UNIVERSITY OF TRENTO

Doctoral School in Civil, Environmental and
Mechanical Engineering

Curriculum 4. Architecture and Planning, Landscape

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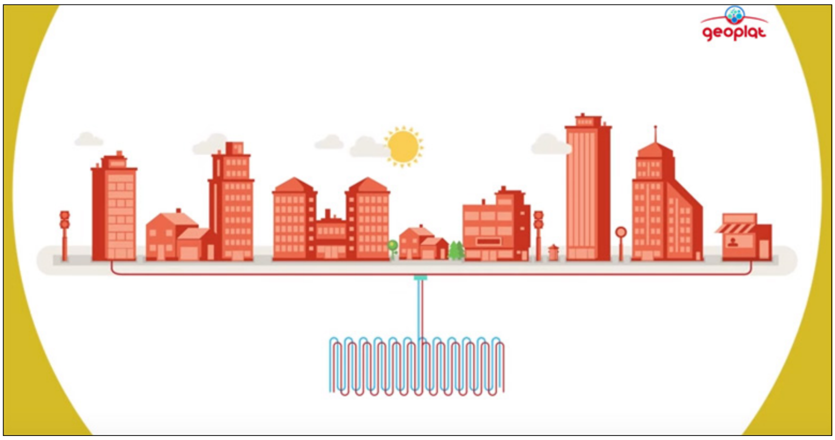
A Spatial Decision Support System for thermal energy planning at the regional scale



2019 - Doctoral thesis

UNIVERSITY OF TRENTO - Italy
Department of Civil, Environmental
and Mechanical Engineering

Doctoral School in Civil, Environmental and Mechanical Engineering
Topic 4. Architecture and Planning, Landscape - XXXI cycle 2015/2018

Doctoral Thesis - May 2019

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A Spatial Decision Support System for thermal energy planning at the regional scale

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Credits of the cover image: GEOPLAT (Spanish Technology and Innovation Platform in Geothermal)

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If you assume that there is no hope, you guarantee that there will be no hope. If you assume that there are opportunities to change things, then there is a possibility that you can contribute to making a better world.

Noam Chomsky (1997)

Look deep into nature,
and then you will understand everything better.

Albert Einstein (1951)

Acknowledgements

This Ph.D. thesis is the result of the research project undertaken within the Doctoral School in Civil, Environmental and Mechanical Engineering (DICAM) of the University of Trento, on a co-tutelle agreement with Eurac Research, the European Academy of Bolzano/Bozen.

I would have never reached the point of finishing my dissertation without the help and support of others. First, I offer my gratitude to my University supervisors: prof. Corrado Diamantini and prof. Rossano Albatici, who guided me through the path of the Ph.D. experience; their advices and feedbacks were always precious. My gratitude also goes to my Eurac tutors: Daniele Vettorato and especially Pietro Zambelli, who affectionately supported me and always believed in the project idea. A special thanks to the whole URS research group of the Institute for Renewable Energy of Eurac that worked with me, trained me, patiently listened to my presentations and followed the evolution of my research, and also to other colleagues of the Institute…I know I'm lucky to have found some people that now are friends and not only colleagues! I would like to thank Paola Gazzola that hosted me during my abroad period at the Newcastle University and assisted me during the last months of the Ph.D. programme. I thank all professors, researchers, Ph.D. students and experts I met during these three years, from whom I received interesting insights. Finally, I would thank all the partners of the GRETA project, the Energy Authority of the Valle d'Aosta Region (COA Energia) and the Department for Statistical Production of the Italian National Statistics Institute (ISTAT) for the help provided in the data collection for the case study area.

These three years have been a challenging trip, full of ups and downs. Fortunately, I was never alone on this road, but accompanied by Richi, who patiently supported and endured me, and by my family, who always encouraged me.

Thank you, this thesis would not have been possible without your help!

With this dissertation, I also would like to remember a great person and Ph.D. student of the DICAM, who unfortunately left us almost two years ago…Ciao Ale!

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Abstract

The focus of the Ph.D. dissertation is on the thermal part of the energy planning issue since the space conditioning (heating and cooling – H&C) of buildings represents about 75% of the energy consumed by European residential buildings and only 16% of the heating and cooling consumption is covered by renewable energy sources (RES). At the same time, the increased complexity of the spatial planning process when energy issues are involved has made clear the need for new "energy-aware" tools and methods used in this field.

The proposed methodology is GIS (Geographical Information System)-based and performed at regional scale given that the movement of energy planning activities from national to regional and local scale allows a much more detailed analysis of both the energy demand and supply, balancing them more effectively. The integration of the spatial dimension within energy analyses can also provide the decision-makers with a spatially-explicit approach towards the energy transition and the development of sustainable energy plans and strategies.

The general aim of the Ph.D. thesis is to develop a Spatial Decision Support System (SDSS) allowing the decision-makers to take into account (during the planning process) both the improvement of the energy production from RES and the energy renovation of the existing building stock. The SDSS aims also to connect the energy planning (supply side) with spatial planning (demand side) by seeking synergies between the two fields. This connection is made taking advantage of the framework of the Strategic Environmental Assessment (SEA).

The Ph.D. thesis is partially developed within a European co-financed project included in the Interreg Alpine Space programme. The GRETA project was designed to foster the use of shallow geothermal energy (SGE) in energy plans and strategies along the Alps. SGE is a low-carbon source for H&C of buildings, which exploits the heat stored within the ground, a local source widely available and less dependent from changes in time compared to other RES. Despite this, its exploitation is not yet diffused and its growth is limited mainly by factors such as scarce knowledge, complicated and fragmented legislation, and high installation costs.

Considering all these issues, the research questions that shaped the Ph.D. activities are:

- How to estimate the thermal energy demand of the residential building stock at the regional scale, as a starting point for developing sustainable energy strategies aimed at the reduction of the thermal energy consumption in the existing buildings.
- How to integrate this appraisal in the energy planning of a region in order to elaborate different scenarios for the energy balance between thermal demand and supply, fostering the use of shallow geothermal energy (SGE) that is a renewable source still not well-known and not exploited.

- ➢ How to encourage the connection between energy planning and spatial planning towards the common goal of sustainable energy transition, helping to fill the gap between the development of plans and strategies and their implementation, thanks to the Strategic Environmental Assessment (SEA) framework.

The proposed methodology has been applied in a case study, i.e. Valle d'Aosta, an Italian alpine region. Almost all the data processing is performed with open-source software (GRASS GIS, QGIS, Python, and R) and applying a spatially-explicit approach, for pushing the integration of the spatial dimension in the energy analysis. The spatial units of analysis are the single building and the census tract. The single building has been chosen as the smallest unit available for ensuring a better characterization of the thermal energy demand and of the potential energy production from SGE. Moreover, the scenario analysis for the energy renovation of buildings is better performed at the building level; so, it is particularly suitable for developing an SDSS.

Nevertheless, some data processing is done at the census tract level, using aggregated and statistical information to estimate the required values at the building level. The reason for this twofold scale of analysis is that the data availability often changes depending on time, space and data provider. For instance, for the case study area only little data was available at the building level for the whole region. Therefore, the methodology integrates data from different sources to fill this knowledge gap.

The methodology applied in the case study is divided into two parts:

1) The first one concerns the data collection and processing for the spatial estimation of the space heating demand of the existing building stock. At the end of it, the technical and economic suitability of SGE (performed within the GRETA project) for covering the energy demand of buildings and replacing some fossil fuels is evaluated.
2) The second one is carried out in the framework of SEA, by defining common objectives and developing scenarios for the integration of SGE in the energy planning process, as the short-term objective, and the coordination of energy and spatial planning goals, as the long-term objective. In the Ph.D. thesis, SEA is intended as a conceptual framework for integrating energy and spatial planning, rather than as an evaluation tool.

The main outputs of the Ph.D. thesis are: (i) the spatial evaluation of the space heating demand of each residential building of the case study, without using the "archetypes approach"; (ii) the development of a method for the integration of data from different sources and for its estimation if missing at the building level; (iii) the use of SEA as a framework for connecting energy planning and spatial planning fields, to support strategic decision-making processes. Even though the Ph.D. case study is a typical alpine region, (iv) the developed methodology can be applied at different scales and not only on alpine regions but potentially in every kind of context. Since it strongly depends on the availability of data, the replicability of the methodology is quite high.

The main expected impacts of these outputs are: (1) SDSS allows to reach a trade-off between the number of input data and the level of detail often required by decision-makers; (2) SDSS can support the decision-makers allowing them to analyse from various viewpoints different energy scenarios and also to localise where is better to address the energy measures; (3) the results at the building level represent a starting point for defining and developing strategies for the energy transition of settlements at different scales; (4) SEA used as a strategic tool for integrating energy and spatial planning, by coordinating strategic objectives, and linking the thesis outputs to the energy decision-making process.

Acronyms and Abbreviations

ACS – Air Conditioning System
ARPA – Agenzia Regionale per la Protezione Ambientale
BSA – Building Stock Analysis
CENED - Certificazione ENergetica degli EDifici
COA Energia – Centro Osservazione e Attività sull’Energia
D&S – Demand and Supply (of energy)
DHN – District Heating Network
DHW – Domestic Hot Water
DPP – Discounted Payback Period
DTM – Digital Terrain Model
DSM – Digital Surface Model
EIA – Environmental Impact Assessment
EPC - Energy Performance Certificate
EU – European Union
GHG – Greenhouse Gas
GIS – Geographic Information System
GRETA – near-surface Geothermal REsources in the Territory of the Alpine space
GSHP – Ground Source Heat Pump
GWHP – Ground Water Heat Pump
H&C – Heating and Cooling
HP – Heat Pump
HS – Heating System
IPCC – Intergovernmental Panel on Climate Change
ISTAT – Istituto Nazionale di Statistica
LCOE – Levelized Cost Of Energy
LiDAR – Light Detection And Ranging
LPG - Liquid Petroleum Gas
MFH – Multi Family House
OSM – OpenStreetMap
PPP – Policies, Plans and Programmes
PV – Photovoltaic
REEP – Regional Energy and Environmental Plan
RES – Renewable Energy Source
RSLP – Regional Spatial and Landscape Plan
SDSS – Spatial Decision Support System
SEA – Strategic Environmental Assessment
SFH – Single Family House
SGE – Shallow Geothermal Energy
SPF – Seasonal Performance Factor
VdA – Valle d’Aosta

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CHAPTER 1

1 Introduction

This Ph.D. dissertation contains the methodology and the results of the development of a Spatial Decision Support System for the thermal energy demand and supply planning process at the regional scale. The research project was undertaken within the Doctoral School in Civil, Environmental and Mechanical Engineering (DICAM) of the University of Trento during the 31° cycle of Ph.D. programme (2015-2018). The Ph.D. thesis was performed on a co-tutelle agreement with Eurac Research (Bolzano/Bozen), at the Institute for Renewable Energy within the Urban and Regional Energy Systems research group[1].

Into the Ph.D. thesis the planning concept is regarded both as a discipline (i.e. a field of study) and as the public activity that is implemented within the planning process (i.e. a field of public intervention). For clarity's sake, along the dissertation when referring to the first meaning the term "planning" is used while for the second one the concept is expressed with "planning process".

A Decision Support System (DSS) can be explained in general as an interactive and flexible computer-based information system developed for supporting the solution of a complex or unstructured management problem and thus improving the decision-making process (Matthies, Giupponi, and Ostendorf 2007). Therefore, supporting the decision-making activity requires both the understanding of the processes involved and the provision of a computer-based system that allows the decision-makers to carry out the related activities more effectively (Hersh 1999).

DSSs can be required in support of strategic planning processes, usually within the context of policy-making and plan-making. When the spatial dimension is relevant for the decision process, DSSs often become spatial decision support systems (SDSSs). They integrate spatially explicit functionalities or couple with GIS (Geographic Information System) tools (Mattiussi, Rosano, and Simeoni 2014). According to (Power 2001), who identified four main types of DSS depending on the main characteristics of the decisional process, the here presented SDSS can be defined as data-driven (main component), for policy-makers and planners (target users), aiming at fostering the sustainable energy transition (purpose) using GIS tools (technology).

