	m^{-1}	0.37
N° apartments	-	-	48
N° floors	-	-	6
Gross heated surface	S	m^2	4734
Gross heated floor	A_l	m^2	3803
Windows area	W	m^2	361
Reference floor area	A_{ref}	m^2	3474

Construction data						
roof	walls		Lower floor	Upper floor	Window	
U(W/m²K)	U_1(W/m²K)	U_2(W/m²K)	U(W/m²K)	U(W/m²K)	U(W/m²K)	$g_{,gl}$
1.85	0.76	0.76	0.97	0.98	3.70	0,75

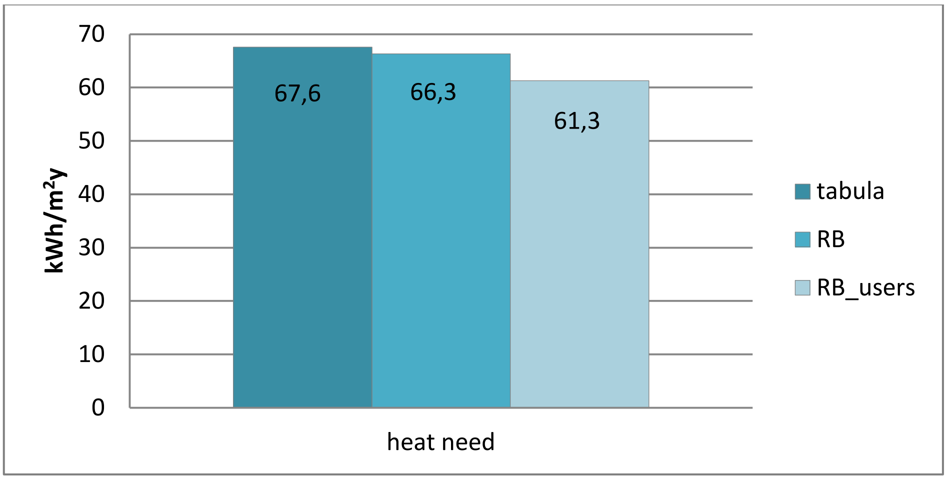


Figure 3.9. Heat need of AB 1976-1990

Standard simulation underestimates heat need of 2% respect to TABULA, and simulation adapt to users provide a heat need reduction of 8% with respect to standard simulation. Heating need for reference building AB 1976-1990 is 61.3 kWh/m^{2}y.

3.3. *Choice of energy building retrofit*

To identify necessary interventions for buildings energy savings with the aim to respect new requirements of energy efficiency, the reference is the environmental energy appendix of building regulation of Turin [49].

In the appendix are described two restriction levels to thermal insulation: the first level is about prescriptive limits, the second one concerns incentive requirements (table 4).

Table 4. Thermal insulation of building envelope, referring to schedule 1 [49]

	Level 1 (W/m^2K)	Level 2 (W/m^2K)
Thermal transmittance U coverage	U≤0.23	U≤0.15
Thermal transmittance U ceiling towards roof not habitable or unheated room	U≤0.26	U≤0.17
Thermal transmittance U external walls	U≤0.25	U≤0.15
Global thermal transmittance U window frames	U≤1.50	U≤1.20
Thermal transmittance U walls towards unheated rooms	U≤0.30	U≤0.20
Thermal transmittance U external floor	U≤0.23	U≤0.15

A correct analysis for energy retrofit leads a total system study, starting from building envelope, heating system, domestic hot water system, lighting system, electrical equipment and behavior habitants.

It's recommended: building envelope interventions, installation of high efficiency systems, the use of renewable energy systems, planning of correct maintenance actions.

Since heat loads can be reduced using materials whit a low thermal transmittance, it's important to define a global strategy for building thermal insulation choosing a correct insulation material and relative thickness.

In table 5 is possible to see insulation materials chosen and the relative performance indicators, that are related to prospect 2 in UNI 10351:2015 [43], for hygrometric properties the reference is UNI 10456:2008 prospect 4 [50].

Table 5. properties of insulation materials

material	λ (W/m K)	Cs (kJ/kg K)	ρ (kg/m^3)	u	Typology
Polyurethane foam	0.028	1400	30	60	thickness external wall
EPS 50	0.038	1450	50	60	Internal wall
EPS 200	0.033	1450	50	60	Ceiling, floor

It's assumed also that thermal bridge are corrected by retrofit measures.

Three scenarios are created to analyze energy savings in buildings:

- V: substitution of windows (U=1.20, $g_{,gl}$=0.30)
- RS: Standard Renovation: all building envelope is insulated according to transmittance limits in Level 1
- RA: Advance Renovation: all building envelope is insulated according to transmittance limits in Level 2

In the following pages thickness insulations and new limits are explained for each RBs, with relative heat saving percentages.

AB, 1945-1960

	V	RS	RA
External wall	U=1.15	U=0.25 (+10 cm)	U=0.15 (+17 cm)
Internal wall	U=2.60	U=0.30 (+12 cm)	U=0.20 (+18 cm)
Windows frame	U=1.2 (substitution)	U=1.5 (substitution, g,gl=0.4)	U=1.2 (substitution, g,gl=0.30)
Ceiling	U=1.65	U=0.26 (+11 cm)	U=0.17 (+18 cm)
Floor	U=1.30	U=0.26 (+ 12 cm)	U=0.17 (+17 cm)

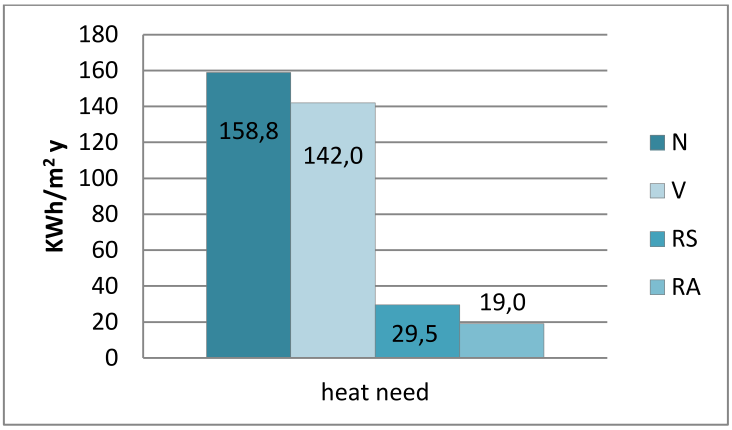


Figure 3.10. Heat need for different Energy saving interventions: standard simulation

Three renovation options are simulated and relative heat need is shown in figure 3.10. for each of them. With respect to base simulation, V scenario comports 11% of heat saving, RS 81% and RA 88%. Percentages don't change when calculations are adapted to user behavior.

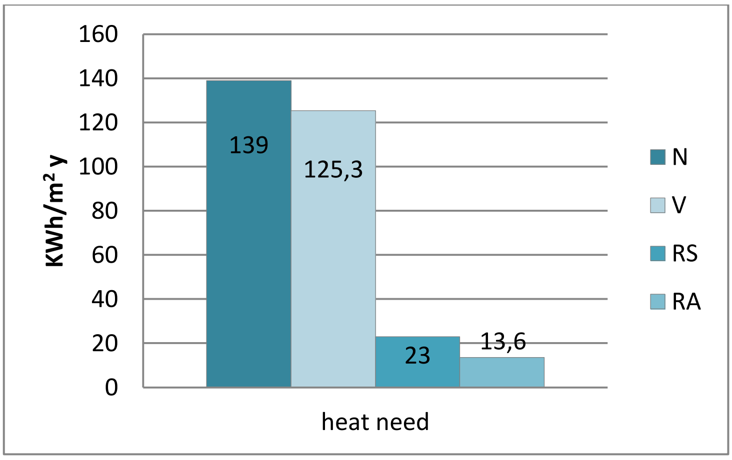


Figure 3.11. Heat need for different energy savings intervention: consumption adapted to users.

AB, 1961-1975

	V	RS	RA
External wall	U=1.10	U=0.25 (+9 cm)	U=0.15 (+17 cm)
Internal wall	U=1.13	U=0.30 (+10 cm)	U=0.20 (+16 cm)
Windows frame	U=1.2 (substitution)	U=1.5 (substitution, g,gl=0.4)	U=1.2 (substitution, g,gl=0.30)
Ceiling	U=1.65	U=0.26 (+11 cm)	U=0.17 (+18 cm)
Floor	U=1.30	U=0.26 (+ 12 cm)	U=0.17 (+17 cm)

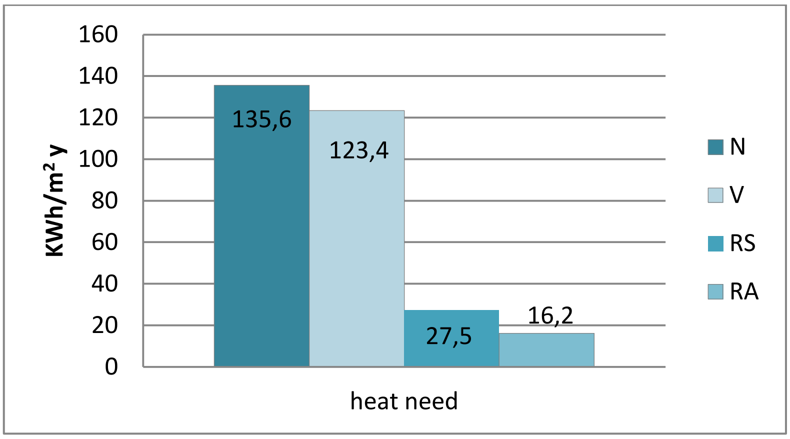


Figure 3.12. Heat need for different Energy saving interventions: standard simulation

Three renovation options are simulated and relative heat need is shown in figure 3.12. for each of them. With respect to base simulation, V scenario comports 9% of heat saving, RS 80% and RA 88%. Percentages don't change when calculations are adapted to user behavior.

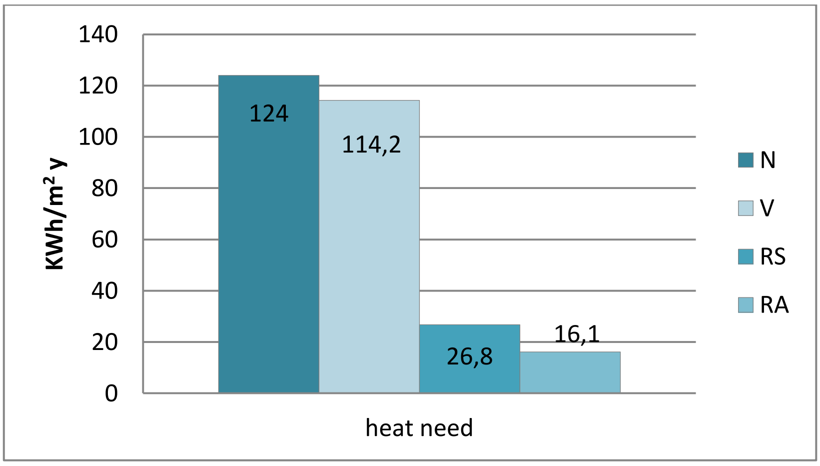


Figure 3.13. Heat need for different energy savings intervention: consumption adapted to users.

AB, 1976-1990

	V	RS	RA
External wall	U=0.76	U=0.25 (+11 cm)	U=0.15 (+16 cm)
Internal wall	U=0.76	U=0.30 (+8 cm)	U=0.20 (+14 cm)
Windows frame	U=1.2 (substitution)	U=1.5 (substitution, g,gl=0.4)	U=1.2 (substitution, g,gl=0.30)
Ceiling	U=0.97	U=0.26 (+10 cm)	U=0.17 (+16 cm)
Floor	U=0.98	U=0.26 (+ 11 cm)	U=0.17 (+19 cm)

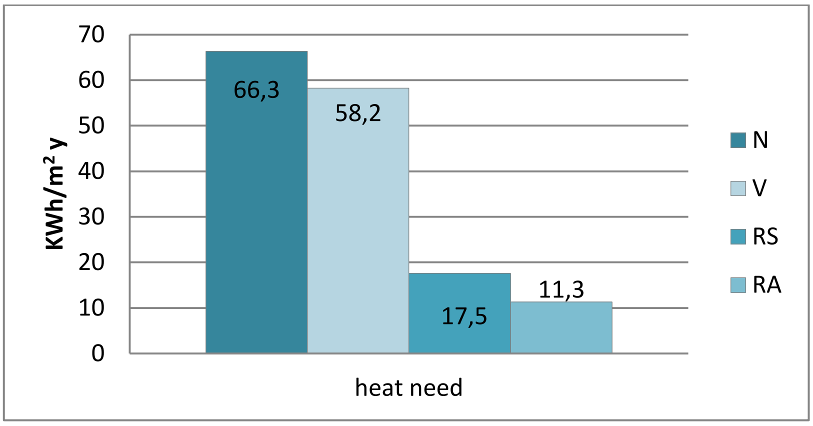


Figure 3.14. Heat need for different Energy saving interventions: standard simulation

Three renovation options are simulated and relative heat need is shown in figure 3.14. for each of them. With respect to base simulation, V scenario comports 12% of heat saving, RS 74% and RA 83%. Percentages don't change when calculations are adapted to user behavior.

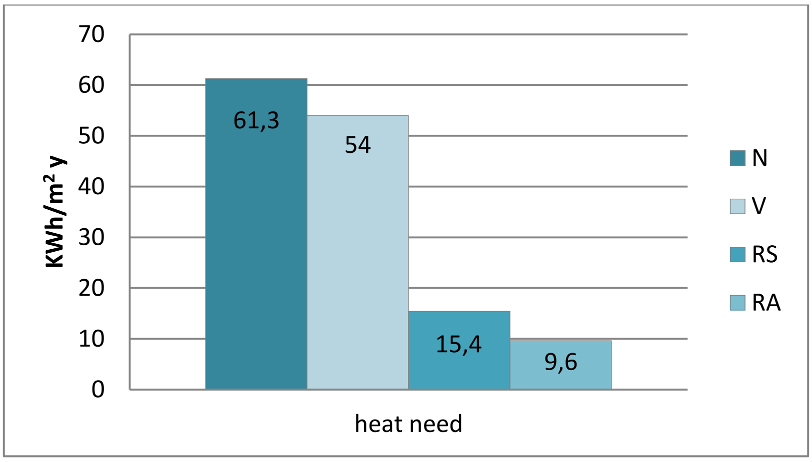


Figure 3.15. Heat need for different energy savings intervention: consumption adapted to users.

In Table 6, RBs energy savings data are summarized.

Table 6 heat consumption of RBs in different scenario

Typology	Base (kWh/m^{2}y)	V (kWh/m^{2}y)	RS (kWh/m^{2}y)	RA (kWh/m^{2}y)
AB 1945-1960	158.8	142	29.5	19
AB 1961-1975	135.6	123.4	27.5	16.2
AB 1976-1990	66.3	58.2	17.5	11.3

Average values underline a heat consumption reduction of 10% with V scenario, 80% with RS and 88% with RA. Studies on reference buildings are now completed, in the following section total heat demand of the city is determined and also energy saving potentials.

3.4. Territorial distribution and creation of total heat load profile.

In this study building typologies connected to district heating in Turin are supposed to be apartment block (AB) and multi-family (MF), under the assumption made in previous section. In total, volumes connected to DH are 57 Mm^3 (year 2014), and how shown in Figure 2.3.1. these volumes are collocated in the west part of the city. For each census section, census data provide information about number of buildings, in turn separated in four building typologies (AB, MF,TH,SH) and in three age classes (pre'80, post' 80, post 2005). Also information about gross heated volume and net surface area are connected to these data.

With the support of GEOPORTALE of Turin [51] it is possible to consult the map with census sections of the city, in this way it is possible to connect territorial distribution of buildings with information about building typologies and construction periods.

Considering for each construction period a uniform distribution in the city, it's possible to further subdivide census data, and for each section the number of buildings comparable to the three reference buildings simulated is calculated.

Volumes connected to DH are identified, and 30.7 Mm^3 of them can be represented with RBs, in particular: 14.1 Mm^3 belong to AB 1945-1960, 10.5 Mm^3 to AB 1961-1975, 6.1 Mm^3 to AB 1976-1990.

This subdivision demonstrate the correct choice of reference buildings, because 54% of volumes connected to DH are associable with analyzed buildings.

The aim of this thesis is also to evaluate a possible network expansion in relation with energy savings measures, so other 43 Mm^3 are analyzed, considering previously literature and assuming that zones near the river are considered not connectable [42]. 19.5 Mm^3 that can be connectable are represented by RBs: 9 Mm^3 to AB 1945-1960, 6.5 Mm^3 to AB 1961-1975, 4 Mm^3 to 1975-1990.

Volumes data that must be connected to RBs simulation are summarized in table 7.

Table 7. Volumes connected to DH and not subject to study

RB typology	Connect to DH	Possible expansion
AB 1945-1960	14.1 Mm^3	9 Mm^3
AB 1961-1975	10.5 Mm^3	6.5 Mm^3
AB 1975-1980	6.1 Mm^3	4 Mm^3
tot	30.7 Mm^3	19.5 Mm^3

Hourly simulation provided by EnergyPlus for each RBs has been normalized with gross heated volume of RB, as done in [52], and then multiplied for respective volumes (Table 7), creating the total heat profile.

Heat loss is considered equal to 13% of total heat demand of DH real data, and this quantity is subtracted from the total. Heat consumption of one day in July extrapolated from DH real data is considered heat consumption for domestic hot water (DHW), equal for every day of the year. Under this assumption, also DHW is subtracted to heat load profile of district heating. The remaining DH heat consumption of real data is compared to heat profile created through RBs simulations. Results are shown in Figure 3.16 for a day in January.

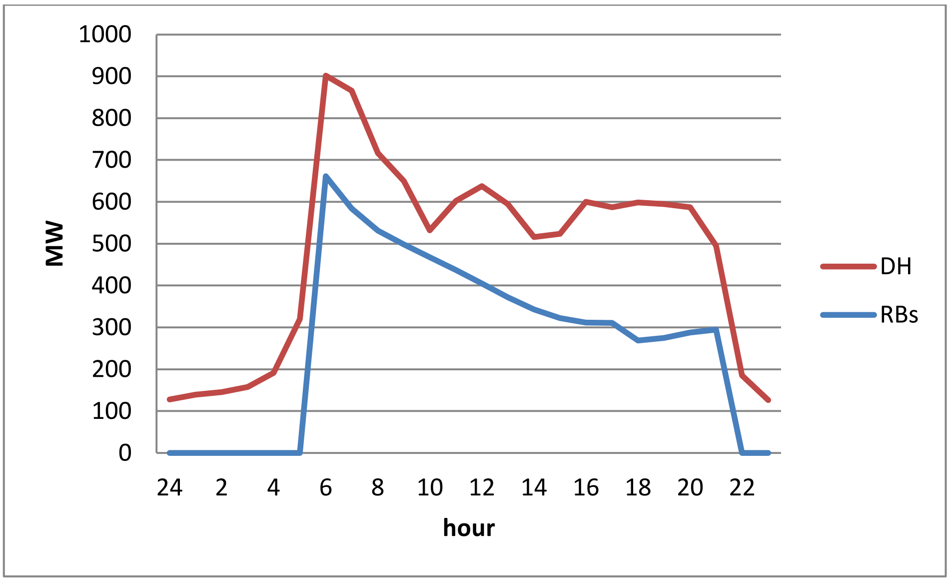


Figure 3.16. DH total real heat profile(red line) compared to RBs total heat profile (blu line)

Volumes not connected to DH are considered with individual heating, and with the same method an individual heat profile is created.

Retrofit actions are analyzed gradually in the same way, and different heat load profile are compared to DH real data.

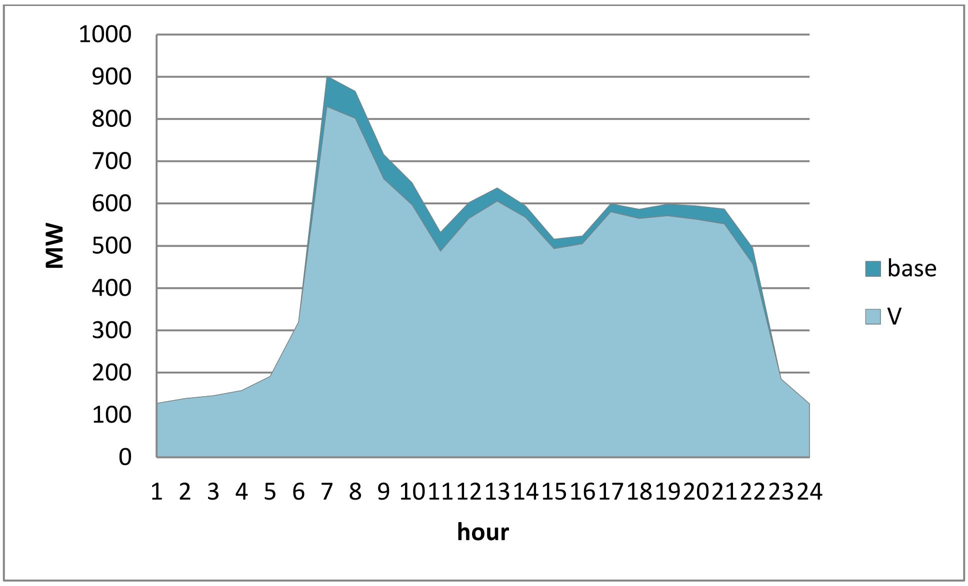


Figure 3.17. Difference between base scenario and heat consumption in V scenario, the difference shows the heat consumption reduction

Figure 3.17 shows the difference in heat load profile between base scenario and retrofit V (substitution of all windows for 30.7 Mm^3), with an annual energy savings of 101 GWh/y.

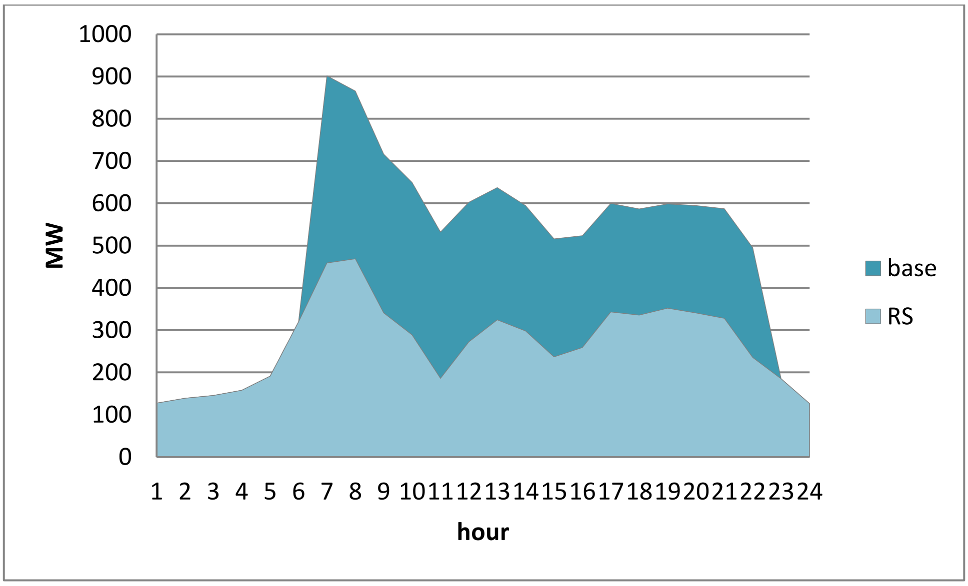


Figure 3.18. Difference between base scenario and heat consumption in RS scenario.

RS retrofit allows to save 751.2 GWh/y (figure 3.18), while RA comports an energy savings of 812 GWh/y (figure 3.19).

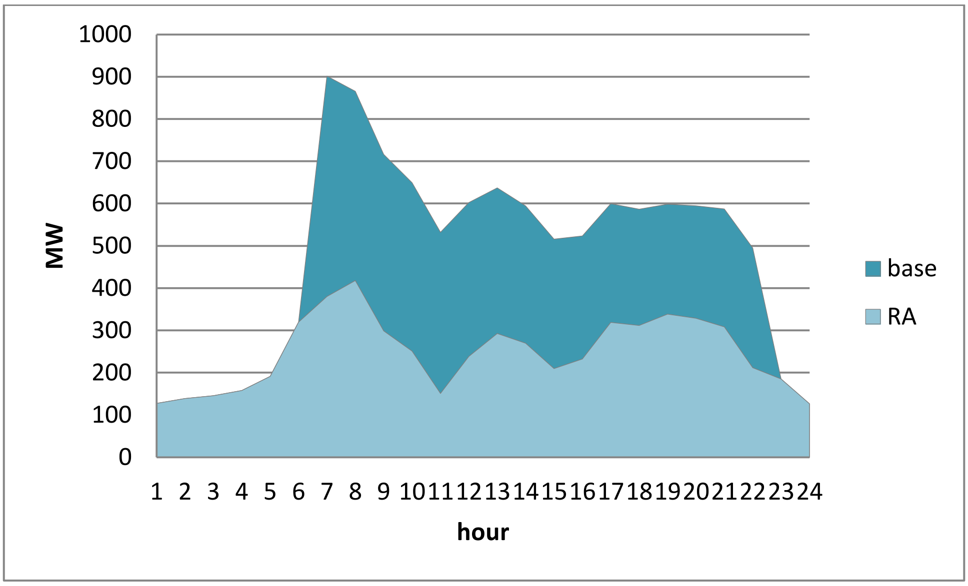


Figure 3.19 Difference between base scenario and heat consumption in RA scenario.

3.4.1. Heat loss assumption

The decrease of heat consumption comports an increase on heat loss, according to the equation 1:

$y = 0.7321 - 1.221x + 0.6462x^2$ if x<1

$y = 0.1773 - 0.014x$ if x>1 (eq.1)

in which y = loss (%) and x= line density in MWh/m .

Considering 500 Km of pipe lines, line density and the correlated heat loss are calculated for each buildings energy saving scenario. In year 2017, line density is equal to 3.5 MWh/m, and it decrease in each scenario. With a line density lower than 2, heat loss are considered too high and DH network became not convenient. According to table 8, RS and RA scenarios provide a line density lower than 2, that means 15% of heat loss, for this reason a network expansion is considered for each scenario. For V scenario, a lower network expansion is considered, equal to 2.9 Mm^3, for RS and RA a higher expansion is supposed, equal to 19.5 Mm^3 (the volume of all buildings with individual heating). With these expansions, in each scenario line density is higher than 3, and heat loss are in the order of 13%.

Table 8 line density and heat loss for each scenario

	base	V	RS	RA	V+exp	RS+exp	RA+exp
Consumption (TWh/y)	1,75	1,65	1	0,94	1,74	1,66	1,60
x (MWh/m)	3,50	3,30	2,00	1,88	3,48	3,32	3,19
y(%)	0,13	0,13	0,15	0,15	0,13	0,13	0,13
production (TWh/y)	1,99	1,88	1,15	1,08	1,97	1,88	1,80

The heat loss percentage is used to increase the heat profile consumption of DH and individual buildings, and together with DHW consumption the heat load profile as input for thermal plant is created.

In the following study, only buildings savings with network expansion are considered, and total heat saving referred to thermal plant demand is reported in table 9.