It is noteworthy that the Ph.D. thesis was partially developed in the framework of a project co-financed by the European Regional Development Fund through the Interreg Alpine Space programme. This project was called GRETA (*near-surface Geothermal*

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[1] http://www.eurac.edu/en/research/technologies/renewableenergy/researchfields/Pages/Energy-strategies-and-planning.aspx

REsources in the Territory of the Alpine space)[2] and it was designed to foster the integration of the shallow geothermal energy (SGE) in energy plans and strategies along the Alps. The project started in December 2015 and ended in December 2018.

In this first chapter, the background of the thesis will be presented together with the main issues arisen and the consequent research questions that shaped the research activity along the 3-years Ph.D. programme. I would like to start with a vision inspired by (Droege 2018): imagine a future where energy is an embedded dimension of cities and regions, an intrinsic spatial function rather than an external source. Territories are all about energy since their spatial structures are being shaped by the energy utilisation since centuries.

1.1 Climate Challenge and Sustainable Energy

1.1.1 International and European context

At the international level, the Sustainable Development Goals (set by the United Nations in 2015 and to be reached by 2030), the New Urban Agenda (Habitat III n.d.), and the Paris Agreement are the main global and complementary initiatives launched to move towards a more sustainable future. The Sustainable Development Goal 7 claims for affordable and clean energy (United Nations n.d.). According to this goal, more progress needs to be made regarding the integration of renewable energy into end-use applications in all sectors, i.e. buildings, transport, and industry. Public and private investments in sustainable energy also need to be increased.

Concerning the Paris Agreement, at the Conference of Parties (COP) 21 that took place in Paris in December 2015, the United Nation Framework Convention on Climate Change (UNFCCC) reached an important agreement to struggle against climate change and intensify actions and investments needed for a sustainable low carbon future (‘UNFCCC EHandbook’ n.d.). For the first time, the Paris Agreement brought all nations into a common cause of undertaking ambitious efforts to adapt to the effects of climate change. Indeed, it designed a new path within the global climate strategy: its central aim is to strengthen the global response to the climate change by keeping the global temperature rise below 2 degrees Celsius in comparison to the pre-industrial levels and to pursue efforts to limit the temperature increase even to 1.5 degrees Celsius.

Climate change threat and depletion of fossil fuels are among the main drivers of sustainable energy transition. Indeed, one of the main cause of CO_2 emissions into the atmosphere are the fossil fuels used to produce both electricity and heat. In this context, renewable energy proves to be a strategic solution, more friendly to people and the environment (Pacesila, Burcea, and Colesca 2016). Aside some issues related to the use of renewable energy sources, whose resolution is considered a priority task because the energy transition is seen as a necessary condition for the sustainable development, the

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[2] http://www.alpine-space.eu/projects/greta/en/home

benefits of sustainable energy for countries and regions are huge (Oudes and Stremke 2018). Thus, energy transition has become a key challenge at different scales and the various agreements, international and national, need now to be turned into regional and local targets.

The European Union has always been very active in the field of climate and energy policies. According to several European directives and policy documents, the development of more renewable and sustainable energy systems represents one of the main objectives of the European energy policy. In the last decades, European countries (and consequently regions and cities) have defined specific targets for cutting greenhouse gas (GHG) emissions, increasing the share of renewable energy sources (RES) in the production and consumption of energy, and improving energy savings through the increase of energy efficiency. See (Reckien et al. 2018) for a reference baseline on the degree of development of local climate and energy plans among European cities.

Currently, the task of developing post-2020 strategies is urgent and the European Union has already set strategic targets until 2050, working by steps through the Climate and Energy Framework 2030 (European Commission 2016) and the Energy Roadmap 2050 (European Commission 2011). These actions do not replace national, regional and local efforts to modernise energy supply systems. On the contrary, they want to develop a long-term European carbon neutral framework in which national, regional and local policies will be more effective, strengthening the European approach to the climate and energy challenge. Specifically, the main European targets for 2030 and 2050 can be summarised as follows.

Climate and Energy Framework 2030:

- At least 40% reduction in GHG emissions, compared to 1990 levels;
- At least 27% in the share between energy production from RES and total consumption;
- At least 27% improvement in energy efficiency.

Energy Roadmap 2050:

- Reduction of GHG emissions by 80-95%, when compared to 1990 levels;
- Reduction of energy demand by 41%, when compared to 2005-2006 peaks;
- High share of renewable energies in gross final energy consumption (75%).

In July 2018, new versions of the Directive on the energy performance of buildings (2010/31/EU) and the Directive on energy efficiency (2012/27/EU) entered into force. Three main changes have been introduced (European Parliament 2018): (i) requirements to improve the energy performance of new and existing buildings; (ii) support for the development of charging infrastructure for electric vehicles; (iii) requirements to update national building renovation strategies and indicators. The update of the Directive 2010/31/EU requires the Member States to develop long-term national strategies to support the efficient renovation of public and private buildings, for reaching the target of a highly decarbonised of the building sector by 2050, with midway steps by 2030 and 2040. The EU countries must transpose the directive by March 2020.

1.1.2 Italian and Alpine context

In the national context, ensuring the development of more competitive and sustainable energy systems is one of the most important challenges for the future of Italy. This is why recently, the Italian Government has considered as essential to work towards the definition of a National Energy Strategy that clearly sets the main objectives to be pursued in the coming years and defines the priorities for action. The National Energy Strategy (Ministero dello Sviluppo Economico 2017) has been established through extensive public consultation with national institutions, research institutes, associations, and social partners. It included also the main economic actors involved in the energy sector. Its main targets for 2030 and 2050 are summarised in the following paragraphs.

Italian targets for 2030:

- 28% of production from RES on the basis of gross final consumption;
- 30% reduction in energy consumption compared to the trend level;
- 39% reduction in CO_2 emissions compared to the level of 1990.

Italian targets for 2050:

- Energy efficiency: reduction of primary consumption from 17% to 26% compared to 2010;
- Production from RES should reach the level of at least 60% of gross final consumption;
- Increase of the electrification process, which is expected to almost double, to at least 38%.

Since the Alpine area is composed of territories with different demographic, social and economic trends and a variety of governance systems and cultural traditions, the EUSALP macro-regional strategy (EUropean Strategy for ALPine region) wants to provide an opportunity to improve the cooperation among the Alpine countries and regions as well to identify common goals and effective implementation measures through transnational collaboration. EUSALP constitutes a strategic agenda that aims to inform relevant policies at European, national and regional level (EUSALP n.d.) and is divided into different thematic areas that address the most relevant topics for the Alpine macro-region.

Among the others, the Action Group 9 of EUSALP strategy focuses on the promotion of energy efficiency and the production and use of local RES in the Alpine area, especially in the public and private sectors. The framework is provided by European directives and policy documents and the actions aim at supporting a significant reduction of energy consumption in the housing and mobility sector, as well as in small and medium enterprises. The actions also promote energy management and monitoring systems at different levels.

In 2017, the Action Group 9 developed the EUSALP Energy Survey that collected information about regional and local energy strategies, aggregating data to the macro-regional scale, and compared medium and long-term policy goals defined by the different entities in the EUSALP territory (Bisello et al. 2017). Experts from states and regions were invited to fill out a questionnaire. The survey consisted of questions about energy production and consumption, energy strategies, policy goals, state of implementation, and (perceived) remaining potentials for the expansion of RES in the macro-region.

From the answers to the section of the survey related to energy strategies, a great variety of targets emerged for a medium and long-term period. The overview of the diversified set of local energy targets, both for RES exploitation and energy saving in the medium and long-term, highlighted the heterogeneity of EUSALP territories (Tomasi et al. 2019). The comparison with European targets showed that the local long-term targets of EUSALP regions are quite ambitious and related to a distant target year (often 2050). On the other hand, the achievement of thermal goals resulted to be more challenging.

1.1.3 Role of Shallow Geothermal Energy

Low-temperature (or low-enthalpy) geothermal energy is the energy contained in the ground and in the water table at less than 200 m depth (and for this called “shallow”). It is considered a renewable energy source that can be used for the heating and cooling (H&C) of buildings, the production of domestic hot water (DHW) and of hot and/or cold water in industrial processes. To bring the extracted thermal energy from the ground to one of these uses, a heat pump (HP) is used. HP is an electrical machine that transfers the heat from a lower temperature body to a higher temperature one (a process that cannot take place spontaneously) (GRETA project 2018d).

The exploitation of shallow geothermal energy (SGE) has been gradually becoming popular in Europe for heating and cooling purposes. The low-enthalpy shallow geothermal source can help European countries to meet their commitments and targets in terms of energy saving, energy production from RES, and CO_2 emissions reduction. However, the contribution of SGE to this last target is still marginal, except for countries such as Sweden and Switzerland (Bayer et al. 2012). The main reason is the high installation cost due to the HP and the drilling work. The growth of the use of SGE is also limited by complicated and fragmented legislation and by the scarce knowledge on the possible applications of this energy source (Casasso, Pestotnik, et al. 2017).

The current state of technology development and regulation varies a lot among the European Member States (see also the comparison among Alpine countries performed in

(GRETA project 2016)) and significant barriers are still limiting the investments for this energy technology. An increase of the use of SGE systems in Europe could be achieved by (Tinti et al. 2018): (1) decreasing investment costs; (2) reducing system complexity and safety issues; and (3) enhancing SGE recovery rates. Besides the technical aspects, also the interaction between SGE systems and environmental components (above all ground and groundwater) must be considered during the system design and construction phase.

Geothermal heat pumps are one of the least carbon-intensive technologies for H&C of buildings (Nejat et al. 2015). Compared to air-source heat pumps, they are more efficient, since the ground has a more constant temperature in comparison to the air (i.e. it is usually warmer during the winter and cooler during the summer) (Rivoire et al. 2018). The European Directive on the energy performance of buildings (Directive 2010/31/EU), which is the main legislation in EU for energy efficiency in buildings, also advocates the use of heat pumps and RES for heating and cooling systems in the housing sector. Furthermore, even the International Energy Agency (IEA) recommends the installation of HP for heating, cooling and domestic hot water as a priority (Miglani, Orehounig, and Carmeliet 2018).

In Italy a widespread interest for SGE is recently growing, mainly due to the increasingly attention to climate protection strategies, the strict regulation for the use of RES to supply the energy demand of buildings, and the availability of incentive schemes that make the HP systems economically more attractive (i.e. Conto Termico, Ecobonus) (Viesi et al. 2018). The EurObservER data of 2017 shows that in Italy around 1,000 new geothermal heat pumps are installed every year. The supply chain is mainly national: more than 80% of investments have an impact on the internal economic and employment system (ARPA Valle d'Aosta n.d.).

The national reference law is the Legislative Decree 28/2011, where the geothermal source is considered as renewable thermal energy. However, the normative framework has some gaps and critical issues, mainly concerning the authorization stage. The regional authorisation framework outlines a very heterogeneous and fragmented situation (see again (GRETA project 2016)). In the last years, some Italian regions have implemented new and advanced regulation, but several limitations remain. According to the National Association of Geothermal Plants (ANIGhp), the main constraint for the development of geothermal energy in Italy is the lack of information and training for technicians.

Nevertheless, Italy has great potential for the development of this technology. The thermal energy consumption represents almost half of the total energy needs (45%), although there is still no adequate measures in energy policies and incentives (10% against 77% of subsidies for electrical RES) (Cesari 2018). Another opportunity is represented by the concern about air quality that is now affecting many parts of Italy (particularly the plain of Po river). The combustion of fossil fuels and biomass for heating the buildings is one of the main cause and geothermal HP can also contribute reducing these emissions. Furthermore, SGE can be used for supplying district heating systems, which seem to be the real keystone for a relevant increase in the exploitation of renewable heat.

1.2 Problem Statement

- *Why focusing on the thermal energy in buildings?*

The Ph.D. dissertation focuses on the thermal side of the energy demand and supply (D&S) in residential buildings since it is impossible to imagine a sustainable energy transition without paying attention to the built environment. In European households, the use of energy for heating and domestic hot water (DHW) account for almost 80% of the total final energy consumption (European Commission, n.d.). Therefore, it is fundamental to implement in this field energy saving solutions and proper energy systems based on RES. As mentioned, both the European Union and Italy have set relevant targets for the reduction of energy consumption and of the related CO_2 emissions. Within these strategies, the building sector has been identified to have a great potential to improve energy efficiency and reduce CO_2 emissions, also thanks to the energy refurbishment of buildings. Thus, the knowledge about the thermal energy demand in a specific territory can help to increase the effectiveness of energy strategies and plans for achieving local, national and European targets (D'Alonzo and Zambelli 2018).

For what concerns the thermal energy sector, the objectives are very ambitious and cannot be achieved without the diffusion of heat pumps for H&C of the buildings (given also the issues related to the biomass use, see previous Section 1.1.3) (Cesari 2018). In this context, the spatially explicit evaluation of the thermal demand of buildings becomes crucial, requiring the punctual characterization and analysis of the building stock. Indeed, the fossil fuel consumption for H&C of existing buildings can be reduced with energy renovation measures or electrification of the heating demand of buildings (Walker et al. 2018). Therefore, electrical heat pumps are a point of interest in such a transition, since they could play a relevant role at the level of individual buildings and neighbourhoods (i.e. mini district-heating networks).

- *Why seeking for the integration of energy planning and spatial planning?*

Improvements in current energy systems, with regard to the reduction of CO_2 emissions and the increase in the energy supply from RES, are particularly dependent on the spatial organisation of different activities. Up to now, the energy field has paid little attention to the spatial aspects of analysing possible future energy systems (Blaschke et al. 2013). Furthermore, cities and regions are often not aware of which spatial characteristics are suitable for accomplishing a low-carbon transition (Oudes and Stremke 2018). Linking the spatial dimension with the energy information can thus provide evidence for decision and policy-makers that want to foster a spatial sensitive approach to the energy transition, developing sustainable energy plans and strategies at different scales.

On the other hand, the increased complexity of spatial planning processes when the energy issue is involved has made clear the need for new "energy-aware" tools and methods in this field (Stoeglehner et al. 2016). Since one of the main tasks of urban and regional planning discipline consists in the organisation of different spatial settings, the creation of synergies between sustainable energy studies and spatial planning can help to analyse and manage the diversity and the peculiarities of diverse contexts and energy systems, delivering at the same time reliable insights for the energy transition (Balta-Ozkan, Watson, and Mocca 2015). I agree with (Stoeglehner et al. 2016) about that the integration of energy planning and spatial planning towards an interdisciplinary approach should represent a central part of the holistic strategy to reach the energy transition targets.

In the Ph.D. thesis, the effort to establish a connection between the energy planning field (i.e. the energy supply side) with the spatial planning one (i.e. the energy demand side) was made by constantly considering the spatial dimension inside the energy analysis. In addition, aiming at the desired integration of energy planning and spatial planning, it was decided to take advantage of the conceptual framework of Strategic Environmental Assessment (SEA). In particular, the SEA structure was used to frame the Spatial Decision Support System (SDSS) that has been developed thinking how to support local authorities, collecting and processing different input data to improve the analysis and the makeover of the thermal energy balance of a region. The proposed connection between energy planning and spatial planning and the relationship between the SDSS and SEA will be further explained in Sections 2.3 and 2.4.1, respectively.

- *Why fostering the shallow geothermal energy?*

As described in the previous Section 1.1.3, geothermal energy is regarded as an environmentally friendly, renewable and sustainable energy (Hähnlein et al. 2013). Low-enthalpy shallow geothermal energy is an attractive alternative to fossil fuels, especially for the heating and cooling of buildings. Global CO_2 emissions deriving from the exploitation of SGE are related to the electricity production mix. Instead at the local level, the SGE impact is very limited in terms of air pollution (NO_x, PM, etc.), depending upon the backup system (if present). This gives SGE a competitive advantage in relation not only to fossil fuels but also to the use of other renewable sources, such as biomass (Zambelli et al. 2018).

Geothermal HP has not a visual impact on the exterior of the building, making this technology attractive also for protected areas and historical buildings. In addition, this kind of heat pumps (and HP in general) have the advantage of shifting the heat demand from a thermal demand to an electrical one. Since the energy systems have several peaks in the electricity production from renewables (particularly due to photovoltaic and wind production), HP are even more interesting because they allow the exploitation of the surplus of energy production by accumulating the thermal energy in the buildings and calming the peaks, at the same time (Finck et al. 2017).

SGE can play a strategic role in increasing the efficiency of H&C systems, strengthening the flexibility of the whole energy system and reducing local CO_2 emissions. Nevertheless, this source has been little considered by European, regional and local energy policies. As we saw, its growth is limited mainly by factors such as the scarce knowledge of the technology, the complicated and fragmented regulation system, and high installation costs (Casasso, Piga, et al. 2017). Hence, it is necessary to increase and spread the awareness of its advantages among policy and decision-makers providing insight and information on how to include SGE source into energy strategies and plans.

1.3 Research Questions

Given the background on the sustainable energy challenge in European and national contexts and the significant role that shallow geothermal energy can have in dealing with these issues, the main research questions that shaped the Ph.D. activities during the research project were:

1) *How to estimate the space heating demand of the residential building stock at the regional scale?*

This should be the starting point for the development of sustainable strategies and/or plans aimed at the reduction of thermal energy consumption and the related CO_2 emissions in the existing building stock. This estimation should be spatially explicit since both the energy demand and the RES-based supply system are characterized by a discontinuity in space due to human activities and behaviour, on one side, and source availability, on the other side. Furthermore, in order to evaluate the use of shallow geothermal energy, it is necessary to start from the energy demand that must be satisfied with this technology. For this reason, the thermal energy demand needs to be well described and consequently, the residential building stock must be characterized from the energy viewpoint.

2) *How to integrate this estimation in the energy planning process of a region, fostering the use of shallow geothermal energy?*

The spatially explicit appraisal of the space heating demand of residential buildings should be integrated into the planning process in order to elaborate on different scenarios for a more sustainable energy balance between thermal demand and supply in the buildings. Scenario analysis is a particularly interesting tool for the energy planning field since it can be used to understand the possible futures of an energy system with and without the implementation of strategic actions and under different conditions. In this case, the actions should be targeted to foster the exploitation of SGE, a renewable source still not well-known and not exploited adequately in spite of its great potential to contribute at the increase of the energy efficiency in buildings.

3) *How to promote the connection between energy planning and spatial planning towards the common goal of the energy transition, thanks to the Strategic Environmental Assessment framework?*

The mutual integration between spatial and energy dimensions into the planning process should be aimed at helping to fill the gap between the development of plans and strategies and their implementation. This is found on the belief that this combination should represent a central part of the holistic strategy to reach the energy transition targets. SEA is recognised to be an effective tool for supporting decisions, it has a strategic nature and when used it adds value to the decision-making process. Therefore, it can support the decision-makers in pursuing energy transition targets by facilitating the integration of sustainability issues in the development of plans and policies.

1.4 Thesis Structure

The Ph.D. dissertation is split into five main chapters, sequenced to logically represent the main steps of the investigation. They can be read sequentially or separately.

Chapter 1 contextualises and introduces the research work: it provides an overview of the sustainable energy issue and the related energy targets at different levels, describes the role that shallow geothermal energy can have in reaching these targets, identifies the main problems related to the development of a Spatial Decision Support System for the thermal energy balance and lists the main research questions.

Chapter 2 illustrates all the main concepts required to handle the energy transition topic: the need of considering the spatial dimension in the analysis of sustainable energy transition, the Building Stock Analysis as a method for addressing the built environment as the main sector for reaching the energy saving targets, the need of integrate energy planning and spatial planning fields, the Strategic Environmental Assessment as an effective framework for this integration, the role of GIS tools for pushing a spatial-based approach in all the previous subjects.

Chapter 3 describes the relationship between the PhD thesis and the EU-funded GRETA project (inside which the thesis was partially developed), the case study area (Valle d'Aosta region, NW Italy), the two parts of the methodology for the development of the Spatial Decision Support System and all the steps followed for the collection, pre-processing and processing of data. In particular, the last Section 3.5 presents in detail the analysis performed to build the two methodological parts of the thesis and to implement them in the case study.

Chapter 4 presents and discusses the results obtained for the case study region, the main strengths, weaknesses and further developments of the main steps of the proposed methodology and the expected impacts of the Ph.D. dissertation. Furthermore, it shows how the outputs of the thesis can be included into the SEA process of a future energy regional plan that wants to integrate the energy planning and spatial planning objectives.

Chapter 5 draws the main conclusions getting back to the research questions and answering them according to the main findings of the Ph.D. research activity.

CHAPTER 2

2 Theoretical and conceptual framework

This Ph.D. dissertation is based on the concept of *Sustainable Energy*. According to (United Nations Development Programme 2000), the term "sustainable energy" means that the energy is produced and used in ways that support the human development over the long period in all its social, economic and environmental dimensions. Another definition of "sustainable energy" that meets our understanding is the one of (Tester et al. 2012):

> <<Effectively, the provision of energy such that it meets the needs of the present without compromising the ability of future generations to meet their own needs. (…) Sustainable Energy has two key components: renewable energy and energy efficiency.>>

Furthermore, I would add a third component of sustainable energy that is the energy saving, i.e. to reduce the number of energy services used. Therefore, the overall concept is composed of three complementary sub-concepts (Vettorato 2011):

- Energy saving and conservation: use less energy reducing the needs;
- Energy efficiency: use less energy reducing the consumption (and providing the same level of energy services);
- Renewable Energy Sources (RES) exploitation: energy production from local and renewable sources to match the energy demand.

Since the relevance of the spatial distribution of energy demand and supply patterns, I agreed with (Bridge et al. 2013) that the transition of cities and regions towards a low-carbon future has to be considered also from the *geographical* point of view.

In the following sections, the literature review about the main topics of the PhD thesis is presented together with the principal points of discussion.

2.1 Spatial Dimension of Sustainable Energy Transition

One can identify three moments of huge transition in human history: agrarian revolution, industrial revolution, and sustainability revolution (Broto 2017) that seems to involve a great transformation and to be as significant as the previous ones. As pointed out by (Coenen, Benneworth, and Truffer 2012) and (Hansen and Coenen 2015) among others, in most studies regarding sustainability transition there is a lack of attention for the spatial dimension of this transition. Indeed, the spatial context is often considered as the passive background variable (Coenen, Benneworth, and Truffer 2012) rather than as an embedded dimension of the shift towards a more sustainable future. Most recently, interest in the geographical aspect of the transition is coming out. Whether sustainability transition is a geographical process, the role of urban and regional spatial-based policies and strategies in the transition path should gain further attention (Hansen and Coenen 2015).

In our perspective, the best example of a sustainability transition regards the decarbonisation of energy systems. The so-called energy transition entails a significant change in the role of different primary fuels and energy technologies. This challenge is moving cities and regions towards more sustainable energy systems characterised by better access to energy services, and security and reliability of energy supply from renewable sources (Bridge et al. 2013). The subject is truly topical and it has been addressing in the scientific literature since several years (see for example the two editions of "Urban Energy Transition" (Multiple Authors 2008) and (Multiple Authors 2018)). It is also widely recognised that ageing of existing energy systems, climate change, energy security, and depletion of conventional fossil fuels are already modifying traditional patterns and scales of energy supply, distribution, and consumption (Bridge et al. 2013). At the same time, the relationship between spatial organisations and energy systems is evolving due to this transition towards a low-carbon future (Balta-Ozkan, Watson, and Mocca 2015).

As well as for sustainability transition, the way in which energy systems are shaped by spatial processes and the spatial influences on their ability for renovation have not been the main points of interest in several analyses. Actually, the temporal dimension of transition – rather than the spatial one – is more often identified (Bridge et al. 2013) when thinking about the changes involved in the sustainable energy transition. Furthermore, cities and regions are often not aware of which spatial characteristics are suitable for accomplishing the energy transition and thus the related targets are frequently based on little evidence concerning technological feasibility (Oudes and Stremke 2018). Whereas, the need to define realistic long-term targets and to implement effective actions was underlined once more by the Paris Climate Agreement (see Section 1.1.1).

Improvements in current energy systems, with regard to CO_2 emissions and energy supply from RES, are particularly dependent on spatial issues. Up to now, the energy field has paid little attention to the spatial aspects in analysing possible future energy systems (Blaschke et al. 2013) and in developing strategies for the energy transition. But, as (Blaschke et al. 2013) pointed out, the importance of the spatial distribution of, i.e., RES for their potential utilization in the energy system is a clear example of the need of spatial sensitivity. The patterns of spatial organisation for different activities will influence the consequences that a sustainable energy transition will have on cities and regions and how it will progress in the different territorial settings. This is not just related to the potential to achieve CO_2 emission targets, but also to the need to influence patterns of clean energy access inside diverse areas (Broto 2017).