Table 9. Heat saving for different scenario in heat production

	GWh/y	Heat saving %
Base DH production	1990	
V+DH exp (2.9 Mm3)	1970	1
RS+DH exp (19.5 Mm3)	1888	6
RA+DH exp(19.5 Mm3)	1800	9

3.5. *Identification of possible change in heat production.*

Synergy between district heating expansion and buildings energy saving interventions is demonstrated in several studies [11][13][40]. Change heat production for DH is possible through several options: interaction of renewable energy, solar thermal production, heat pumps, geothermal installations or change in fuels used in already existing plants. For this study, renewable energy sources have not been considered because electricity field is not traded. In Turin, heat loads are already uses for DH, so following the line of previous literature and actual previsions, this study focuses the attention on changing the fuel mix in CHP technology and on the integration of heat pumps. Two scenario are analyzed, according to [40].

- MOD: Moderate scenario, decommission of 260 MW of natural gas CHP, replaced by 105 MW of heat pump ,106 MW of biomass CHP and 150 MW of natural gas CHP.
- ADV: Advanced scenario, decommission of 260 MW of natural gas CHP, replaced by 250 MW of heat pump, 106 MW of biomass CHP and 530 MW of daily thermal storage.

Biomass CHP is chosen because simulation with EnergyPLAN allows a restrictive possibility in fuels choice.

3.6. *Costs*

Costs associated to energy savings measures are found in "Prezzario Regione Piemonte 2016"[53]. For each RBs, 3 different costs analysis are done, one for each type of buildings retrofit options (V,RS,RA). Costs includes: construction material costs, installation costs and manpower costs. (See appendix 6.3.)

In table 10 total costs normalized to heated volume are summarized:

Table 10 average costs of retrofit

	AB 1945-1960	AB 1961-1975	AB 1976-1990	average
V (€/m^3)	10,68	9,96	5,12	8,59
RS (€/m^3)	34,23	34,35	25,61	31,40
RA (€/m^3)	46,27	46,01	35,09	42,46

Average costs are almost 9 €/m^3 for windows substitutions, 32 €/m^3 for standard renovation and 43 €/m^3 for advanced renovation. Energy savings interventions are considered only for buildings connected to DH, so average prices are considered for 30,7 Mm^3, results are shown in table 11.

Table 11 total cost of energy savings measures for volumes connected to DH

	Average (€/m^3)	Volumes DH Mm^3	Total cost (M€)
V	8,59	30.7	263,62
RS	31,40	30.7	963,6
RA	42,46	30.7	1303,38

EnergyPLAN analysis requires also consideration on supply costs as input data, with information about investment costs, operations and maintenance fixed costs (O&M fix) in terms of investment cost percentage, and also a percentage of manpower costs.

Fuels cost, handling costs and variable O&M are also required for each type of supply, together with CO_2 cost and the investment ratio, assumed equal to 3%.

In EnergyPLAN there is the possibility to insert additional costs, as energy savings measures or network expansion in terms of total annual cost.

Assumptions for this type of costs are based on previously literature [40] and on Stratego analysis for Italian nation. Fuel price is taken from GME statistic of year 2017, while CO_2 emission factor from natural gas is considered equal to 56 tCO_2/TJ [54].

Under the assumption of feasibility study, no taxes are considered.

In the following tables prices are shown divided into four categories: investment and fixed O&M, Fuel costs, Variable O&M, additional costs.

Table 12 Investment and fixed O&M*

	Investment cost (M€)	Period (years)	Fixed O&M (%)
small CHP units	0,85	25	3,75
heat storage CHP	3	20	0,7
Large scale Heat Pump	1,7	25	0,9
Boilers (CHP)	0,12	20	3,8
Boilers (residential)pr 1000 units	12	25	3,8

*[40]

Table 13 Fuel costs year 2017**

	Natural gas (€/GJ)	Biomass (€/GJ)
Fuel price	6	5.65
Fuel handling costs (distribution and refinery)		
To dec CHP, DH and Industry	2,05	1,186
To individual house holds	3,146	-

**[18]

Table 14 Variable O&M costs*

		Variable O&M	unit
DH and CHP system			
	Boiler	7	€/MWh_{th}
	CHP	2,4	€/MWh_{el}
	Heat Pump	70	€/MWh_{el}
Individual			
	Boiler	7	€/MWh_{th}

*[40]

Additional costs consider O&M costs for existing district heating pipe and costs for new DH pipes plus heat exchanger costs for each KW connected. Reference buildings simulation provide the installed power of each building, details in table 15.

Table 15 installed power

	Installed power (KW)	N° buildings connected to DH	N° of individual buildings
AB 1945-1960	101.85	2059	1023
AB 1961-1975	169.69	1526	732
AB 1976-1990	131.74	898	446
total		4483	2201

Data about installed powers are used for calculate additional costs, taking in care for DH expansion volumes considered in previously sections: 2.9 Mm^3 for V retrofit and 19.5 Mm^3 for RS and RA.

Table 16 Additional costs

	Period (years)	O&M (%)	Investment (€/KW)	Total investment (M€)
Existing DH pipes + heat exchanger	40	100	10.20	5.92
New DH pipes+ heat exchanger	40	1	1018.40	V: 30.54 RS: 292.45 RA:292.45
Heat saving retrofit	30	-	-	V: 263.62 RS: 963.6 RA: 1303.38

To compare future energy saving measures and change in heat supply, the actual scenario must be considered to year 2050, with the creation of a Base as Usual (BAU) scenario, that represents a future scenario without change in heat consumption and production. Different assumptions are made: it's not considered population growth and its influence on DHW consumption [13], actual power plants have a lifetime lower than 30 years, so power plant investment costs are considered also for BAU scenario, change in fuel prices and CO_2 price are considered following the assumptions made in Stratego simulation, as shown in table 17.

Carbon price is assumed equal to 6 €/tCO_2 in 2017, as reported in [55], and a optimistic price of 25 €/tCO_2 is considered for 2050, following the hypothesis made on Heat Roadmap 2050, in which a price of 20-30 €/tCO_2 is expected.

Table 17 fuel costs 2017-2050**

		2017	2050
Fuel price (€/GJ)			
	Natural gas	6	11.83
	Biomass	5.65	8.1
CO_2 (€/tCO_2)		6	25

**[18]

3.7. EnergyPLAN analysis and results.

Different scenarios are created for year 2050, without assuming change in DHW consumption and in electricity consumption.

Hourly consumption profile obtained for individual buildings in previous section is used as input in EnergyPLAN software, together with DH real profile provided by IREN to create a base scenario. Individual heating is considered supply by natural gas boilers with an efficiency of 0.85. Each cost is introduced in the base simulation for 2017, and a technical optimization with strategy 1-Only heat balance is performed, under the assumptions made in section 3.1.

Total heat demand (DH plus individual heating) is 2.65 TWh/y, 1.99 TWh/y for DH and 0.66 TWh/y for individual heating (19.5 Mm^3). DH demand is supplied by natural gas CHP (1.93 TWh/y) and natural gas boilers (0.06 TWh/y). Total primary energy supply (PES) is equal to 6.19 TWh/y, divided into 5.41 TWh/y for CHP+boilers and 0.78 Twh/y for individual heating. CO_2 emission are 1.250 Mt, and total annual costs are 295 M€/y.

BAU scenario (business as usual) has the same input data of base scenario in terms of heat demand and supply technologies, but costs are related to 2050 year, to perform energy system cost if no change in heat consumption or heat supply will be applied in future. In this situation, total annual costs increase to 458 M€/y_{2050}. BAU is used as reference for the other simulations performed in terms of energy savings, PES, CO_2 emissions and total annual cost for year 2050.

Table 18 assumption made to make different scenarios

Building retrofit	V	Windows substitution
	RS	Standard renovation
	RA	Advanced renovation
Network expansion	1	2.9 Mm^3
	2	19.5 Mm^3
Heat production change	MOD	105 MW HP
		106 MW CHP biomass
	ADV	250 MW HP
		106 MW CHP biomass
		560 MW heat storage

Table 19 Different combining of building retrofit, network expansion and heat production change

		Building retrofit (V,RS,RA) and network expansion (1,2) scenarios			
		Base	V + 1 (V: Windows substitution)	RS + 2 (RS: standard renovation)	RA + 2 (RA: advanced renovation)
Supply side scenarios	Base	BAU	A	B	C
	MOD (105 MW HP, 106 MW CHP_B)	L	D	E	F
	ADV (250 MW HP,106 MW CHP_B 560 MW HS)	M	G	H	I

In the following figures outputs about CO_2 emissions, costs and PES are shown for different buildings scenarios, DH expansion and change in heat supply.

CO_2 emissions are shown in figure 3.17., three different buildings retrofit with two different levels of DH expansion are compared for three different heat supply change. Buildings retrofit together with DH expansion without change in heat supply comport a reduction of CO_2 emission and in primary energy supply of 2% for A, 15% for B, 18% for C respect to BAU scenario. In these scenarios, heat supply is attributed to natural gas CHP and natural gas boilers, and the reduction of heat demand comports a reduction in heat production. However costs are the same for A and decrease for 4% in B scenario and 3% in C.

Changing heat production together with buildings retrofit and DH expansion, lower values in each terms are performed.

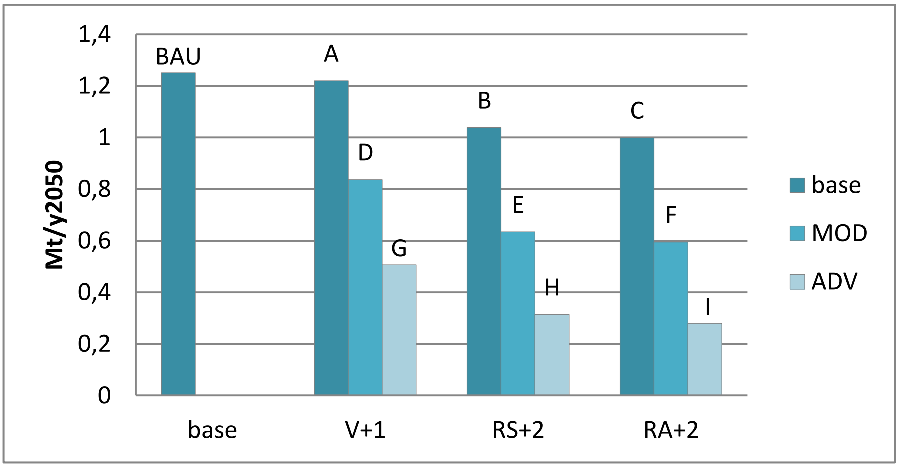


Figure 3.20. CO2 emissions for different scenarios from EnergyPLAN simulations

MOD scenarios provides a CO_2 decrease from 33% in D scenario to 52% in F scenario, PES decrease 24% for D, 41% for E, 45% for F, while in terms of costs it also provides decreasing of 15% for D, 18% for E, 18% for F. In these scenarios heat pumps (HP) are integrated with natural gas CHP and biomass CHP. According to EnergyPLAN optimization, electricity produced by CHP is used by heat pumps to produce heat, so CHP operating follow the electricity need of HP and heat storages are used to storage CHP heat production excess. Furthermore, CHP production is primarily satisfied by biomass CHP because biomass is considered a fuel with zero-CO_2 emissions. Natural gas consumption and related gas emissions decrease further with a higher integration of heat pumps in ADV scenarios that are the best scenarios, providing an emission reduction from 59% to 78%, a PES reduction of 52% for G, 69% for H, 72% I and costs saving of 34% G, 38% H, 37% I.

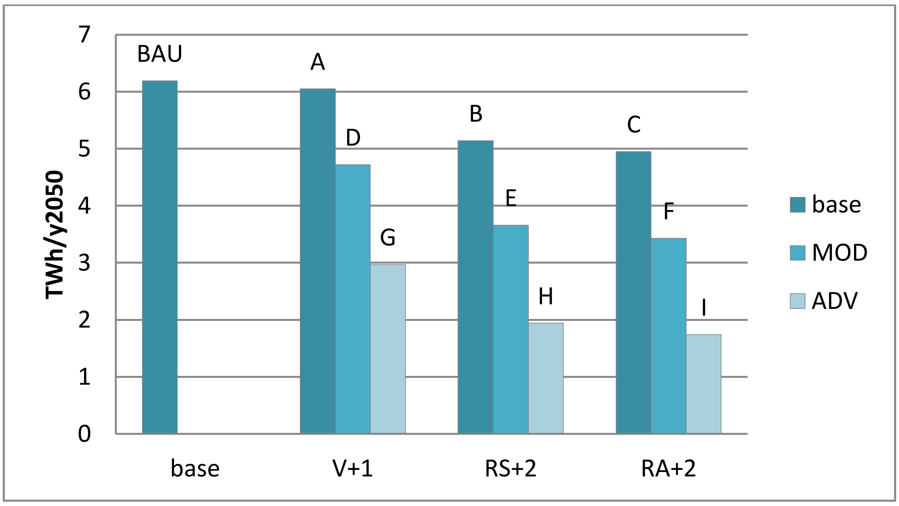


Figure 3.21. PES outputs from EnergyPLAN simulations

How is shown in figures, benefits in terms of emissions reduction, lower costs and reduction in PES are provided integrating buildings retrofit together with DH expansion and heat production changes.