The need to consider the spatial issues when planning the transition to a low-carbon future is increasing thanks to studies that describe how regional and local conditions can generate important impacts on the transition pathway (Morton, Wilson, and Anable 2018)

(Nabielek, Dumke, and Weninger 2018). Moreover, geographical diversity is intrinsic inside the energy system, concerning the spatial differences in energy production, demand, and (as already mentioned) RES availability. The lack of spatial sensitivity may be found also in the development of policies that aim to the diffusion of “new” energy technologies, to implement financial incentives for promoting the adoption of these technologies, and in information campaigns to raise the awareness (Morton, Wilson, and Anable 2018). Thus, the evidence of energy-related spatial patterns can support the decision makers in defining plans and strategies for RES production and energy conservation. Effective energy strategies call for a comprehensive knowledge of the territorial context where they will be carried out (Scaramuzzino, Garegnani, and Zambelli 2019).

2.1.1 Role of GIS tools and Housing Sector

Geographic Information Systems (GIS) are currently considered a mature technology and are also used for proactive planning and policy-making processes. The community, as well as decision and policy-makers, have understood the importance of making sound decisions based on spatial information derived from properly geographical databases (Blaschke et al. 2013). Analysis and data processing based on GIS are being often used to provide insights into the potential for energy saving and RES generation at different scales, to determine energy targets, and to support collaboration among different administrative entities (Oudes and Stremke 2018). With the maturation of GIS tools, the demand for spatially explicit information has also increased. GIS today may not distinguish between “good” and “bad” energy transition but they can allow us to figure out optimal solutions in decision-making and energy planning processes (Blaschke et al. 2013).

In relation to the energy planning field, taking into account the spatial dimension of the transition to sustainable energy systems makes arise relevant challenges, inter alia (Stoeglehner, Niemetz, and Kettl 2011): (i) decreasing the energy demand by re-thinking the (urban and not-urban) built environment in order to achieve multi-functional, dense and energy efficient housing units; (ii) guaranteeing for energy production within the capacity limits of the environmental context; (iii) coordinating energy planning and spatial planning to reach the better exploitation of the already generated energy.

Since it is impossible to imagine a sustainable energy transition without paying attention to the built environment, as introduced in Section 1.2, the building sector was chosen as target sector of this dissertation because it is responsible for a huge part of the global energy consumption, i.e. about 40% of the total final energy use in the European Union (European Parliament 2010). In particular, the space conditioning (heating and cooling – H&C) of buildings represented about 75% of the energy consumed by European residential buildings and only 16% of the heating and cooling (H&C) consumption is covered by renewable energy sources (RES) (European Commission, n.d.).

Due to the ageing of the building stock (at least in Italy), the building sector represents also a great opportunity for reaching the energy saving targets. In most European countries only 1% per year of the total building stock is represented by new constructions. Thus, the impact of the energy regulations is limited and often inadequate if not applied to the existing buildings (Albatici et al. 2016). Moreover, public administrations are called to have a leading role in planning the energy renovation interventions and to put forward energy efficient solutions with a broad impact on the territory (European Parliament 2010). For these reasons, a spatial approach at the energy transition can make the process more effective, reducing also the barriers for local authorities.

2.2 Building Stock Analysis

2.2.1 Summary of Literature Review

All along the PhD activities, a literature review was performed about the topic of Building Stock Analysis (BSA) for energy purposes, reviewing the recent literature in order to find the most common data, tools and scales of analysis used to estimate the energy demand of the residential building stock in Europe. In general, the results clearly showed the strong influence of data availability over the existing assessment tools, as we will experience later in the thesis section about data collection and processing (see Section 3.5).

Concerning data sources, the most used ones are: national or regional census, digital cartography, energy certificates and audits, national and European standards, law and regulation, environmental agencies, public databases and statistics. While, the most common tools can be summarised in (they are often used in combination of two or more):

- Geographical Information Systems (GIS): these tools are used to georeferenced and visualise a large variety of data on the maps, and usually to detect renovation priorities (or greatest benefit) zones;
- Statistics: regression models are often employed to fill the gaps in the existing datasets;
- "Archetypes" methods: they are applied to cluster the buildings (thus speeding up the analysis) according to some characteristics (usually period of construction, typology, function, etc.);
- Simulation models: these tools are used to simulate the building energy performances and compare them with measured data, if available (i.e. the validation procedure).

In the studied papers, the scale of analysis often worked like a constraint; however, the building stock analysis was usually set either at the urban/district scale or at the regional/national scale. As an example, in the following Table 2.1 some of the examined papers are reported, subdivided in terms of scale of analysis and tools employed in BSA. It is worth noting that GIS tools are commonly used when the analysis is performed at urban and suburban scale, while statistics methods are preferred when the case study is a region or an entire nation. In Figure 2.1, the main elements and the process of this kind of analysis are synthetized given the literature review performed about BSA different methods.

Table 2.1: Some examples of reviewed papers on BSA. Source: Thesis 2019.

Reference	***Scale of analysis***	***Tools and methods***
(Girardin et al. 2010)	urban	GIS, statistics, energy modelling
(Dall'O', Galante, and Torri 2012)	town	GIS, statistics
(Caputo, Costa, and Ferrari 2013)	urban and district	GIS, energy simulations
(Tian et al. 2015)	urban and district	GIS, statistics
(Calderón et al. 2015)	suburban	GIS, statistics
(Dascalaki et al. 2010)	national	statistics
(Kavgic et al. 2010)	national	building physics model
(Fracastoro and Serraino 2011)	regional	statistics
(Tuominen et al. 2014)	national	calculation tool

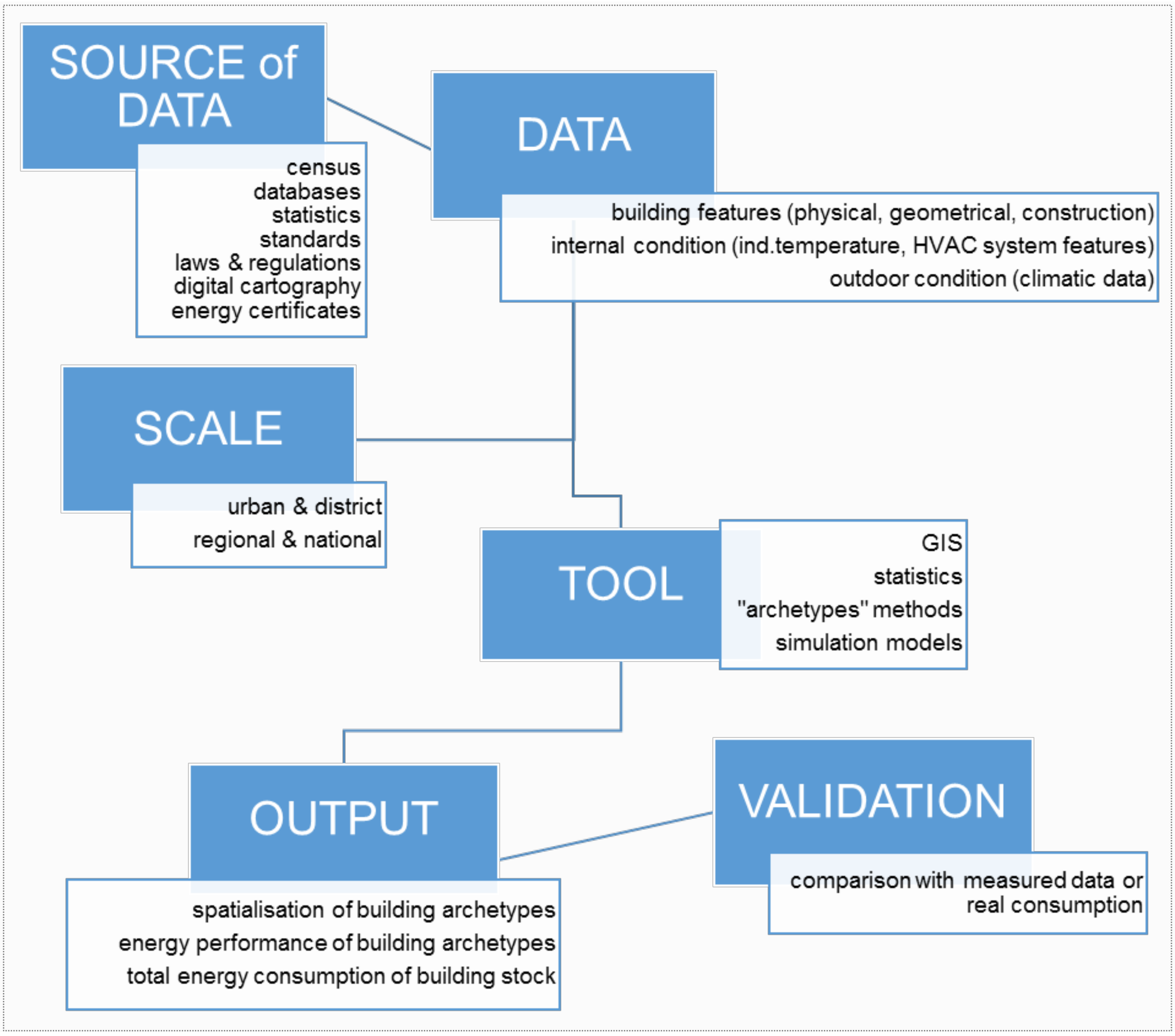

Figure 2.1: Prevalent BSA structure with data, sources of data, scales, tools, and outputs. Source: Thesis 2019.

2.2.2 Methods and Scales of Analysis

Focusing more on the methods, in the literature is recognized that there are two main BSA approaches: (1) "top-down" and (2) "bottom-up" (Yu 2018). The first one is based on the analysis of impacts of energy measures on economic indicators, looking for the relationship between statistical information (mainly economic variables) and energy consumption. Examples of these studies can be found in (Caldera, Corgnati, and Filippi 2008) and (Halicioglu 2009). The second ones, the "bottom-up" models, define the overall energy performance of the building stock starting from the assessment of some reference buildings, which are assumed to be representative of each category in terms of building features and thermal properties and are often called "archetypes" (Caputo, Costa, and Ferrari 2013). However, the question of what makes a building representative has been rarely addressed, as pointed out recently by (Brøgger and Wittchen 2018). Examples of "bottom-up" applications can be found in (Tuominen et al. 2014) and (Exner et al. 2017).

Top-down models rely on the availability of aggregated data and existing energy data for the residential sector. Their main drawbacks are the difficulty in handling technology discontinuities and the little accuracy in identifying key areas where improvements in energy consumption are needed, due mainly to the lack of details regarding the final energy consumption. The high level of details is instead a strength of the bottom-up approaches. Compared to top-down models, they are characterized by a higher level of details that allows them to: (i) consider technological changes; (ii) determine the energy consumption of each end-use and thus (iii) identify areas suited for improvements; (iv) identify the impact of different combinations of technologies on the supply of the energy demand. Their main drawbacks are the need for large amounts of input data, which are often difficult to gather at the needed level, and the more complex calculation and simulation techniques required. A more exhaustive description of these models can be found in (Swan and Ugursal 2009).

To analyse and plan the energy transition, the top-down approaches are inappropriate (Nouvel et al. 2015): as we just saw they consider long term forecast without any discontinuity, whereas the energy transition involves a severe change of habits, an increase of building retrofitting and RES exploitation, and the introduction of new technologies. Moreover, several studies proposed a building stock analysis based on spatially explicit bottom-up methods. For instance, (Nouvel et al. 2015) combined different bottom-up models for improving the estimation of heating demand and energy saving potential of a building stock at several scales. In particular, the two models that were integrated are: (1) a statistical model based on 2D-GIS and multiple linear regression; and (2) an engineering model using 3D city models and calculation of monthly energy balance. Instead, (Oregi et al. 2018) implemented a method to calculate and visualise in a GIS environment the thermal energy demand for each building of a district with hourly resolution. This method was based on cartography, cadastre and degree-day values.

Concerning the scale, the analysis focused on the energy retrofit of buildings is only possible at the building scale (Monteiro et al. 2018), highlighting even more the potential of the *full detailed* spatial-based bottom-up approaches. This kind of BSA models is expected to become a key planning tool for utilities, municipalities and planners (Reinhart and Cerezo Davila 2016). According to (Frayssinet et al. 2018), the models that perform the analysis at the building level are considered part of the micro-simulation tools. In contrast to top-down and large scale bottom-up models, they are able to take into account each building in order to evaluate the distribution of the energy demand at different scales. Following the already mentioned classification of (Swan and Ugursal 2009), this type of models belongs to “sample engineering bottom-up models” where the sample size is equal to the domain size of the case study. As the micro-simulation considers each building of the studied area, it represents the strictest bottom-up approach. Therefore, this kind of models seems to be particularly suitable for spatially-explicit “decision support systems” (Frayssinet et al. 2018), the so-called Spatial Decision Support Systems (SDSS).