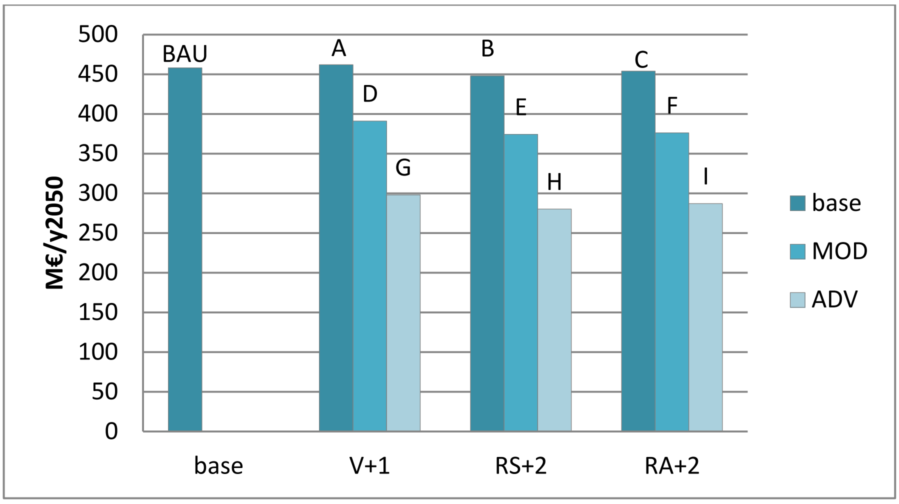


Figure 3.22. Costs outputs from EnergyPLAN simulations

Costs outputs are further analyzed in figure 3.23. in order to understand how each intervention influences costs. Compared to BAU scenario, each intervention regarding change in heat production provides a costs decreasing. Fuel cost is the most influencer cost item, covering 58% of total annual costs for BAU, in scenarios without changes in heat production fuel cost is 51% of total costs, while it decreases to 39% in MOD scenarios, with minimum value in ADV scenarios, almost equal to the 27% of the total annual cost. Lower fuel costs due to heat production change mitigate investment costs for buildings retrofit and for heat generation interventions.

ADV scenario with standard renovation in buildings together with DH expansions provides lower costs with respect to all scenarios simulated. Compared to standard renovation, advanced renovation on buildings comports a higher reduction in heat consumption but also higher investment costs. These increasing costs are not balanced by the costs reduction due to CO_2 emissions reduction and PES savings, while standard renovation scenario provides a better balancing between new investment costs and decreasing costs as consequence of energy savings measures.

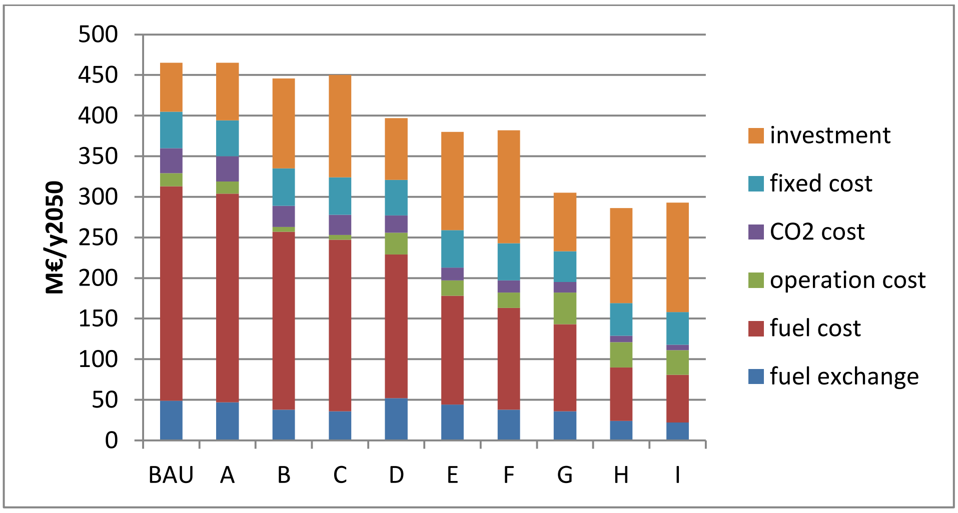


Figure 3.23. Total annual Costs subdivision for each scenario from EnergyPLAN outputs

Results from energy system simulations show the synergy between buildings retrofit interventions and changes in district heating, in terms of network expansion and heat production configuration. Correlating buildings energy savings with DH expansion and integrating low-carbon energy system as heat pumps in heat production allows reduction in term of greenhouse gas emission, total costs and primary energy supply. To achieve national goals for energy saving, an integrated approach for urban planning that considers energy synergies between demand, supply and network expansion is the way to pursue. Higher interventions will allow a reductions of 78% in greenhouse gas emission (-970000 tCO_2/y) and of 72% in PES, with benefits in terms of annual costs.

It's important to understand how EnergyPLAN decides that an energy system is better than another, as explain in [56] there are five variables that the software uses to perform an optimization simulation:

1. PES (primary energy supply): total energy required by the system
2. CO_2: the amount of CO_2 produced
3. Annual costs
4. EEEP (Exportable Excess Electricity Production)
5. CEEP (Critical Excess Electricity Production)

For better understand the importance of change in heat supply, especially the main role of heat pumps, base scenario (without buildings savings measures and DH expansion) is analyzed for MOD and ADV scenario, in terms of PES and CO_2 emissions. Results are reported in Table 20.

Table 20 results from scenarios with change in heat supply without buildings savings and DH expansion

	PES (TWh/y)	CO_2 (Mt/y)
base	6.19	1.25
MOD	4.89	0.87
ADV	3.14	0.54

MOD scenario guarantees the 21% of PES reduction, related to the introduction of 105 MW heat pump, ADV scenario with 250 MW of heat pumps allows a PES reduction of 49%. Reduction in PES is due to the fact that heat pumps don't require fuel consumption, electricity demand is satisfied from CHP, further CHP fuel consumption is divided into natural gas consumption and biomass consumption. Biomass CHP and heat pumps don't produce CO_2 emission, because CO_2 emission in the tool is due to natural gas consumption only (biomass emission is considered equal to zero). This is the explanation of the high reduction in terms of emission and PES in MOD and ADV respect to base scenario.

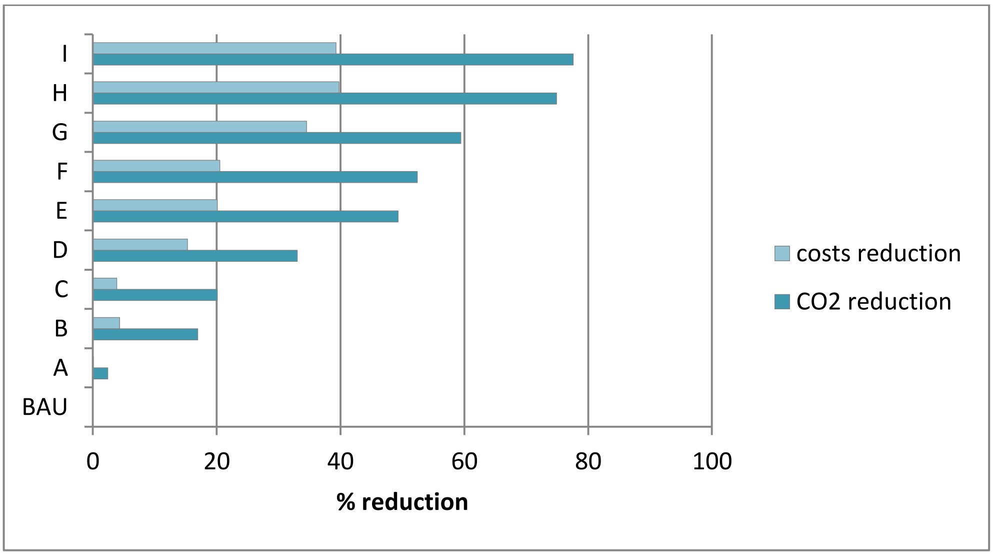


Figure 3.24. relation between costs reduction and emission reduction

In figure 3.24. is shown how increase CO_2 reduction provide a higher reduction in term of total annual costs.

To understand which is the cost for the decarbonization system in different scenarios, a decarbonization cost is evaluated C_{dec} (€/t_{CO2}), calculated as in equation 2.

$$C_{dec,i} = \frac{C_{in,i} - C_{in,BAU}}{CO_{2,BAU} - CO_{2,i}} \quad \text{(eq.2)}$$

With $C_{in,i}$ = investement costs for scenario i, $C_{in,BAU}$= investment costs BAU scenario, $CO_{2,i}$= CO2 emission in scenario i, $CO_{2,BAU}$= CO2 emission in BAU scenario.

Decarbonization cost is the rate between the increasing in investment cost and the CO_2 reduction due to low-carbon measures.

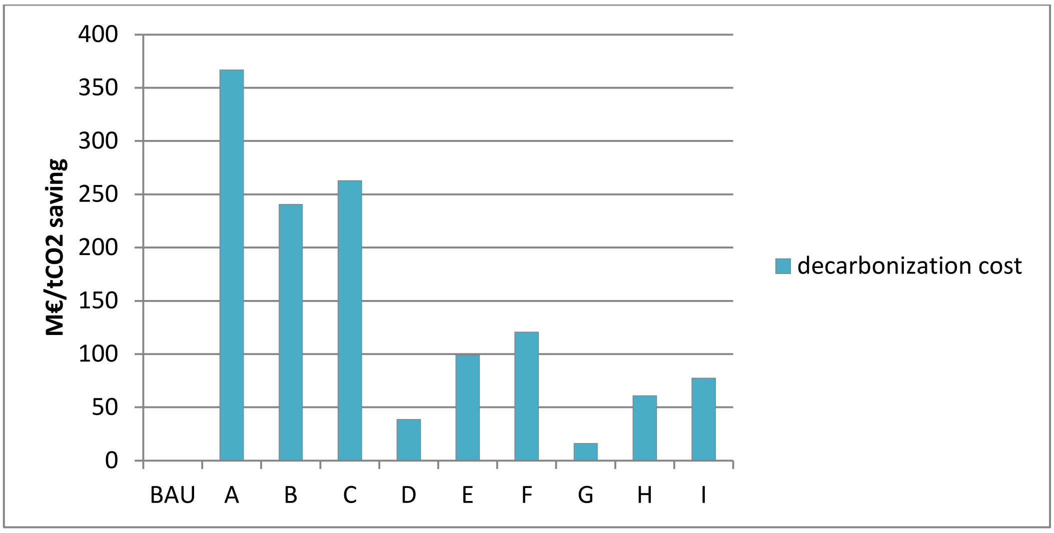


Figure 3.25. Decarbonization costs in different scenarios

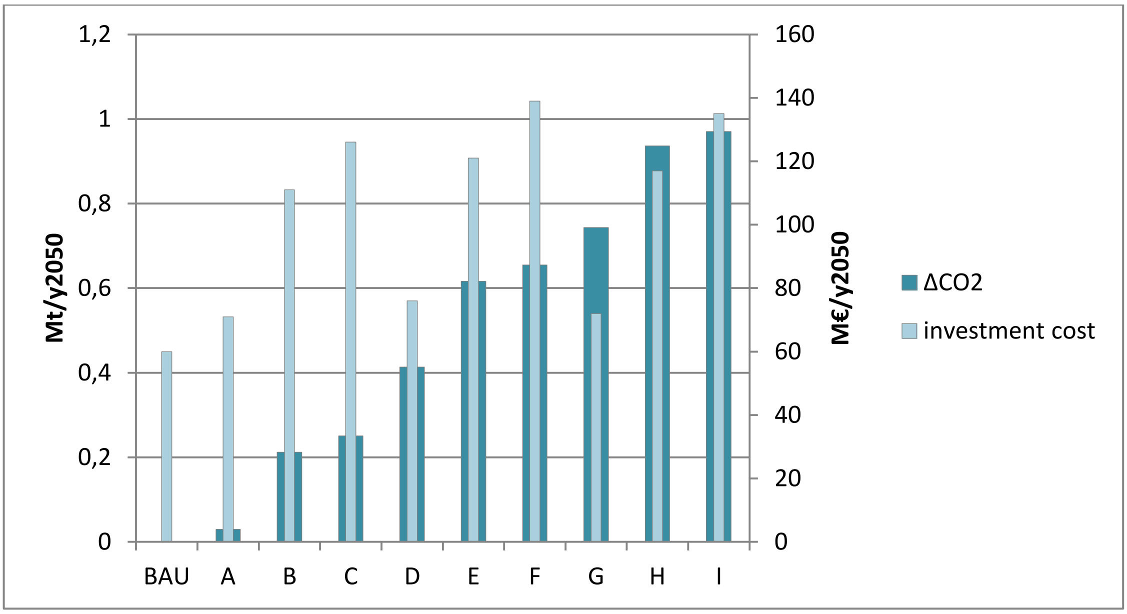


Figure 3.26. Investment costs and relate CO_2 emission for each scenario

Comparing the two graphs in figure 3.25. and 3.26, it is possible to affirm that for A, B and C scenarios, with no change in heat production, the decarbonization cost is almost triple of MOD and ADV scenarios. In base scenario, investment costs are higher than BAU due to buildings retrofit, but CO_2 reduction is not enough to justify investments.

Other scenarios provide a decarbonization costs lower than 100 €/t_{CO2} saving, that is considerated acceptable.

3.7.1. Costs analysis

A further analysis is done to better understand costs outputs.

EnergyPLAN calculates investment cost according to the equation 3, as reported in [16]

$$A_{inves} = \frac{C_{invest} * i}{1 - \frac{1}{(1+i)^n}} \qquad \text{(eq.3)}$$

with C_{inv}= investment costs; i=interest; n= lifetime.

In this way each investment with different lifetime can be compared, as an equivalent annual costs. Total annual costs is provided in M€/y_{ref}, summing A_{invest} with fixed and variable annual costs calculated from the tool. Total annual costs is related to a single year in which all investments are supposed to be applied, in this way it is possible to compare different annual costs provided from different energy efficiency investments, to understand which is the best solution.

Usually investment on energy system are distributed on different years, for this reason a further analysis in needed to analyze the change in energy system due to investment and change made in different period of time.

The global cost of each scenario is calculated following the methodology in [40] and in [32]: a time period horizon is defined (2017-2025), divided into 3 period step (2017-2025,2025-2035,2035-2050).