2.3 Integration of Energy Planning and Spatial Planning

Several current global issues (e.g. energy poverty, access to energy, resource scarcity, peak oil, climate change, increase of fuel prices, etc.) are closely linked to energy use in human settlements. As a consequence, the relationship between urban and regional planning on one hand, and energy consumption in different sectors on the other, has been deeply investigated in the last decades. As mentioned, the transition of territories toward a more sustainable and low-carbon future relies on the use of RES. The use of such intermittent and low-density resources requires development strategies based on the principles of “capture/harvest when available” and “store until required” (O’Brien and Hope 2010). Fundamental to this approach are: high end-use energy efficiency, energy conservation, and promotion of energy self-sufficiency together with the mitigation of local vulnerabilities.

In addition, in the last decades the energy systems have been undergoing important trends (Cormio et al. 2003):

- ✓ Shift from centralized and fossil fuel-based energy supply systems to de-centralized and/or RES-based ones;
- ✓ Fragmentation of the energy issue in different fields (e.g. urban planning, energy engineering, environmental assessment), each acting with different tools, approaches and languages, and thus hindering interaction and coordination;
- ✓ Growing community awareness about environmental impacts of energy production, joined with a greater interest towards distributed generation technologies based on RES and cogeneration;
- ✓ Regarding small communities (in rural and alpine context): the creation of short-chains from renewable sources for the energy supply;
- ✓ Moving of the energy planning activities from the national scale to the regional and local scale.

Concerning the last point, as stated by (Droege 2014), the scale of the energy analysis and planning process should be shifted from the national to the regional and local scale for effectively integrating RES into the energy system. At this scale, a much more detailed approach to thermal energy demand and supply (D&S) can be performed, thus reaching a more effective balance between the two sides thanks to the consideration of both spatial and time distribution. Indeed, both the energy demand and the RES-based supply system are characterized by a discontinuity in space and/or intermittence in time: the former is driven by human activities and behaviour; the latter by source availability. Therefore, it is necessary to introduce a different planning perspective to match these different spatial-temporal distributions and increase the reliability of the whole energy system. The increased complexity of the spatial planning process, when energy issues become involved, also requires a new quality for tools and methods used in this field (Stoeglehner et al. 2016).

Multiple issues raise questions about the sustainability of the centralised energy paradigm: the ageing of infrastructures, the impacts of climate change, the uncertainty about energy price and the security of energy supply (Balta-Ozkan, Watson, and Mocca 2015). An alternative and decentralised paradigm in which energy is produced at different levels, from households up to the community, is gaining attention in many European countries. Furthermore, different spatial features require different energy strategies, which may result in solutions that also differ within the context and imply cooperation among entities. In order to support decision-makers upon the energy transition, several tools have been developed. These methods range from the analysis of the current situation of the energy system and the estimation of the present energy demand to the generation of different scenarios at various spatial scales (Nabielek, Dumke, and Weninger 2018).

One of the main tasks of urban and regional planning discipline stands in the spatial organisation of different activities and this can represent a valuable contribution to analyse the abovementioned issues. Thus, synergies between sustainable energy studies and spatial planning can help to manage the diversity and the peculiarities of the energy systems to deliver reliable outcomes for the energy transition (Balta-Ozkan, Watson, and Mocca 2015). Stöglehner was one of the first researchers who described and wrote about the so-called *Integrated Spatial and Energy Planning*, a topic that inspired also this PhD thesis.

In the last decades, energy issues and spatial planning have become increasingly connected. Even more when we deal with topics like sustainable energy systems, energy transition, renewable energy sources, greenhouse gas reduction, and climate change mitigation, we are weaving strong relations between energy and space. I agree with (Stoeglehner et al. 2016) that the integration of energy planning and spatial planning should represent a central part of the holistic strategy to reach the energy transition targets. These two fields are tightly linked because the spatial features have considerable influence on the energy demand and, conversely, the spatial plans are able to modify the availability of energy resources and their use (Stoeglehner et al. 2016). In this dissertation, the integration of energy planning and spatial planning refers to the development of energy plans and strategies that take into consideration the spatial dimension of energy D&S in a certain territory.

2.3.1 Drivers and Barriers of GIS Contribution

As we saw in Section 2.1.1, a way to foster the consideration of spatial dimensions in the energy planning is to improve the penetration of GIS in research activities on renewable energy and sustainable energy modelling. This would increase the use of geospatial analysis and visualization methods for the support of decision-making processes in the energy planning field. Indeed, one of the main shortcoming in the current energy systems research seems to be the lack of connection to spatial planning activities (Resch et al. 2014). This claims again for the adoption of spatially-explicit approaches within the energy system models. In the last decades, GIS software has assumed growing importance as decision support tools for data analysing and defining energy strategies for territorial issues. Particularly, they have been used to evaluate the potential of energy production form RES, as highlighted by (Gemelli, Mancini, and Longhi 2011), (Zambelli et al. 2012) and (Garegnani et al. 2018), and to improve BSA, as we saw in Table 2.1.

Nevertheless, this integration is not trivial for several reasons (Resch et al. 2014). They are summarised in the following list:

1) Both energy system models and geospatial analysis are complex processes in terms of the combination of several parameters.
2) For integrating the spatial dimension into energy system models, huge computational requirements are needed, due to the high amount of datasets necessary for obtaining reliable and detailed results.
3) Another big challenge arises from the heterogeneity of data and formats used; this problem can be split in diverse issues, e.g. data availability, proprietary data formats, data integration methods, lack of standardization in data exchange.
4) Limited data availability: spatially-explicit energy analyses require several data sources that are often not available or their accessibility may be limited by the data providers. This represents a relevant constraint for the analysis methods and the accuracy of the results.
5) Related to the limited data availability is the inhomogeneity in the granularity of data. Often, for the same administrative area (region, province or municipality) some data may be accessible at the building level, while others may be accessible at the district or city level. Usually, the combination of different scales of analysis is a complex issue that requires some approximations and assumptions in the evaluation of the considered variables.

All the above-mentioned concerns are focused on technical issues, but it seems fundamental to include also other issues, and primarily some reflections on the environmental, institutional and governance assets involved (Moroni, Antoniucci, and Bisello 2016). In this Ph.D. thesis the effort was made to go towards the connection between the energy planning field (i.e. the energy supply side) and the spatial planning one (i.e. the energy demand side) by seeking synergies between the two disciplines. Given the aforementioned considerations and limitations listed, for this integration it was decided to take advantage of the structured framework of Strategic Environmental Assessment (SEA). In particular, for the case study area, this was done focusing on the coordination of energy planning and spatial planning goals, so that they will be consistent and working towards the common vision of sustainable energy transition.

2.4 Strategic Environmental Assessment

Strategic Environmental Assessment is a procedural tool useful to integrate environmental and sustainability issues in the decision-making processes (Thérivel 2004). Indeed, SEA can help the decision-makers in pursuing sustainability targets by facilitating the integration of broad environmental issues in the development of plans, policies and programmes (PPP) (Partidario 2012), which have medium or long-term vision and objectives. The focus of SEA on sustainability gives it a completely different mission in comparison to the Environmental Impact Assessment (EIA). Indeed, in EIA the evaluation procedure used to be a corrective practice to modify or mitigate the project impacts on the environmental components; in SEA it becomes a proactive and strategic process to promote the integration of the sustainable development in plans and policies (Diamantini and Geneletti 2004).

To be effective, SEA should act directly on the process of formulation and all along the development of PPP, in order to be able to release its capacity of influencing priorities and facilitating the integration of sustainability issues in the decision-making process. SEA inherited EIA assumptions, as well as tools and concepts. This is one of the main reason why many SEA procedures are still focused only on assessing environmental impacts following an EIA-based approach (Lobos and Partidario 2014). As pointed out by the two authors, there is a gap between the theory and the practice of SEA and an evident tendency among many practitioners to confuse “strategic” with “other-non-project” levels of decision-making.

However, the definition of SEA effectiveness may vary in different planning systems together with the elements and benefits that seem to make SEA an effective process. How presented and discussed in (Gazzola 2008), most of the context and methodological elements found in SEA literature are based on practices and experiences of a selected number of countries, i.e. Northern-European countries (since we are looking at the European context). Therefore, SEA processes should be tailored to the specific conditions under assessment and the knowledge about the particular policy-making context can improve its effectiveness in order to adapt the process for its integration in different planning and policy systems.

The use of SEA can add value to the decision-making process by preventing conflicts and enabling PPP to integrate environmental, social and economic considerations. According to the SEA practice guide of (Partidario 2012), its main purposes are to: (i) aid in understanding the context of the strategy under assessment, (ii) identify problems and alternatives, (iii) address the key trends, and (iv) evaluate different sustainable options that will achieve strategic objectives. The relevance of SEA as a way to support the decision-making process is demonstrated also by the European Directive 2001/42/EC on the assessment of environmental effects from plans and programmes in different sectors, among them both energy and spatial planning. Thus, SEA is a tool for supporting decisions, it has a strategic nature and when used it adds value to the decision-making process (Finnveden et al. 2003).

At the same time, SEA should not overlook the challenges associated to the complexity of the context within which strategic decisions take place. Indeed, the planning/decision-making process is no more a logical activity, linearly structured and carried out by a central authority but rather an interactive, dynamic, and complex process (Lobos and Partidario 2014). Above all, decisions that can have relevant consequences related to key topics of sustainability, such as those concerning the management of natural resources, spatial planning and energy planning (among many others), may have a complex nature. Thus, SEA needs to integrate this complexity aspect in its practice. Its final aim should not be merely to predict and weight possible effects on the environment in order to enable the decision-makers to choose among different alternatives, but also to facilitate a dialogue between decision-makers, implementers and affected groups about the opportunities and the results related to these development options (Lobos and Partidario 2014).

2.4.1 Scale, Content and Methods

As mentioned, according to the European Directive 2001/42/EC (European Parliament 2001) this kind of assessment is mandatory for PPP both in the energy planning and spatial planning sector and is handled in European and national regulation. SEA is now well established in the spatial planning field and in many countries' regulation. This discipline would also benefit from a spatially-explicit approach of SEA, shifting the evaluation from the level of general objectives and principles to the level of real implementation of actions (Geneletti 2012). The consideration of environmental and sustainability issues is currently central also in the development of energy policies and in the search for more sustainable sources of energy production. Therefore, the use of SEA should be significant within this sector, given its role in the carbon reduction process, and for other significant concerns, such as air quality and landscape issues (Jay 2010).

For these reasons, in the last years SEA has become increasingly considered as a decision support process that should be developed together (in terms of timing) with the related decision or plan-making process. It should add strategic value to the decision-making becoming part of it rather than a tool to assess the impacts of decisions (Höjer et al. 2008). Furthermore, the scale of analysis should be the regional or local context, more than the national one, since in Italy (as in many other countries) the regional/local administrations are in charge to set their targets and the connected paths for sustainable development (Diamantini and Geneletti 2004). In this dissertation, SEA is intended as a conceptual framework aimed at integrating energy planning and spatial planning, rather than as an evaluation tool, and it is applied at the regional scale.

Being a procedural instrument, SEA can be filled with different analytical content and can employ diverse tools and techniques (e.g. expert judgements, matrices, mapping, modelling). Matrix-based assessment has probably been the most used method in SEA practice because it allows easy identification of conflicts and trade-offs between plans and policies, on one side, and environmental components, on the other. At the same time, it often fails to address the spatial-temporal dimension of planning issues (González et al. 2011). GIS tools can help to overcome this gap since they have the potential to improve the conventional techniques by providing spatial evidence to the decision or plan-making process. Furthermore, SEA practice needs both visualisation tools and also robust spatial data analysis; thus the use of GIS can increase the understanding of environmental and planning considerations for these aims (Multiple Authors 2015).

Scenario analysis is another method often used in SEA processes and it is usually listed in SEA tool-box (Thérivel 2004). Scenarios may be particularly interesting tools for SEA in the energy field since they can be used to understand the possible futures of an energy system with and without the implementation of strategic actions and under different conditions (Geneletti 2012). There are several different approaches at the scenario analysis; according to the schematisation proposed by (Höjer et al. 2008), the "explorative strategic" type of scenarios can be recommended for SEA procedures in the energy field. For our case, the strategic decision may concern the expansion of specific energy technologies or infrastructures and the combination between various efficiency measures. In the end, one should bear in mind that the implications for the sustainability context of the decisions depend not only on the plan/strategy itself but also on other factors, such as external driving forces and exogenous variables.

Following the rethinking of SEA practice in line with the more strategic theoretical model, the structure of the SEA process that considers as steps screening, scoping, reporting, review, decision, and follow-up (with some variations), is being replaced by different models. In this context, the main phases of SEA process can be summarised as follows, inspired by (Partidario 2012) and trying to define SEA in a more specific way in comparison to EIA procedure:

1. Definition of sustainable objectives;
2. Formulation of alternatives (or strategic options) with targets and indicators;
3. Scenario analysis (with opportunities and risks);
4. Environmental analysis: description of environmental baseline, prediction and evaluation of impacts;
5. Evaluation of scenarios;
6. Conclusions, follow-up measures: actions to mitigate the impacts, establishment of environmental guidelines, monitoring programme.

CHAPTER 3

3 Materials and Methods

3.1 Introduction

In this chapter, the methodology developed within the Ph.D. thesis is presented and the different phases of the data processing are described. As explained in Chapter 2, to analyse and plan a sustainable energy transition, BSA bottom-up approaches are considered more appropriate. Moreover, the development of scenarios for the energy renovation of buildings is better performed at the building level. Since this kind of analysis is expected to become a key planning tool for utilities, municipalities, and planners, a detailed analysis at the *building level* would be particularly suitable for the development of a Spatial Decision Support System even at *regional scale*. Following (Coenen, Benneworth, and Truffer 2012), in the dissertation "level" and "scale" were considered as two dimensions along which energy transition can be described.

The developed methodology aims also to represent an effort to connect the energy planning field (supply side of energy transition issue) with the spatial planning one (demand side) by seeking synergies between the two disciplines. For the integration of energy planning and spatial planning, it was decided to take advantage of the framework of Strategic Environmental Assessment (SEA). This choice was done because SEA is considered a support instrument that is able to facilitate the integration of sustainability issues in the development of plans and programmes. As already mentioned, in the Ph.D. thesis SEA is intended as a conceptual structure for connecting energy planning and spatial planning, rather than as an evaluation tool.

3.1.1 Relationship between Ph.D. thesis and GRETA project

The Ph.D. thesis was partially developed in the framework of a project co-financed by the European Regional Development Fund through the Interreg Alpine Space programme. The project was called GRETA (*near-surface Geothermal REsources in the Territory of the Alpine space*) and was designed to foster the use of shallow geothermal energy (SGE) in energy plans and strategies along the Alps. The project started in December 2015 and ended in December 2018; the consortium was composed of 12 partners from 6 countries and was led by the Technische Universität of Munich (TUM). Within the project, Eurac Research oversaw the activities of the work package aimed at supporting the process of integrating SGE into energy plans and strategies (WP5).

As introduced in Section 1.1.3, SGE concerns the exploitation of the heat stored within the ground (between the surface and 200 m depth), a local and low-carbon source widely available across territories and less dependent from changes in time compared to other RES. Indeed, the use of SGE is based on the property of the soil (and of the groundwater) to have an almost constant temperature along the whole year (see Figure 3.1). This property can be exploited for both heating and cooling purpose by employing electrical heat pumps. Currently, the exploitation of SGE is not particularly diffused. Its growth is limited mainly by factors such as the scarce knowledge, the complicated and fragmented legislation, and high installation costs (Casasso, Piga, et al. 2017).

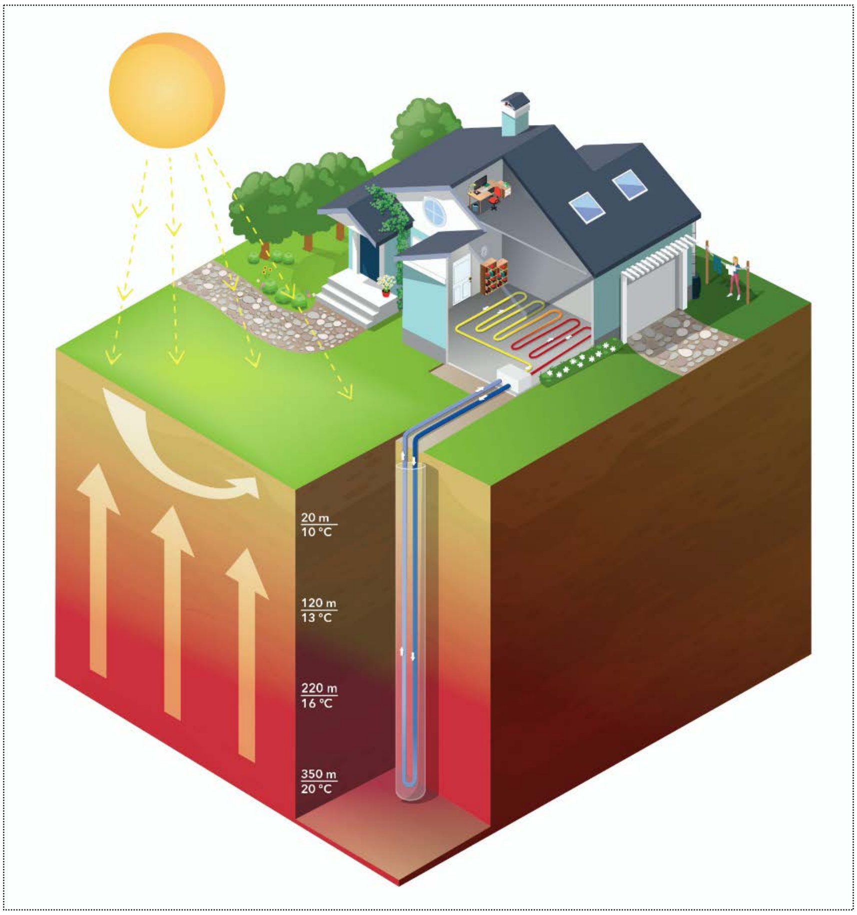

Figure 3.1: A closed-loop geothermal system used for heating a house. Below a first superficial ground level (about 20m) where seasonal temperatures are affected by solar radiation, the temperature remains generally stable all the year, with a trend that slowly but regularly increases with depth. Source: © GRETA - Interreg Alpine Space ERDF.

SGE has been scarcely considered in European and regional energy policies, as well. In this case, the main reasons are related to the difficulty of gathering information regarding the potential of this energy source to cover the heating and cooling demand of the building stock, and to the lack of awareness of its advantages among policy and decision-makers (GRETA project 2018b). In particular, the knowledge of the potential of an energy resource is the essential information for integrating it in sound energy planning processes. Some analyses performed within the GRETA project were employed in the Ph.D. thesis to develop part of the methodology. Likewise, some outputs of the Ph.D. thesis were used inside the activities of GRETA project, as described in the following table (Table 3.1).

Table 3.1: Relationship between the analyses performed within the Ph.D. project and the EU-funded GRETA project. Source: Thesis 2019.

	Ph.D.	**GRETA**
Spatial evaluation of space heating demand of buildings	OUTPUT →	INPUT
Spatial financial analysis of SGE	INPUT ←	OUTPUT
Spatial suitability for SGE plants	INPUT ←	OUTPUT
Comparing VdA energy planning and spatial planning objectives	OUTPUT →	INPUT
Developing scenarios for the VdA energy system	OUTPUT →	INPUT

3.1.2 The Case Study

In the following subsection, the case study where the Ph.D. methodology was applied is described and the background for the subsequent data processing phase is presented. In particular, the energy-related issues and the geographical and temporal boundaries inside which our analysis was performed are presented. Even though the Ph.D. case study is a typical alpine region, the developed methodology can be applied at different scales and not only on alpine cities and regions but potentially in every kind of context. Since it strongly depends on the availability of data (as will be deepened later), the replicability of the methodology is quite high.

The case study is the Valle d'Aosta Region (NW of Italy, see Figure 3.2). Valle d'Aosta is an alpine Italian region and it was one of the pilot areas of the GRETA project. It was considered as the case study of the Ph.D. thesis because it can be representative of other territories in Italy and Europe, besides the availability of data due to the EU-funded project. In addition, being an Italian Region made easier the analysis of official documents on energy and spatial planning and policy procedures, and the dialogue with local stakeholders and decision-makers. Since the whole Region was considered in the analysis, Valle d'Aosta is a large case study area of about 3,000 km^2. At the same time, it is the smallest Italian region featuring on its borders the highest European summits. The main valley hosts about 120,000 people and some industrial plants, while lateral valleys are well known touristic and ski centres (GRETA project 2018c).

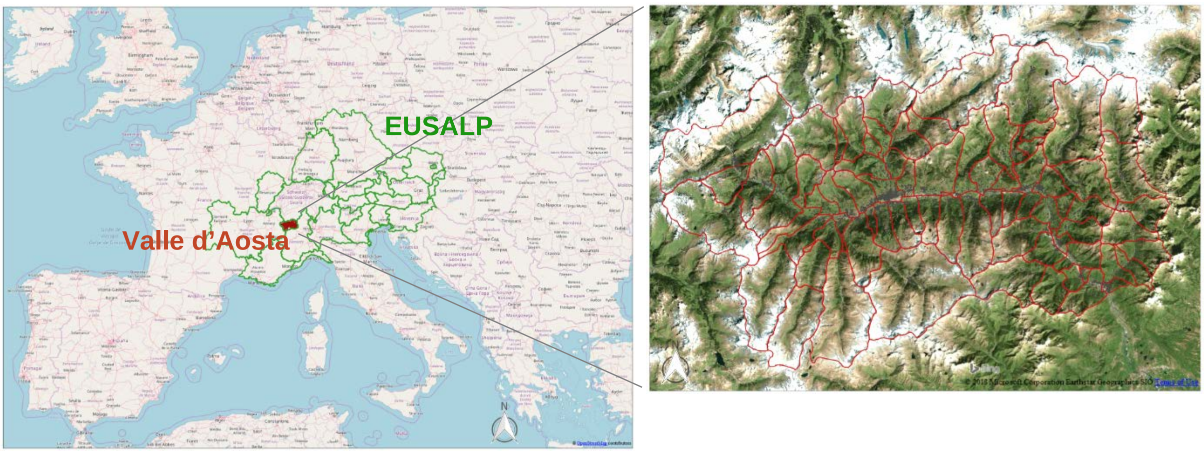

Figure 3.2: Framework of the case study area inside the EUSALP macro-region and satellite image with municipal borders. Source: Thesis 2019, OpenStreetMap and Google Satellite.

The current energy objectives of the Valle d'Aosta region are described in the Regional Energy and Environmental Plan (REEP) (Regione Autonoma Valle d'Aosta 2012). Recently, a Monitoring Report of this plan (Regione Autonoma Valle d'Aosta 2018) was elaborated and published by COA Energia, which represents the Regional Energy Agency. In this report, the regional energy targets are reviewed and new objectives are set when the previous ones are considered reached or not in line with the current situation. REEP has the year 2020 as target year and the main objectives are based on 20-20-20 European targets; they will be described in detail in Section 3.5.5.

During the phase of data collection, several information on the Valle d'Aosta residential building stock (see also Table 3.5) was gathered, e.g. the total energy consumption of the residential sector per fuel, the period of construction of the buildings, the number of residential buildings per period of construction, the surface heated with different kinds of heating system. The first data was gathered for the whole Region from the COA Energia, and then estimated by us at the building level. The other data was acquired from the Italian National Statistics Institute (ISTAT) and then the information was processed in order to calculate a value for each building starting from the information at the census tract level.

In the following tables, data on the building stock from REEP and other documents is presented and later it will be compared with our estimation in Section 4.1.1 about the results. Specifically, Table 3.2 contains the percentages of residential buildings built in different periods of construction. Table 3.3 summarised the energy performance of the buildings' envelope, according to 22,000 Energy Performance Certificates (EPC) of Valle d'Aosta recorded until June 2016. Table 3.4 describes the distribution of heating plants divided among the different fuels used for the heating supply of residential buildings. This information is reported in the Monitoring Report of REEP (Regione Autonoma Valle d'Aosta 2018).