Building renovation rate is setted equal to 3% for each year starting from 2018, while DH expansion is planned with a year rate of 4% starting in 2025 (Table 21). Investments in thermal plant are planned according to the end-life of each system based on starting year([57],[58]), as explain in table 22.

Table 21 building retrofit and DH expansion rate for time period

	2018-2025	2025-2035	2035-2050
Building retrofit	3% renovation volume for year	3% renovation volume for year	3% renovation volume for year
DH expansion		4% connected volume for year	4% connected volume for year

Table 22 thermal plant investments for time period

	2018-2025	2025-2035	2035-2050
Base	No investment	New natural gas CHP (662 MW_{el}) New industrial boiler (1000 MW) New heat storage (430 MW)	New natural gas CHP (360 MW $_{el}$)
MOD	No investment	New natural gas CHP (662 MW_{el}) New industrial boiler (1000 MW) New heat storage (430 MW) Heat pump (35 MW_{el})	New natural gas and biomass CHP (338 MW_{el})
ADV	No investment	New natural gas CHP (662 MW_{el}) New industrial boiler (1000 MW) New heat storage (1000 MW) Heat pump (85 MW_{el})	New biomass CHP (134 MW_{el})

Building renovation rate and DH expansion rate are used to create a heat distribution demand for DH and individual buildings (as explain in section 3.2.) for each time step, that is used as input for EnergyPLAN. Time periods are simulated considering CO_2 cost and natural gas cost evolution as reported in table 23.

Table 23 evolution costs for different step time

	2018-2025	2025-2035	2035-2050
CO_2 (€/tCO_2)	6	10,75	25
Natural gas (€/GJ)	6	7,4575	11,83

EnergyPLAN simulations are used to calculate variable annual costs and fixed annual costs for three periods, than considering a discount rate of 3% a present value factor (R_i) is calculated for each mid-year (4,13,25.5), and the total costs discounted at 2017 is calculated according to equation 4.

$$C_{tot} = \sum_{i=1}^{n=3}\left(C_{inv,RB,i} + C_{inv,dh,i} + \left(C_{fix,i} + C_{var,i}\right) * t\right) * R_i \qquad \text{(eq.4.)}$$

with C_{tot}= total cost discounted at 2017 level, $C_{inv,RB,i}$= investment cost for building retrofit on period i, $C_{inv,dh,i}$= investment cost on DH expansion and heat supply on period i, C_{fix} and C_{var}= fixed and variable costs (€/y) on period i provide from

EnergyPLAN, t= years in period I, R_i= present value factor for mid-year of each time step.

Results are shown in figure 3.27.

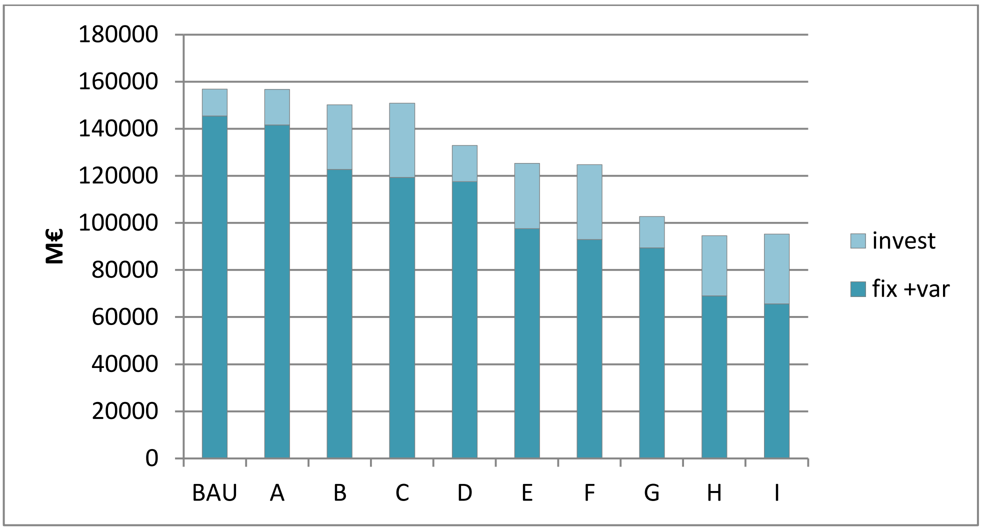


Figure 3.27. total costs discounted at 2017 level for different scenarios, divided into investment costs and fix+var costs.

Total costs to 2050 discounted at 2017 level provide lower costs for MOD and ADV scenarios respect to BAU scenario. In this cost analysis, scenarios C,F and I (advanced renovation on buildings for different change in heat production) provide the same total costs compared to standard renovation scenarios. This is due to the fact that in EnergyPLAN simulation investment costs are higher because they are all applied at the same time. The total cost approach provides major benefits to advanced energy investment because, thanks to the discount rate, future costs (that are represented from energy consumptions) have a bigger influence [59].

A sensitivity analysis for discount rate variation must be performed, because a lower discount rate provides a higher influence on future energy costs, while a higher discount rate provides lower influence on future costs and higher influence of investment costs. In figure 3.28. total costs for BAU scenario and D scenario are analyzed with different discount rate. Higher discount rate comports a lower costs difference between BAU and D, this means that a BAU scenario with few energy efficiency investments becomes more convenient respect to D scenario (bigger energy investments) if discount rate increases.

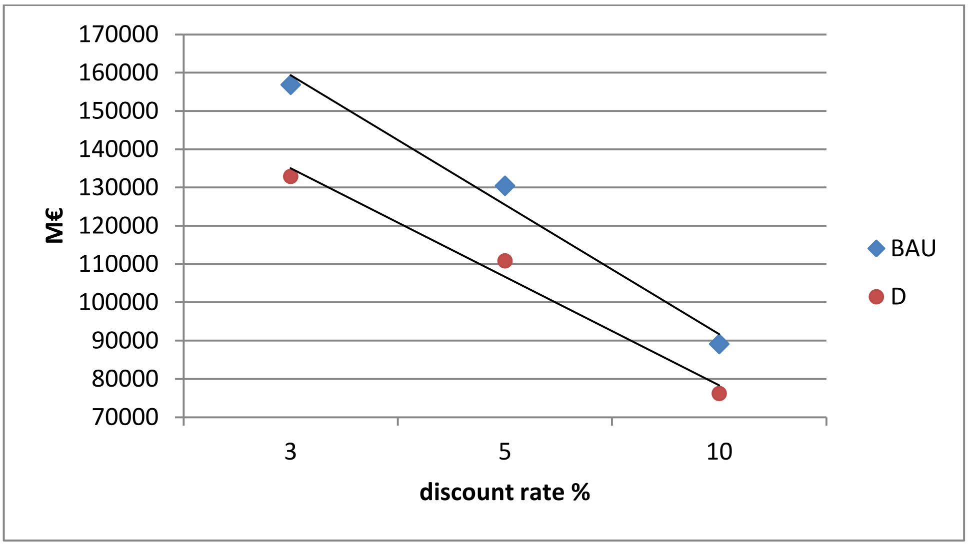


Figure 3.28. discount rate impact on total costs for different scenarios

4. Discussion

In this thesis is proposed a methodology for analyze the energy consumption at urban level, with a focus on the impact for the energy urban system of buildings energy savings together with change in energy system, to stress correlations between savings in heat consumption and possible investments in heat production. Buildings retrofit are analyzed with a dynamic simulation software, while their relation with the energy system and possible change of it are analyzed with an energy planning tool.

The aim of this methodology is to investigated energy measures for provide a urban energy planning, but it presents different uncertainties.

4.1. The creation of base scenario with EnergyPLAN

As underlined in section 2.3.1., EnergyPLAN is an optimization software so it's difficult to create a correct base scenario. Base scenario uses for simulations is different to the real case in terms of CHP production. This is due to the fact that EnergyPLAN doesn't allow the use of heat storage if electricity balance is not considered. In EnergyPLAN documentation [16] is explained that "*heat storage capacity is included to minimizing the electricity export. Such storage capacities are used for minimizing the excess and power-only production in the system.*

Storage can be loaded by:

1. Increasing the use of HP in situations with electricity export

2. Moving the electricity production from condensing plants to CHP plants.

Storage can be unloaded by:

3. Reducing the CHP production in situations with electricity export

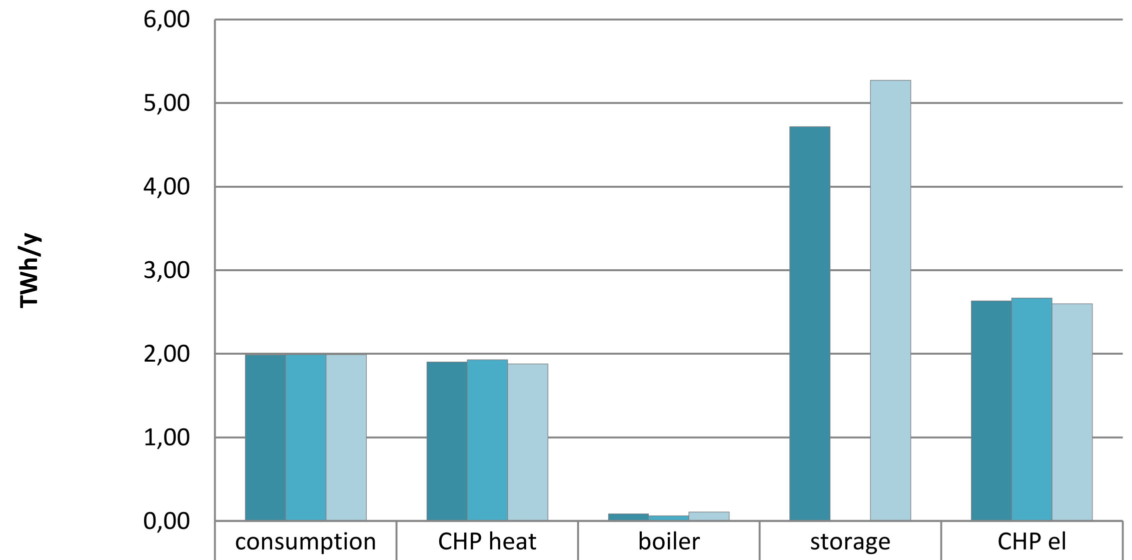
4. Reducing the boiler production,

5. Reducing the use of HP in situation of PP." [16]

The tool uses loading and unloading cases in this order: 3-1-2-4-5, and are applied to group 2 and 3 in case of critical excess electricity production or exportable excess electricity export.

Without considering electricity demand for the city, storage can't be loaded and unloaded according to EnergyPLAN, it's not possible to load the storage with heat excess production of CHP, as in the real case. EnergyPLAN simulation provides a lower production of heat from boilers and a higher production from CHP respect to real situation, with an increase of 1% in terms of CO_2 emission and PES.

It's possible to force EnergyPLAN to use heat storage and perform a similar production of heat using as electricity demand input the electricity demand extracted from CHP real data. Strategy 2 –Heat and electricity balance- is performed with electricity demand of 2.63 TWh/y and CHP from group 2 is moved to group 3 (CHP can operate in electricity configuration, with an efficiency of 0.56). Results are similar to the real case, heat storages are used and CHP production decreases while boilers production increases, as shown in figure 4.1.



	consumption	CHP heat	boiler	storage	CHP el
Real data	1,99	1,90	0,09	4,72	2,63
EnergyPLAN	1,99	1,93	0,06	0,00	2,67
EnPlan Forced	1,99	1,88	0,11	5,27	2,60

Figure 4.1. Forced scenario in EnergyPLAN vs real scenario

With respect to Real data, the forced EnergyPLAN model has the same value of CO_2 emissions and PES. However the possibility to force the tool is useless because is based on incorrect input data (electricity demand is not the total demand of the city, is only the electricity produce from CHP in real situation) and request an electricity balance that is not the aim of this thesis, so this forced scenario is not applied. Furthermore, CO_2 emissions and PES increase 1% in base scenario respect to the real situation, it's considerate acceptable.

4.2. CO_2 emission

In order to understand if the methodology gives correct outputs, the case study is compared to [40], in which a different approach is used to investigate synergies between buildings savings and DH expansion and change in heat production. The study presents a different network expansion and a different total volume as boundary condition, but buildings savings and heat production scenarios are similar. Also for it, outputs regard CO_2 emissions and total costs. The methodology applied in this thesis provides higher reduction in CO_2 emissions and total costs with respect to the other study. Difference in CO_2 emission are due to the aggregate emissions in EnergyPLAN, in fact the tool requests as input the emission factor for CO_2 content in fuel (kg/GJ). Furthermore, technologies that don't use directly fuels, as heat pumps or solar thermal heat plant, don't participate to CO_2 emissions. Another problem is the restrict choice of fuels, due to the fact that EnergyPLAN is a software mostly used for integrating renewable sources in energy systems. For this reason, to substitute natural gas boilers for individual heating with DH supplied by natural gas CHP is not convenient in EnergyPLAN simulation, since with the same emission factor, boilers request a lower amount of fuel with respect to CHP for heat production, because the only reference value is energy efficiency.

Despite this difference in total amount of emissions and costs, trend in the two studies is the same, underlining the importance of correlating buildings savings with DH renovation and investments. EnergyPLAN simulation provides a strongly attentions on the integration of energy sources different from typical fuels, and outputs show how it is possible to obtain major results substituting natural gas plants with other type of sources.

The simulation doesn't take in care the costs for the electricity production because the technical analysis do not consider electricity demand, so the electricity price is considered equal to zero, to avoid that electricity export price was included in total costs. It is assumed that the electricity required by HP is produced from CHP, electricity excess is exported, but the price is not accounted in the costs analysis. This assumption is acceptable considering that the CHP of the case study is sized for heat production and the electricity production can contribute to satisfy HP demand, but a more precise analysis must be done considering the electricity balance.