Table 3.2: Residential buildings of Valle d'Aosta (%) per period of construction. Source: Monitoring Report of REEP (data processing from national Census 2011).

Period of construction	***% of tot buildings***
before 1918	19%
1919-1945	9%
1946-1960	12%
1961-1970	14%
1971-1980	16%
1981-1990	12%
1991-2000	9%
2001-2005	5%
after 2006	4%

Table 3.3: Energy performance of building envelope (%) from the EPC register of Valle d'Aosta until June 2016. Source: Monitoring Report of REEP.

kWh/m^2 year	***% of EPC***
0 – 25	1.5%
25 – 50	6%
50 – 100	21.3%
100 – 250	51.5%
250 – 500	18%
> 500	1.7%

Table 3.4: Fuels used for the heating system of the residential building stock in Valle d'Aosta. Source: Region Valle d'Aosta (Renerfor project, survey on a sample of 3,168 families).

Fuel for heating	***% of tot heating systems***
Heating oil	22%
Heating oil + biomass	18%
Natural gas	22%
Natural gas + biomass	10%
LPG	6%
LPG + biomass	10%
Biomass	9%

District heating	1%
Electricity and other	2%

From the previous tables, one can see as the majority of the residential building stock was built during the two decades after the Second World War (between 1946 and 1970). This represents the so-called Italian "building-industry boom" period, when many buildings were built in few years and with very low attention at their energy performance, in Valle d'Aosta as in the other Italian regions. Indeed, more than half of the buildings are now included in the range between 100 and 250 kWh/m^2 per year, while buildings with lower space heating demand (less than 50 kWh/m^2 year) are residual.

Concerning the heating fuels, the majority of the residential buildings are still using fossil fuels (especially heating oil and natural gas). Overall, the use of biomass in the residential sector is also relevant, representing about 48% of the total households in Valle d'Aosta, mainly as an integration system to the primary heating plant. This is a common figure in the alpine regions but the use of biomass should be oriented by the principle of local harvesting and widespread generation, with a clear aim to minimise its transport on the road and to exploit its potential as far as possible inside the territory (Regione Autonoma Valle d'Aosta 2013). The use of biomass heating systems should also be assessed based on the requirements for the air quality protection and considering that many biomass plants are old and they need to be gradually replaced by others technologically more advanced.

3.2 Spatial Decision Support System

Within the Ph.D. research activities, a methodology was established and applied for the development of a Spatial Decision Support System (SDSS). As introduced in Section 1, a decision support system is a computerized tool that helps the user to identify a simple solution to a complex system enforcing the decision-making process (Multiple Authors 2015). When it considers the spatial dimension of the analysed issues it is defined as spatially explicit. The proposed SDSS aims to support local decision-makers in fostering sustainable energy plans capable of taking into account both the improvement of the energy production from renewable energy sources and the energy renovation of the existing building stock. Moreover, SDSS intends to foster the connection between the energy planning field and the urban planning one by creating synergies between the two disciplines inside a structured framework.

SDSS is divided into two methodological sections (Figure 3.3). The first part concerns the preliminary analysis useful to describe the studied context and to structure the collection of information and data required for the spatial evaluation of the thermal energy demand of the analysed building stock. The second part concerns an objective-specific approach to develop alternative and strategic scenarios for the integration of SGE in the energy planning process as short-term objective and the integration of spatial issues in the energy planning process, taking advantage of the Strategic Environmental Assessment (SEA) structure, as long-term aim. The methodology is applied in the case study of Valle d'Aosta region; almost all the data processing was done using open-source software (i.e. GRASS GIS, QGIS, R and Python) and following a spatially-explicit approach, for pushing the inclusion of the spatial dimension in the energy analysis.

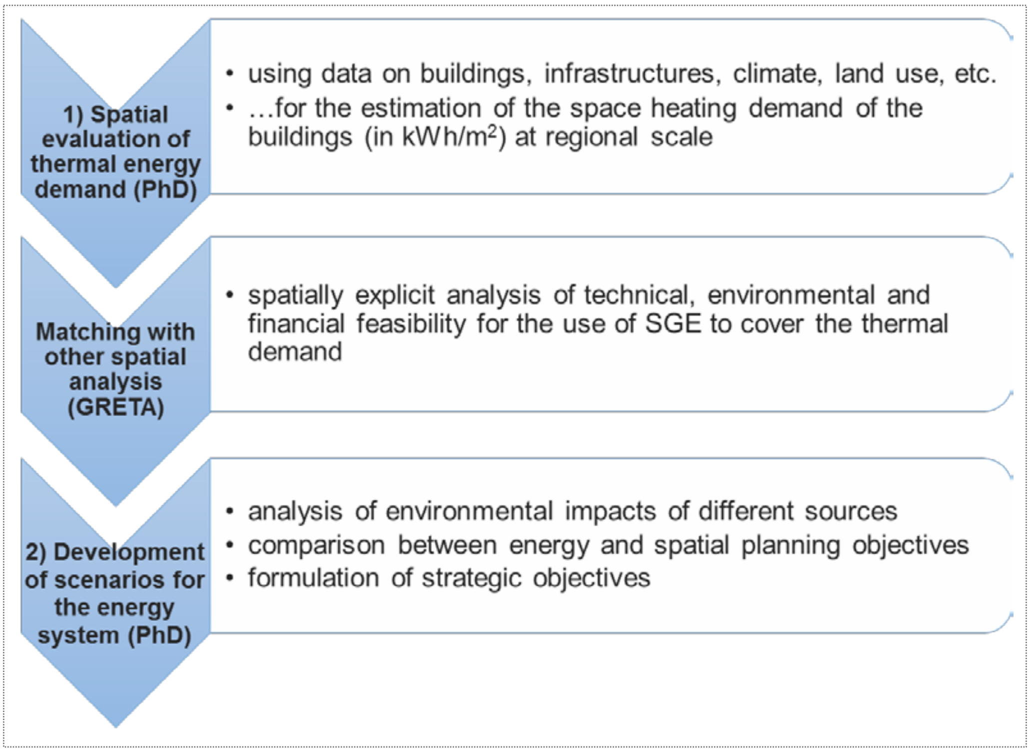

Figure 3.3: Schema of the SDSS divided into the different methodological sections. Source: Thesis 2019.

The spatial scales of analysis are the single building and the census tract. The level of single building has been chosen as the smallest unit of analysis to characterise, better and at the same time, the thermal energy demand (that depends on the age and the geometrical features of the buildings) and the potential energy production from the geothermal source (that is spatial dependant and tightly linked to the energy demand, see Section 3.5). Nevertheless, some data processing is performed at the census tract level. In this case, the methodology starts with aggregated and statistical information to estimate the required values at the building level. The reason is that the availability of data changes depending on the source of them (as described in the next Section 3.2.1). For the case study, little information was available at the building level, covering the whole region. Therefore, the described SDSS processes data from different sources to fill this knowledge gap.

3.2.1 The Methodology

The first methodological part of SDSS regards the collection and integration of different kind of data for the spatial evaluation of space heating demand of the existing residential building stock in the case study area. With "space heating demand" is intended the amount of active heating input required to heat a building, and it is usually expressed in kWh/m^2 per year ('Space Heating Demand - Glossary' n.d.). Since Valle d'Aosta is one of the three pilot areas of the GRETA project, part of the data collection was performed within this project. However, the Region was chosen as Ph.D. case study for several reasons: (i) the synergy with the EU-funded project in data collection and processing; (ii) the availability of documents in Italian and therefore the clearer understanding of the local policy and planning context; (iii) its representativeness of other alpine territories in Italy and Europe for the replicability of the research outputs.

For the development of the first part of the methodology, the required data was mainly related to the characterisation of the residential building stock from the geometrical and energy viewpoint. In the following table (Table 3.5), this data is listed with the related source and scale. One relevant issue faced in implementing this activity was the lack of homogeneity and sometimes the limited availability of data. As shown in Table 3.5, the scale of the gathered information changes a lot. For instance, for the same administrative area (i.e. the Valle d'Aosta region) some data was accessible at the building level, while other was available at the census tract or municipal level.

This heterogeneity in the detail level of input data and in formats represents a relevant constraint for the analysis methods and the accuracy of the results (Resch et al. 2014). Indeed, the combination of different scales of analysis is a complex issue that requires some approximations and assumptions in the evaluation and processing of the considered variables. The root of the issue can be identified in the fact that public administrations do not collect this kind of data at the same detail level (i.e. single building) and, above all, in a systematic way. Here rises the need for fostering the use of geospatial analysis (Resch et al. 2014) and a spatially-explicit approach in the energy analyses aimed at supporting the decision-making process.

Table 3.5: List of data collected to perform the analyses for the Valle d'Aosta region, with the related data source and scale. Source: EURAC for GRETA project.

Source	**Data**	**Scale**
Region VdA - GeoBrowser	DSM and DTM with spatial resolution of 2x2m and 0.5x0.5m, vector file of buildings (polygon), vector file of historic centres (point)	building
Region VdA - Tourism website, GeoBrowser OpenStreetMap	tourist (hotels, B&B, camping, residence, etc.) and service (hospitals, schools, swimming pools, ice rinks, etc.) buildings	building

Region Lombardia – CENED+2.0 dataset	age, energy performance parameters, geometrical features of certified buildings	building
ISTAT - National Census 2011	number of residential buildings per age, total heated surface per age, number of permanent occupied flats and total flats	census tract
Region VdA - Energy Agency (COA)	mean energy demand (kWh/m² year) per age of the buildings, total energy consumption of residential sector per fuel	municipality, union of municipalities
Region VdA - Environmental Agency (ARPA)	temporal dataset of temperatures from 75 official weather stations	region

As already mentioned, the second methodological part of Ph.D. thesis was carried out in the framework of Strategic Environmental Assessment by following some analytic steps: (i) analysis of the possible environmental impacts of different thermal sources for the energy supply of the building stock; (ii) comparison among the current energy planning and spatial planning objectives; (iii) formulation of strategic energy-driven objectives; (iv) development of alternative scenarios for the energy system of the case study (Figure 3.4). One objective of this second part of the methodology is to try to coordinate the energy planning and spatial planning goals into some shared scenarios so that they will be consistent and working towards the common vision of the sustainable energy transition. As already mentioned, in the Ph.D. thesis SEA was intended as a framework for integrating energy planning and spatial planning, rather than as an evaluation tool.

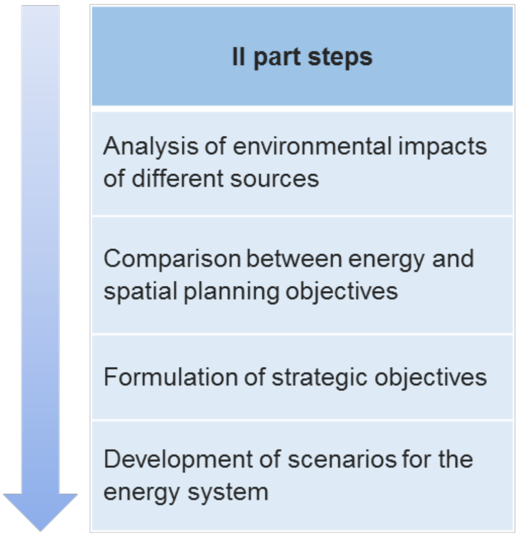

Figure 3.4: Schema of the second part of the Ph.D. methodology, based on the SEA structure. Source: Thesis 2019.

3.3 First Part of Methodology

The first part of the Ph.D. methodology represented also the first stage of the analysis performed within WP5 of the GRETA project, as summarised in Table 3.6 and explained in Section 3.1.1. Its principal aim is the spatial estimation of the space heating demand of each residential building of the case study region. After that, the financial feasibility and the spatial suitability of SGE for covering this space heating demand and replacing some fossil fuels were evaluated. Both the financial feasibility and the spatial suitability were performed within the GRETA project by the Urban and Regional Energy Systems group of Eurac Research. The space heating demand was also matched with the spatial evaluation of the shallow geothermal potential in the project's pilot areas. This analysis was carried out by another partner of GRETA project, the Groundwater Engineering research group of the Politecnico of Torino (PoliTO). To support the decision-makers in the assessment of SGE potential, a GRASS GIS *add-on* has been developed. This tool allows the user to calculate the amount of power and/or energy that can be extracted from the ground in a certain location[3].