4.3. RBs uncertainty

Reference buildings approach used in this thesis present different issues, thermal behavior of a building is strongly influenced by three parameters: the shading profiles of the buildings, the internal loads and the infiltration rates, as explain in [52]. The shading profile is influenced by the orientation of the buildings and surroundings buildings, but using RBs without a geographic support this aspect is not taken in care. Also for internal loads and infiltration rates, values considered are standard values, this comports another uncertainties on results because they are largely influenced by occupant's behavior (they can vary from building to building, but also from floors of the same building, as analyzed in previous section). Furthermore, simulations made in this study doesn't present a calibration of results, due to the fact that real data for each RBs simulated are not provided.

Nevertheless using a dynamic simulation tool is the best solution for take in care occupant's behavior and climatic change in the country. The impact on district heat demand of building renovation measures together with climatic change is analyzed in [60], three different weather scenario are supposed for years 2020,2050,2080 (low scenario, medium scenario, high scenario) and this data are used to simulate district heat demand with different building renovation rates. Results underline the correlation between climatic change and heat demand, the difference in savings between renovation interventions in buildings decrease with the increase of outdoor temperature, so the increase of temperature must be considered for select the most appropriate building retrofits. A dynamic simulation tool can provide this type of analysis (also in the study EnergyPlus is used to verify the results) thanks to the possibility of change the climatic data file. A dynamic simulation software provides also an accurate analysis concerning summer period, cooling demand is not taken in care in this thesis, but must be developed in future studies.

4.4. Network contribution on DH heat demand

The aim of the thesis is to understand relations between building energy savings and change in district heating using buildings dynamic simulation outputs as input data for the energy system optimization tool. Total heat demand is created multiplying hourly profile from dynamic simulation of each RBs for the buildings volume analyzed, then it is compared to the DH real data provided by the supplier. Heat consumption from real data is calculated as the sum of the heat produce by CHP, boilers and heat storages of the city. Under this assumptions, heat loss are not considered separately but are included in heat consumption. For this reason, as explain in section 3.4.1., heat loss are calculated as percentage of heat demand and it is subtracted from DH real data consumption together with DHW consumption. In this way heat load profile from dynamic simulation can be compared with DH real data. However, considering the DH demand as the sum of users demand is a simplified approach, because network is not taken in care. Network connects users requests to the heat plant and it influences the heat demand. In particular the load profile of the plant is different from heat profile of users because heat loss of the network, must be considered, but also delay effect. Delay effect is associated to flow variation, a change in heat need from users corresponds to a flow variation that means a change in return temperature to the plant. This temperature variation depends on water velocity and is the cause of delay effect on load profile of thermal plant. Delay effect and heat loss, together with mixing effects due to return flows of each building comport a heat load profile of thermal plant different from that of buildings, especially from the peak load, that is different for magnitude (lower than user peak) and for duration (peak of thermal plant lasts for hours, for buildings lasts for few minutes). The assumption made for creating heat load profile from real data doesn’t take in care this important network contributions, for this reason regulation efficiency intervention, as the anticipation of the thermal request of buildings to reduce morning peak analyzed in [61] that can be easily performed with dynamic simulation tool, can’t be studied without a correct analysis on network operating.

For a better demand and supply relationship evaluation, a tool for simulate the network is necessary in order to analyze load profile of thermal plant.

4.5. Aggregate input in EnergyPLAN

The major problem in the use of EnergyPLAN for urban planning is the aggregated input data request. Aggregated data of production doesn't allow to analyze each thermal plant singularly, only average values for efficiency and total value for installed power can be used as input data, this means that the introduction of a new thermal plant (e.g. biomass CHP in case study) can't be analyzed individually. Also costs are aggregated costs, requiring average value. Aggregated data of demand and production can be easily applied to national level, in which average values are perfect for estimating a general demand and production, but urban level requires specific data in order to be well represented. Furthermore, usually power plants are projected to satisfy different cities, while an aggregated simulation requires a sort of close control volume, in which enter flow and exit flow are well known. Urban analysis requires a lot of assumption that can be not representative of the real situation. EnergyPLAN has three sister models [15] that can be used to supplement and support one and another: EnergyBALANCE, EnergyPRO and COMPOSE. EnergyPRO model is used to perform simulation for single station, in particularly CHP station, but it requires a lot of data and implies a high knowledge of specific performance characteristics of the station. However, it doesn't consider the station on the total energy system. COMPOSE model is a cost-benefit toolbox assessing a realistic evaluation of the distribution of costs and benefits for different sustainable energy options decided by user, including also uncertainty derived from a risk analysis (Monte Carlo risk assessment).

EnergyPRO is applied in [62] for modeling district heating of a Denmark city, together with a Least Cost Tool (LCT) for costs analysis. EnergyPRO is used to evaluate the difference in heat production of DH due to heat buildings savings, while investment costs are analyzed trough LCT, to take in care how heat savings of buildings influence costs of heat production.

In future analysis EnergyPRO simulation for production plants can be integrated with EnergyPLAN to reduce the uncertainty due to the use of aggregated values.

5. *Conclusions and future developments*

The aim of this thesis is to investigate the relation between buildings savings and change in energy system at urban level, to help the energy planning in future investments choices, with a focus on buildings savings correlate to new investments on district heating. Buildings savings are analyzed with a dynamic simulation of reference buildings, permitting a deep analysis on effective measures applied for heat saving at building level. Hourly heat demand obtained for the city is used as input data in EnergyPLAN, an energy optimization software able to investigate the energy system and the correlation trough difference energy sources. DH of the city is analyzed in the tool and several future scenarios are simulated, considering buildings savings, possible network expansion (natural gas boilers for individual heating are substituted from DH) and change in heat production. Outputs are related to 2050, and with respect to BAU scenario all other scenarios provide a reduction on CO_2 emission and PES. However, scenarios that don't consider change in heat production but only buildings savings and DH expansion show an increase on total costs with respect to BAU. New investments for heat savings and DH expansions are not compensated by reduction on variable costs and on PES. Scenarios with change in heat production provide a big reduction on CO_2 and PES, due to the integration of heat pumps and on biomass CHP. In particular ADV scenarios, with the integration of 250 MW heat pumps, 560 MW of heat storage and 106 MW of biomass CHP comport a CO_2 reduction from a minimum of 56% (without considering buildings savings and DH expansion) to a maximum of 76% considering advanced renovation level for building retrofit together with DH expansion. CO_2 reduction in these scenarios is due to the decrease of PES, especially the reduction on natural gas consumption. The integration of large scale heat pumps in district heating provides a strong reduction on natural gas consumption, a lower dependence on natural gas assures a safety energy system. New investments on district heating and on buildings stock are supported by the strong decrease of fuel consumption and its relative costs. Following the actual European trend, carbon taxes on 2050 are considered equal to 25 €/t_{CO2} , differently from other studies that provide carbon prices higher than 100 €/t_{CO2}. Results of this study show that energy efficiency scenarios are supportable in terms of total costs and provide also a decrease in costs with respect to a future scenario without change in energy system (BAU). Outputs of different scenarios well underline the necessity to correlate heat savings measures in buildings with investments on thermal plants and DH expansion.

EnergyPLAN is a tool for analyze renewable energy sources and for studying their integration in the actual energy system. DH systems allow the integration of different renewable sources, for example heat pumps can be supplied by electricity produced by wind power or solar power, or heat produce by geothermal and solar plants can be integrated by DH with CHP plants.

The methodology presented in this thesis allows the integration of an accurate analysis of buildings savings through a dynamic tool, and future analysis can be done to study the effectiveness of buildings savings related to the increase of temperatures. Integrating this type of analysis with an evaluation of the total energy system provides a strong tool for helping the urban energy planning process. However, some future developments must be taken in care. Dynamic simulation of buildings must be integrated with a GIS to allow an analysis of the built environment; a study on DH network must be done to connect heat demand of users to load profile of thermal plant; and heat supply must be performed trough accurate analysis on single station, maybe by the application of EnergyPRO model., in order to overcome the limit of EnergyPLAN of requiring aggregate data.

In conclusion, the methodology provides a method to use EnergyPLAN tool to perform urban analysis, thanks to the integration of a dynamic simulation tool to explore buildings retrofit interventions at urban level. Further tools must be integrated in future analysis to provide lower uncertainties and a more detailed study, as required by a urban planning process.

6. Appendix

6.1. RBs stratigraphies

AB 1945-1960

External wall: vertical closure

stratigrafia	s cm	ρ Kg/m³	μ -	c J/KgK	λ W/mK	R m²K/W
Strato liminare interno						0,13
intonaco	1,5	1800	11	840	0,900	
Laterizio forato	8	775	7	840		0,20
Intercapedine d'aria	7	1	1	1000		0,16
Laterizio forato	12	717	7	840		0,31
intonaco	1,5	1800	11	840	0,9	
Strato liminare esterno						0,04

parametro		Modulo
spessore	S	30,0 cm
Massa superficiale	M	202 kg/m²
sfasamento	φ	6,76 h
Capacità termica areica interna	Ki	54,1 kJ/m²K
Capacità termica areica esterna	Ke	70,7 kJ/m²K
Resistenza termica	R	0,873 m²K/W
Trasmittanza termica	U	1,145 W/m²K
Fattore di attenuazione	f	0,670

Internal wall: vertical closure on unheated space

stratigrafia	s cm	ρ Kg/m³	μ -	c J/KgK	λ W/mK	R m²K/W
Strato liminare interno						0,13
intonaco	2,5	1800	11	840	0,9	
calcestruzzo	13	2400	1	920	1,910	
intonaco	2,5	1800	11	840	0,9	
Strato liminare esterno						0,13

parametro		Modulo
spessore	S	18,0 cm
Massa superficiale	M	402 kg/m²
sfasamento	φ	5,69 h
Capacità termica areica interna	Ki	77,7 kJ/m²K
Capacità termica areica esterna	Ke	77,7 kJ/m²K
Resistenza termica	R	0,384 m²K/W
Trasmittanza termica	U	2,607 W/m²K
Fattore di attenuazione	f	0,420

Lower floor: horizontal closure on unheated space

stratigrafia	s cm	ρ Kg/m³	μ -	c J/KgK	λ W/mK	R m²K/W
Strato liminare interno						0,13
Piastrelle	1	2300	213	840	1	
Calcestruzzo	8	1000	36	880	0,5	
Blocco da solaio	22	1005	32	840		0,32
Intonaco	1,5	1800	11	840	0,9	
Strato liminare esterno						0,13

parametro		Modulo
spessore	S	32,5 cm
Massa superficiale	M	361 kg/m²
sfasamento	φ	8,72 h
Capacità termica areica interna	Ki	59,2 kJ/m²K
Capacità termica areica esterna	Ke	62,3 kJ/m²K
Resistenza termica	R	0,767 m²K/W
Trasmittanza termica	U	1,304 W/m²K
Fattore di attenuazione	f	0,342

Upper floor: horizontal closure on unheated space

stratigrafia	s cm	ρ Kg/m³	μ -	c J/KgK	λ W/mK	R m²K/W
Strato liminare interno						0,13
Intonaco	1,5	1800	11	840	0,9	
Blocco da solaio	18	1005	32	840		0,30
calcestruzzo	2	2400	1	920	1,910	
Malta	1,5	1800	24	840	0,9	
Strato liminare esterno						0,13

parametro		Modulo
spessore	S	23 cm
Massa superficiale	M	283 kg/m²
sfasamento	φ	6,51 h
Capacità termica areica interna	Ki	61,9 kJ/m²K
Capacità termica areica esterna	Ke	72,1 kJ/m²K
Resistenza termica	R	0,604 m²K/W
Trasmittanza termica	U	1,656 W/m²K
Fattore di attenuazione	f	0,509

AB 1961-1975

External wall: vertical closure

stratigrafia	s cm	ρ Kg/m^3	μ -	c J/KgK	λ W/mK	R m^{2}K/W
Strato liminare interno						0,13
intonaco	1,5	1800	11	840	0,900	
Laterizio forato	10	760	7	840		0,27
Intercapedine d'aria	17	1	1	1000		0,16
Laterizio forato	10	760	7	840		0,27
intonaco	1,5	1800	11	840	0,9	
Strato liminare esterno						0,04

parametro		Modulo
spessore	S	40,0 cm
Massa superficiale	M	206 kg/m^2
sfasamento	φ	5.99 h
Capacità termica areica interna	Ki	54,2 kJ/m^{2}K
Capacità termica areica esterna	Ke	70,2 kJ/m^{2}K
Resistenza termica	R	0,903 m^{2}K/W
Trasmittanza termica	U	1,107 W/m^{2}K
Fattore di attenuazione	f	0,649

Internal wall: vertical closure on unheated space

stratigrafia	s cm	ρ Kg/m^3	μ -	c J/KgK	λ W/mK	R m^{2}K/W
Strato liminare interno						0,13
intonaco	1,5	1800	11	840	0,9	
Laterizio forato	12	760	7	840		0.31
Laterizio forato	25	760	7	840		0.27
intonaco	1,5	1800	11	840	0,9	
Strato liminare esterno						0,13

parametro		Modulo
spessore	S	40,0 cm
Massa superficiale	M	335 kg/m^2
sfasamento	φ	9.03 h
Capacità termica areica interna	Ki	51.5 kJ/m^{2}K
Capacità termica areica esterna	Ke	61.5 kJ/m^{2}K
Resistenza termica	R	0,883 m^{2}K/W
Trasmittanza termica	U	1.133 W/m^{2}K
Fattore di attenuazione	f	0,329

Lower floor: horizontal closure on unheated space

stratigrafia	s cm	ρ Kg/m^3	μ -	c J/KgK	λ W/mK	R m^{2}K/W
Strato liminare interno						0,13
Piastrelle	1	2300	213	840	1	
Calcestruzzo	8	1000	36	880	0,5	
Blocco da solaio	22	1005	32	840		0,32
Intonaco	1,5	1800	11	840	0,9	
Strato liminare esterno						0,13

parametro		Modulo
spessore	S	32,5 cm
Massa superficiale	M	361 kg/m^2
sfasamento	φ	8,72 h
Capacità termica areica interna	Ki	59,2 kJ/m^{2}K
Capacità termica areica esterna	Ke	62,3 kJ/m^{2}K
Resistenza termica	R	0,767 m^{2}K/W
Trasmittanza termica	U	1,304 W/m^{2}K
Fattore di attenuazione	f	0,342

Upper floor: horizontal closure on unheated space

stratigrafia	s cm	ρ Kg/m^3	μ -	c J/KgK	λ W/mK	R m^{2}K/W
Strato liminare interno						0,13
Intonaco	1,5	1800	11	840	0,9	
Blocco da solaio	18	1005	32	840		0,30
calcestruzzo	2	2400	1	920	1,910	
Malta	1,5	1800	24	840	0,9	
Strato liminare esterno						0,13

parametro		Modulo
spessore	S	23 cm
Massa superficiale	M	283 kg/m^2
sfasamento	φ	6,51 h
Capacità termica areica interna	Ki	61,9 kJ/m^{2}K
Capacità termica areica esterna	Ke	72,1 kJ/m^{2}K
Resistenza termica	R	0,604 m^{2}K/W
Trasmittanza termica	U	1,656 W/m^{2}K
Fattore di attenuazione	f	0,509

AB 1976-1990

External wall: vertical closure

stratigrafia	s cm	ρ Kg/m^3	μ -	c J/KgK	λ W/mK	R m^{2}K/W
Strato liminare interno						0,13
intonaco	1,5	1800	11	840	0,900	
Laterizio forato	12	717	7	840		0,31
isolante	2	50	213	2111	0.060	
Intercapedine d'aria	11	1	1	1000		0,16
Laterizio forato	12	717	7	840		0,31
intonaco	1,5	1800	11	840	0,9	
Strato liminare esterno						0,04

parametro		Modulo
spessore	S	40,0 cm
Massa superficiale	M	227 kg/m^2
sfasamento	φ	7.64 h
Capacità termica areica interna	Ki	54,7 kJ/m^{2}K
Capacità termica areica esterna	Ke	70,2 kJ/m^{2}K
Resistenza termica	R	1.317 m^{2}K/W
Trasmittanza termica	U	0.759 W/m^{2}K
Fattore di attenuazione	f	0,522

Internal wall: vertical closure on unheated space

stratigrafia	s cm	ρ Kg/m^3	μ -	c J/KgK	λ W/mK	R m^{2}K/W
Strato liminare interno						0,13
intonaco	1,5	1800	11	840	0,9	
isolante	3	20	47	1250	0.041	
calcestruzzo	12	1000	5	880	0.420	
intonaco	1,5	1800	11	840	0,9	
Strato liminare esterno						0,13

parametro		Modulo
spessore	S	18,0 cm
Massa superficiale	M	175 kg/m^2
sfasamento	φ	6.03 h
Capacità termica areica interna	Ki	29.4 kJ/m^{2}K
Capacità termica areica esterna	Ke	58.5 kJ/m^{2}K
Resistenza termica	R	1.311 m^{2}K/W
Trasmittanza termica	U	0.763 W/m^{2}K
Fattore di attenuazione	f	0,526

Lower floor: horizontal closure on unheated space

stratigrafia	s cm	ρ Kg/m^3	μ -	c J/KgK	λ W/mK	R m^{2}K/W
Strato liminare interno						0,13
Piastrelle	1	2300	213	840	1	
Calcestruzzo	6	1000	36	880	0,5	
isolante	1	30	143	1250	0.041	
calcestruzzo	4	1300	3	880	0.740	
Blocco da solaio	22	1005	32	840		0,32
Intonaco	1,5	1800	11	840	0,9	
Strato liminare esterno						0,13

parametro		Modulo
spessore	S	35,5 cm
Massa superficiale	M	383 kg/m^2
sfasamento	φ	10.41 h
Capacità termica areica interna	Ki	52.5 kJ/m^{2}K
Capacità termica areica esterna	Ke	59.9 kJ/m^{2}K
Resistenza termica	R	1.025 m^{2}K/W
Trasmittanza termica	U	0.976 W/m^{2}K
Fattore di attenuazione	f	0,241

Upper floor: horizontal closure on unheated space

stratigrafia	s cm	ρ Kg/m^3	μ -	c J/KgK	λ W/mK	R m^{2}K/W
Strato liminare interno						0,13
Intonaco	1,5	1800	11	840	0,9	
Blocco da solaio	22	1005	32	840		0,32
calcestruzzo	4	1300	3	880	0.740	
Isolante	1	30	143	1250	0.041	
calcestruzzo	6	1000	36	8800	0.500	
Malta	1,5	1800	24	840	0,9	
Strato liminare esterno						0,13

parametro		Modulo
spessore	S	36 cm
Massa superficiale	M	387 kg/m^2
sfasamento	φ	10.54 h
Capacità termica areica interna	Ki	59.8 kJ/m^{2}K
Capacità termica areica esterna	Ke	53.0 kJ/m^{2}K
Resistenza termica	R	1.031 m^{2}K/W
Trasmittanza termica	U	0.970 W/m^{2}K
Fattore di attenuazione	f	0,236

6.2. *Internal gains schedules*

AB 1945-1960

	m^2
Area appartamento	62
Stanza letto	26
Cucina+sogg	36

		UNI 11300-1		AB 1945-1960
giorni	ore	cucina+sogg (W/m^2)	stanza letto (W/m^2)	Average value (W/m^2)
lun-ven	dalle 7 alle 17	8	1	5,06
	dalle 17 alle 23	20	1	12,03
	dalle 23 alle 7	2	6	3,68
sab-dom	dalle 7 alle 17	8	2	5,48
	dalle 17 alle 23	20	4	13,29
	dalle 23 alle 7	2	6	3,68

AB 1961-1975

	m^2
Area appartamento	55
Stanza letto	28
Cucina+sogg	27

		UNI 11300-1		AB 1961-1975
giorni	ore	cucina+sogg (W/m^2)	stanza letto (W/m^2)	Average value (W/m^2)
lun-ven	dalle 7 alle 17	8	1	4.44
	dalle 17 alle 23	20	1	10.33
	dalle 23 alle 7	2	6	4.04
sab-dom	dalle 7 alle 17	8	2	4.95
	dalle 17 alle 23	20	4	11.85
	dalle 23 alle 7	2	6	4.04

AB 1976-1990

	m^2
Area appartamento	72
Stanza letto	37
Cucina+sogg	35

		UNI 11300-1		AB 1976-1990
giorni	ore	cucina+sogg (W/m^2)	stanza letto (W/m^2)	Average value (W/m^2)
lun-ven	dalle 7 alle 17	8	1	4.42
	dalle 17 alle 23	20	1	10.29
	dalle 23 alle 7	2	6	4.04
sab-dom	dalle 7 alle 17	8	2	4.93
	dalle 17 alle 23	20	4	11.82
	dalle 23 alle 7	2	6	4.04

6.3. Building retrofit costs

V	building retrofit 1945-1960							
			mq	N	TOTALE	€/MQ	TOTALE	% MAN
01.P08.B03	Serramenti esterni in PVC comprensivi di vetro montato tipo camera bassoemissivo; trasmittanza termica complessiva Uw= <1,6 e 1,2 W/m^2K (UNI EN ISO 10077-1)							
	di superficie fino a 2,0 m^2	mq	217,00	1,00	217,00	€ 265,01	€ 57.507,17	
01.A16.B00	Posa di serramenti esterni completi di telaio e vetrata aventi qualsiasi dimensione e tipo di apertura							
	In PVC antiurto	mq	217,00	1,00	217,00	€ 27,76	€ 6.023,92	93,98
							€ 63.531,09	

RS	building retrofit 1945-1960							
			mq	N	TOTALE	€/MQ	TOTALE €	% MAN
01.P09.A01	Pannello in polistirene espanso sintetizzato (EPS),λ inferiore a 0,038 W/mK. Per isolamento termico di pareti e solai							
01.P09.A01.005	spessore 10 mm	mq	507,00	12,00	6084,00	€ 0,53	€ 3.224,52	
01.P09.A04	Pannello in polistirene espanso sintetizzato (EPS) λ pari a 0,033 W/mK. Per isolamento termico di pareti e solai							
	spessore 50 mm	mq	440,70	1,00	440,70	€ 3,54	€ 1.560,08	
	spessore 60 mm	mq	440,70	1,00	440,70	€ 4,25	€ 1.872,98	
	spessore 120 mm	mq	440,70	1,00	440,70	€ 8,50	€ 3.745,95	
01.A09.G50	Posa in opera di materiali per isolamento termico							
	Per superfici in piano e simili	mq	881,40			€ 6,54	€ 5.764,36	100
	Per superfici verticali o simili	mq	1864,00			€ 10,16	€ 18.938,24	96,55
01.P08.B03	Serramenti esterni in PVC comprensivi di vetro montato tipo camera bassoemissivo; con trasmittanza termica complessiva U_w= <1,6 e 1,2 W/m²K (UNI EN ISO 10077-1)							
	di superficie fino a 2,0 m²	mq	217,00	1,00	217,00	€ 265,01	€ 57.507,17	
01.A16.B00	Posa di serramenti esterni completi di telaio e vetrata aventi qualsiasi dimensione e tipo di apertura							
	In PVC antiurto	mq	217,00	1,00	217,00	€ 27,76	€ 6.023,92	93,98
01.P25.A60	Nolo di ponteggio tubolare esterno eseguito con tubo - giunto							
	Per i primi 30 giorni	mq			1464,50	€ 9,31	€ 13.634,50	
	Per ogni mese oltre al primo	mq	1464,50	2,00	2929,00	€ 1,59	€ 4.657,11	
01.P25.A91	Nolo di piano di lavoro, per ponteggi							
	Per ogni mese	mq	471,20	2	942,40	€ 2,45	€ 2.308,88	
NP1	Fornitura e posa tramite insuflaggio per isolamento termico con schiuma poliuretanica, conducibilità termica stabile nel tempo compresa tra 0.026 e 0.031 W/mK	mc	135,70		135,70	€ 420,00	€ 56.994,00	20
02.P60.O20	Cappa per pavimenti formata con calcestruzzo	mq	440,7			€ 20,49	€ 9.029,94	61,6
02.P55.N05	Posa in opera di rete da intonaco su pareti e soffitti	mq	947,70			€ 3,50	€ 3.316,95	99,85
01.A10.B20	Intonaco eseguito con malta di cemento							
	Eseguito ad un'altezza superiore a m 4, per una superficie complessiva di almeno m² 1 e per uno spessore di cm 0.5	mq	947,70	1,00	947,70	€ 15,91	€ 15.077,91	96,79
TOT							€ 203.656,49	

RA	building retrofit 1945-1960						
			mq	N	TOTALE	€/MQ	TOTALE	% MAN
01.P09.A01	Pannello in polistirene espanso sintetizzato (EPS), λ inferiore a 0,038 W/mK. Per isolamento termico di pareti e solai						
01.P09.A01.005	spessore 10 mm	mq	507,00	18,00	9126,00	€ 0,53	€ 4.836,78	
01.P09.A04	Pannello in polistirene espanso sintetizzato (EPS), λ pari a 0,033 W/mK. Per isolamento termico di pareti e solai							
	spessore 50 mm	mq	440,70	1,00	440,70	€ 3,54	€ 1.560,08	
	spessore 60 mm	mq	440,70	1,00	440,70	€ 4,25	€ 1.872,98	
	spessore 120 mm	mq	440,70	2,00	881,40	€ 8,50	€ 7.491,90	
01.A09.G50	Posa in opera di materiali per isolamento termico							
	Per superfici in piano e simili	mq	881,40			€ 6,54	€ 5.764,36	100
	Per superfici verticali o simili	mq	1864,00			€ 10,16	€ 18.938,24	96,55
01.P08.B03	Serramenti esterni in PVC comprensivi di vetro montato tipo camera bassoemissivo; trasmittanza termica complessiva U_w= <1,6 e 1,2 W/m²K (UNI EN ISO 10077-1)							
	di superficie fino a 2,0 m²	mq	217,00	1,00	217,00	€ 265,01	€ 57.507,17	
01.A16.B00	Posa di serramenti esterni completi di telaio e vetrata aventi qualsiasi dimensione e tipo di apertura							
	In PVC antiurto	mq	217,00	1,00	217,00	€ 27,76	€ 6.023,92	93,98
01.P25.A60	Nolo di ponteggio tubolare esterno eseguito con tubo - giunto							
	Per i primi 30 giorni	mq			1464,50	€ 9,31	€ 13.634,50	
	Per ogni mese oltre al primo	mq	1464,50	2,00	2929,00	€ 1,59	€ 4.657,11	
01.P25.A91	Nolo di piano di lavoro							
	Per ogni mese	mq	471,20	2	942,40	€ 2,45	€ 2.308,88	
NP1	Fornitura e posa tramite insuflaggio per isolamento termico con schiuma poliuretanica, conducibilità termica stabile nel tempo compresa tra 0.026 e 0.031 W/mK	mc	230,70		230,70	€ 420,00	€ 96.894,00	20
02.P60.O20	Cappa per pavimenti formata con calcestruzzo	mq	440,7			€ 20,49	€ 9.029,94	61,6
02.P55.N05	Posa in opera di rete da intonaco su pareti e soffitti		2304,70			€ 3,50	€ 8.066,45	99,85
01.A10.B20	Intonaco eseguito con malta di cemento, su rinzaffo							
	Eseguito ad un'altezza superiore a m 4, per una superficie complessiva di almeno m² 1 e per uno spessore di cm 0.5		2304,70	1,00	2304,70	€ 15,91	€ 36.667,78	96,79
	TOTALE						€ 275.254,07	

V	building retrofit 1961-1975							
			mq	N	TOTALE	€/MQ	TOTALE	% MAN
01.P08.B03	Serramenti esterni in PVC trasmittanza termica complessiva U_w= <1,6 e 1,2 W/m²K (UNI EN ISO 10077-1)							
	di superficie fino a 2,0 m²	mq	321,00		321,00	€ 265,01	€ 85.068,21	
01.A16.B00	Posa di serramenti esterni completi di telaio e vetrata aventi qualsiasi dimensione e tipo di apertura							
	In PVC antiurto	mq	321,00		321,00	€ 27,76	€ 8.910,96	93,98
	TOTALE						€ 93.979,17	

RS	building retrofit 1960-1975							
			mq	N	TOTALE	€/MQ	TOTALE	% MAN
01.P09.A01	Pannello in polistirene espanso sintetizzato (EPS), λ inferiore a 0,038 W/mK. Per isolamento termico di pareti e solai							
01.P09.A01.005	spessore 10 mm	mq	497,00	9,00	4473,00	€ 0,53	€ 2.370,69	
01.P09.A04	Pannello in polistirene espanso sintetizzato (EPS), λ pari a 0,033 W/mK. Per isolamento termico di pareti e solai							
	spessore 50 mm	mq	358,70	1,00	358,70	€ 3,54	€ 1.269,80	
	spessore 60 mm	mq	358,70	1,00	358,70	€ 4,25	€ 1.524,48	
	spessore 120 mm	mq	358,70	1,00	358,70	€ 8,50	€ 3.048,95	
01.A09.G50	Posa in opera di materiali per isolamento termico							
	Per superfici in piano e simili	mq	717,40		717,40	€ 6,54	€ 4.691,80	100
	Per superfici verticali o simili	mq	3628,80		3628,80	€ 10,16	€ 36.868,61	96,55
01.P08.B03	Serramenti esterni in PVC comprensivi di vetro montato tipo camera basso emissivo, trasmittanza termica complessiva U_w= <1,6 e 1,2 W/m²K (UNI EN ISO 10077-1)							
	di superficie fino a 2,0 m²	mq	321,00		321,00	€ 265,01	€ 85.068,21	
01.A16.B00	Posa di serramenti esterni completi di telaio e vetrata aventi qualsiasi dimensione e tipo di apertura							
	In PVC antiurto	mq	321,00		321,00	€ 27,76	€ 8.910,96	93,98
01.P25.A60	Nolo di ponteggio tubolare esterno eseguito con tubo - giunto							
	Per i primi 30 giorni	mq	2568,60	1,00	2568,60	€ 9,31	€ 23.913,67	
	Per ogni mese oltre al primo	mq	2568,60	2,00	5137,20	€ 1,59	€ 8.168,15	
01.P25.A91	Nolo di piano di lavoro							
	Per ogni mese	mq	811,00	3	2433,00	€ 2,45	€ 5.960,85	
NP1	Fornitura e posa tramite insuflaggio per isolamento termico con schiuma poliuretanica, conducibilità termica stabile nel tempo compresa tra 0.026 e 0.031 W/mK	mc	281,90		281,90	€ 420,00	€ 118.398,00	20
02.P60.O20	Cappa per pavimenti formata con calcestruzzo	mq	358,7		358,7	€ 20,49	€ 7.349,76	61,6
02.P55.N05	Posa in opera di rete da intonaco su pareti e soffitti	mq	855,70		855,70	€ 3,50	€ 2.994,95	99,85
01.A10.B20	Intonaco eseguito con malta di cemento							
	Eseguito ad un'altezza superiore a m 4, per una superficie complessiva di almeno m² 1 e per uno spessore di cm 0.5	mq	855,70		855,70	€ 15,91	€ 13.614,19	96,79
	TOTALE						€ 324.153,05	

RA	building retrofit 1961-1975							
			mq	N	TOTALE	€/MQ	TOTALE	% MAN
01.P09.A01	Pannello in polistirene espanso sintetizzato (EPS). Per isolamento termico di pareti e solai							
01.P09.A01.005	spessore 10 mm	mq	497,00	16,00	7952,00	€ 0,53	€ 4.214,56	
01.P09.A04	Pannello in polistirene espanso sintetizzato (EPS), λ pari a 0,033 W/mK. Per isolamento termico di pareti e solai							
	spessore 50 mm	mq	358,70	1,00	358,70	€ 3,54	€ 1.269,80	
	spessore 60 mm	mq	358,70	1,00	358,70	€ 4,25	€ 1.524,48	
	spessore 120 mm	mq	358,70	2,00	717,40	€ 8,50	€ 6.097,90	
01.A09.G50	Posa in opera di materiali per isolamento termico							
	Per superfici in piano e simili	mq	717,40		717,40	€ 6,54	€ 4.691,80	100
	Per superfici verticali o simili	mq	3628,80		3628,80	€ 10,16	€ 36.868,61	96,55
01.P08.B03	Serramenti esterni in PVC comprensivi di vetro montato tipo camera bassoemissivo; trasmittanza termica complessiva U_w= <1,6 e 1,2 W/m²K (UNI EN ISO 10077-1)							
	di superficie fino a 2,0 m²	mq	321,00		321,00	€ 265,01	€ 85.068,21	
01.A16.B00	Posa di serramenti esterni completi di telaio e vetrata aventi qualsiasi dimensione e tipo di apertura							
	In PVC antiurto	mq	321,00		321,00	€ 27,76	€ 8.910,96	93,98
01.P25.A60	Nolo di ponteggio tubolare esterno eseguito con tubo - giunto							
	Per i primi 30 giorni	mq	2568,60	1,00	2568,60	€ 9,31	€ 23.913,67	
	Per ogni mese oltre al primo	mq	2568,60	2,00	5137,20	€ 1,59	€ 8.168,15	
01.P25.A91	Nolo di piano di lavoro, per ponteggi							
	Per ogni mese	mq	811,00	3	2433,00	€ 2,45	€ 5.960,85	
NP1	Fornitura e posa tramite insuflaggio per isolamento termico con schiuma poliuretanica, conducibilità termica stabile nel tempo compresa tra 0.026 e 0.031 W/mK	mc	532,40		532,40	€ 420,00	€ 223.608,00	20
02.P60.O20	Cappa per pavimenti formata con calcestruzzo	mq	358,7		358,7	€ 20,49	€ 7.349,76	61,6
02.P55.N05	Posa in opera di rete da intonaco su pareti e soffitti	mq	855,70		855,70	€ 3,50	€ 2.994,95	99,85
01.A10.B20	Intonaco eseguito con malta di cemento							
	Eseguito ad un'altezza superiore a m 4, per una superficie complessiva di almeno m² 1 e per uno spessore di cm 0.5	mq	855,70		855,70	€ 15,91	€ 13.614,19	96,79
	TOTALE						€ 434.255,87	

V	building retrofit 1976-1990							
			mq	N	TOTALE	€/MQ	TOTALE	% MAN
01.P08.B03	Serramenti esterni in comprensivi di vetro montato tipo camera bassoemissivo; trasmittanza termica complessiva U_w= <1,6 e 1,2 W/m²K (UNI EN ISO 10077-1)							
	di superficie fino a 2,0 m²	mq	222,00		222,00	€ 265,01	€ 58.832,22	
01.A16.B00	Posa di serramenti esterni completi di telaio e vetrata aventi qualsiasi dimensione e tipo di apertura							
	In PVC antiurto	mq	222,00		222,00	€ 27,76	€ 6.162,72	93,98
	TOTALE						€ 64.994,94	

RS	building retrofit 1976-1990							
			mq	N	TOTALE	€/MQ	TOTALE	% MAN
01.P09.A01	Pannello in polistirene espanso sintetizzato (EPS), λ inferiore a 0,038 W/mK. Per isolamento termico di pareti e solai							
01.P09.A01.005	spessore 10 mm	mq	601,00	8,00	4808,00	€ 0,53	€ 2.548,24	
01.P09.A04	Pannello in polistirene espanso sintetizzato (EPS), λ pari a 0,033 W/mK. Per isolamento termico di pareti e solai							
	spessore 50 mm	mq	688,00	1,00	688,00	€ 3,54	€ 2.435,52	
	spessore 60 mm	mq	688,00	1,00	688,00	€ 4,25	€ 2.924,00	
	spessore 100 mm	mq	688,00	1,00	688,00	€ 7,09	€ 4.877,92	
01.A09.G50	Posa in opera di materiali per isolamento termico							
	Per superfici in piano e simili	mq	1376,00		1376,00	€ 6,54	€ 8.999,04	100
	Per superfici verticali o simili	mq	3358,00		3358,00	€ 10,16	€ 34.117,28	96,55
01.P08.B03	Serramenti esterni in PVC comprensivi di vetro montato tipo camera bassoemissivo; trasmittanza termica complessiva U_w= <1,6 e 1,2 W/m²K (UNI EN ISO 10077-1)							
	di superficie fino a 2,0 m²	mq	222,00		222,00	€ 265,01	€ 58.832,22	
01.A16.B00	Posa di serramenti esterni completi di telaio e vetrata aventi qualsiasi dimensione e tipo di apertura							
	In PVC antiurto	mq	222,00		222,00	€ 27,76	€ 6.162,72	93,98
01.P25.A60	Nolo di ponteggio tubolare esterno eseguito con tubo - giunto							
	Per i primi 30 giorni	mq	2484,00	1,00	2484,00	€ 9,31	€ 23.126,04	
	Per ogni mese oltre al primo	mq	2484,00	2,00	4968,00	€ 1,59	€ 7.899,12	
01.P25.A91	Nolo di piano di lavoro				0,00		€ 0,00	
	Per ogni mese	mq	892,00	3	2676,00	€ 2,45	€ 6.556,20	
NP1	Fornitura e posa tramite insuflaggio per isolamento termico con schiuma poliuretanica, conducibilità termica stabile nel tempo compresa tra 0.026 e 0.031 W/mK	mc	303,00		303,00	€ 420,00	€ 127.260,00	20
02.P60.O20	Cappa per pavimenti formata con calcestruzzo	mq	688		688	€ 20,49	€ 14.097,12	61,6
02.P55.N05	Posa in opera di rete da intonaco su pareti e soffitti	mq	1289,00		1289,00	€ 3,50	€ 4.511,50	99,85
01.A10.B20	Intonaco eseguito con malta di cemento							
	Eseguito ad un'altezza superiore a m 4, per una superficie complessiva di almeno m² 1 e per uno spessore di cm 0.5	mq	1289,00		1289,00	€ 15,91	€ 20.507,99	96,79
	TOTALE						€ 324.854,91	

RA	building retrofit 1976-1990							
			mq	N	TOTALE	€/MQ	TOTALE	% MAN
01.P09.A01	Pannello in polistirene espanso sintetizzato (EPS), λ inferiore a 0,038 W/mK. Per isolamento termico di pareti e solai							
01.P09.A01.005	spessore 10 mm	mq	601,00	14,00	8414,00	€ 0,53	€ 4.459,42	
01.P09.A04	Pannello in polistirene espanso sintetizzato (EPS), λ pari a 0,033 W/mK. Per isolamento termico di pareti e solai							
	spessore 50 mm	mq	688,00	1,00	688,00	€ 3,54	€ 2.435,52	
	spessore 140 mm	mq	688,00	1,00	688,00	€ 9,92	€ 6.824,96	
	spessore 160 mm	mq	688,00	1,00	688,00	€ 11,34	€ 7.801,92	
01.A09.G50	Posa in opera di materiali per isolamento termico							
	Per superfici in piano e simili	mq	1376,00		1376,00	€ 6,54	€ 8.999,04	100
	Per superfici verticali o simili	mq	3358,00		3358,00	€ 10,16	€ 34.117,28	96,55
01.P08.B03	Serramenti esterni in PVC comprensivi di vetro montato tipo camera bassoemissivo; trasmittanza termica complessiva U_w= <1,6 e 1,2 W/m^{2}K (UNI EN ISO 10077-1)							
	di superficie fino a 2,0 m^2	mq	222,00		222,00	€ 265,01	€ 58.832,22	
01.A16.B00	Posa di serramenti esterni completi di telaio e vetrata aventi qualsiasi dimensione e tipo di apertura							
	In PVC antiurto	mq	222,00		222,00	€ 27,76	€ 6.162,72	93,98
01.P25.A60	Nolo di ponteggio tubolare esterno eseguito con tubo - giunto							
	Per i primi 30 giorni	mq	2484,00	1,00	2484,00	€ 9,31	€ 23.126,04	
	Per ogni mese oltre al primo	mq	2484,00	2,00	4968,00	€ 1,59	€ 7.899,12	
01.P25.A91	Nolo di piano di lavoro				0,00		€ 0,00	
	Per ogni mese	mq	892,00	3	2676,00	€ 2,45	€ 6.556,20	
NP1	Fornitura e posa tramite insuflaggio per isolamento termico con schiuma poliuretanica, conducibilità termica stabile nel tempo compresa tra 0.026 e 0.031 W/mK	mc	441,00		441,00	€ 420,00	€ 185.220,00	20
02.P60.O20	Cappa per pavimenti formata con calcestruzzo	mq	688		688	€ 20,49	€ 14.097,12	61,6
02.P55.N05	Posa in opera di rete da intonaco su pareti e soffitti	mq	4046,00		4046,00	€ 3,50	€ 14.161,00	99,85
01.A10.B20	Intonaco eseguito con malta di cemento						€ 0,00	
	Eseguito ad un'altezza superiore a m 4, per una superficie complessiva di almeno m^2 1 e per uno spessore di cm 0.5	mq	4046,00		4046,00	€ 15,91	€ 64.371,86	96,79
	TOTALE						€ 445.064,42	

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