All together the four spatial assessments allowed us to individuate and calculate the percentage of buildings that can be potentially covered with SGE in Valle d'Aosta, taking into account different kind of constraints (technical, environmental, financial, etc.) (see also Sections 3.5.2 and 3.5.3). Further details about methods, procedures and analysis performed can be found in several project's deliverables ('Deliverables – Alpine Space GRETA Project', n.d.). The following table summarises these steps, highlighting the role of the Ph.D. activities inside the tasks of the GRETA project.

Table 3.6: Schema of the first part of the Ph.D. methodology together with the analyses performed within the GRETA project. Source: EURAC for GRETA project.

Spatial evaluation of	Type of data	Step 1	Step 2
Thermal energy DEMAND **(Ph.D.)**	Estimated/official data on buildings, climate, infrastructures, land use, etc.	Estimation of **space heating demand** of resid. buildings at the regional scale	*Spatially explicit* analysis of **technical, environmental and financial feasibility** for the use of SGE to cover the thermal demand of buildings
Geothermal energy POTENTIAL **(GRETA by PoliTO)**	Hydrogeological characteristics; environmental, legal and technical constraints	Mapping **geothermal potential** by combining hydrogeological characteristics and different constraints	
FINANCIAL feasibility **(GRETA by Eurac)**	Capital and operative costs, national subsidies	**Financial analysis** of the use of SGE compared to other technologies	

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[3] The tool is freely available via a dedicated web-service at the following address: https://tools.greta.eurac.edu.

SPATIAL suitability **(GRETA by Eurac)**	Area of pertinence of buildings, water protection areas, buffer areas around roads and buildings	Evaluation of maximum **spatial density** for SGE plants	

In particular, concerning the estimation of the space heating demand of the residential buildings, Figure 3.5 represents the method developed within the Ph.D. thesis and applied to the case study. The different steps will be described in details together with the pre-processing of data in the next Sections 3.3.1; while the data processing will be illustrated in Section 3.5.1.

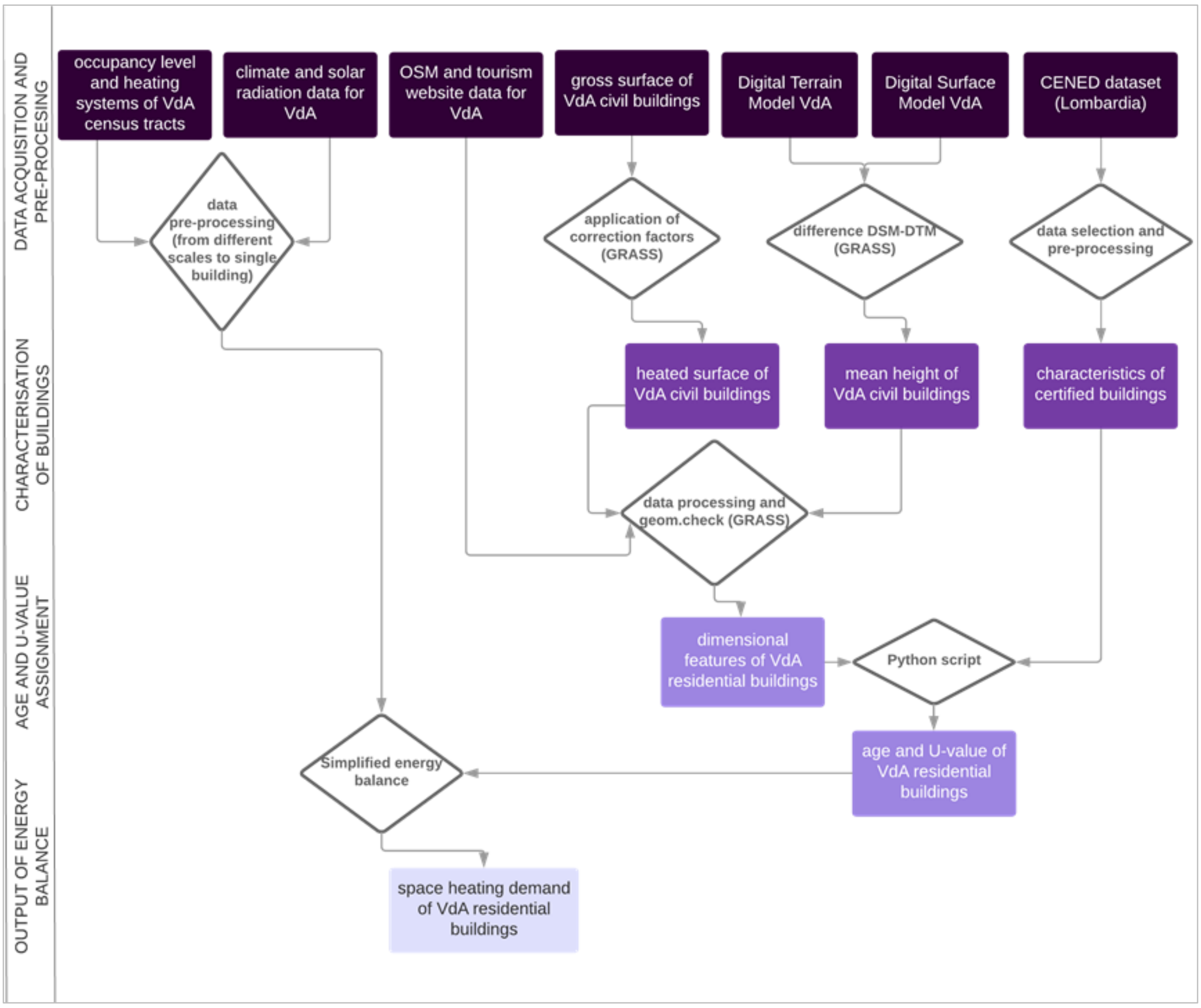

Figure 3.5: Flowchart of the method developed for the spatial estimation of space heating demand of residential buildings in the case study. Source: Thesis 2019.

3.3.1 Pre-processing of data for Building Stock Analysis

In this subsection, the steps followed for the pre-processing of data aimed at the thermal characterisation of the regional building stock are explained. The type of data used and the analyses performed are reported as well.

A ***Source***	***Data***	***Scale***	***…used for***
Region VdA – GeoBrowser	Raster data of DSM and DTM with spatial resolution of 2x2m and 0.5x0.5m, polygon vector data of buildings, point vector data of historic centres	Building	Calculation of geometrical features and age of buildings; estimation of solar radiation

The method elaborated for the evaluation of the space heating demand started from the geometrical features of the buildings and in particular from the following data: surface, height, and volume. Since part of this information was missing, the geometrical features of the buildings were characterized starting from two digital models, both derived from airborne Light Detection And Ranging (LiDAR) data, which are becoming commonplace in municipal and regional datasets. The two models are the Digital Surface Model (DSM), which represents the elevation of the highest features above the ground, and the Digital Terrain Model (DTM), which represents the elevation of the ground surface of the study area (Figure 3.6). Subtracting DTM values from DSM ones, the height of the aboveground features, the so-called normalised-DSM, was obtained following the procedure described in (Tooke, Laan, and Coops 2014).

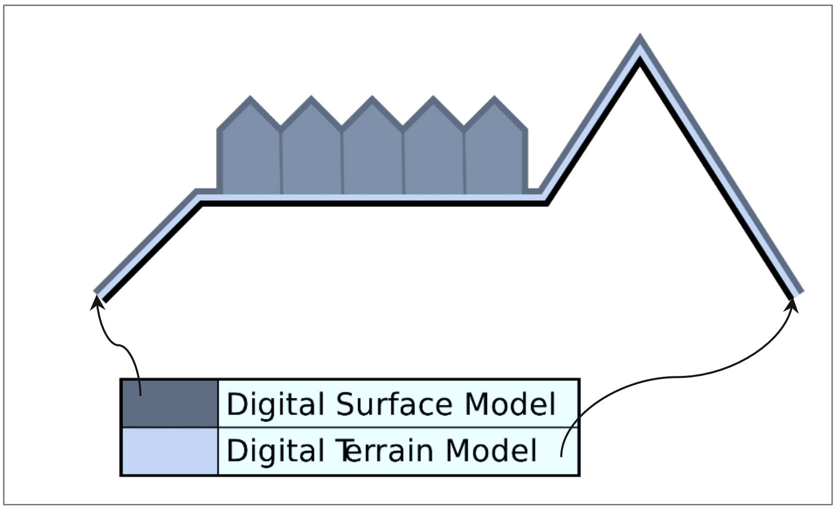

Figure 3.6: Surfaces represented by the Digital Surface Model and Digital Terrain Model. Source: Wikimedia Commons.

The available data (as Creative Commons – CC0) on the regional GeoBrowser of Valle d'Aosta ('GeoPortale – Portale dei dati territoriale della Valle d'Aosta' n.d.) are divided in high and low resolution. In particular, DTM and DSM with a resolution of 0.5x0.5m are available for the main valleys, while for the rest of the regional territory the data resolution is 2x2m. Therefore for the calculation of the height, the buildings were divided among those that felt into the high-resolution area and those that felt into the low-resolution one. After re-joining the two parts of the building stock, some geometrical issues were fixed. For instance, the agglomerations of buildings divided by the border of a census tract were divided themselves (Figure 3.7), not to assign the entire heated surface of a big building to only one census tract. Furthermore, the centroids of buildings that fell close to the border between census tracts with and without population were moved inside the census tract with population (Figure 3.8). Then, the needed geometrical features (i.e. mean height from the difference DSM–DTM, gross volume, number of floors, dispersing surface, S/V ratio) were calculated for each building. A fixed value for the height equal to 2.7m was also assigned when the mean height of the building was less than 2.7m or missing.

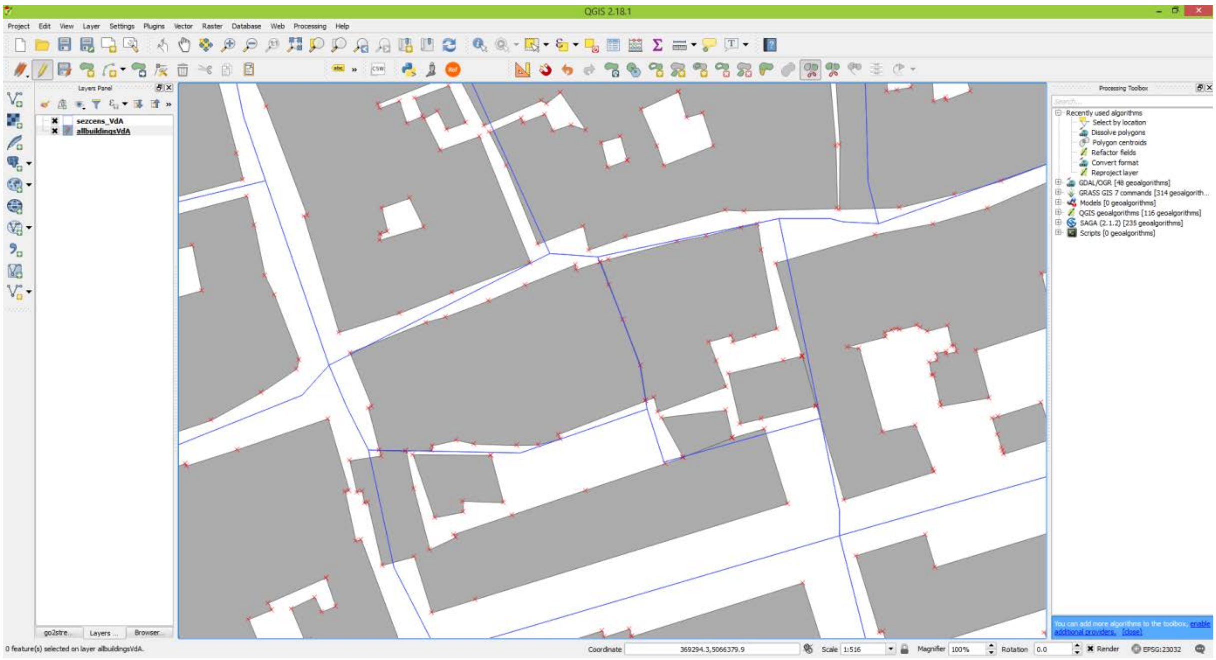

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Figure 3.7: Example of geometrical fix: buildings divided by the border of a census tract were divided themselves. Source: Thesis 2019.

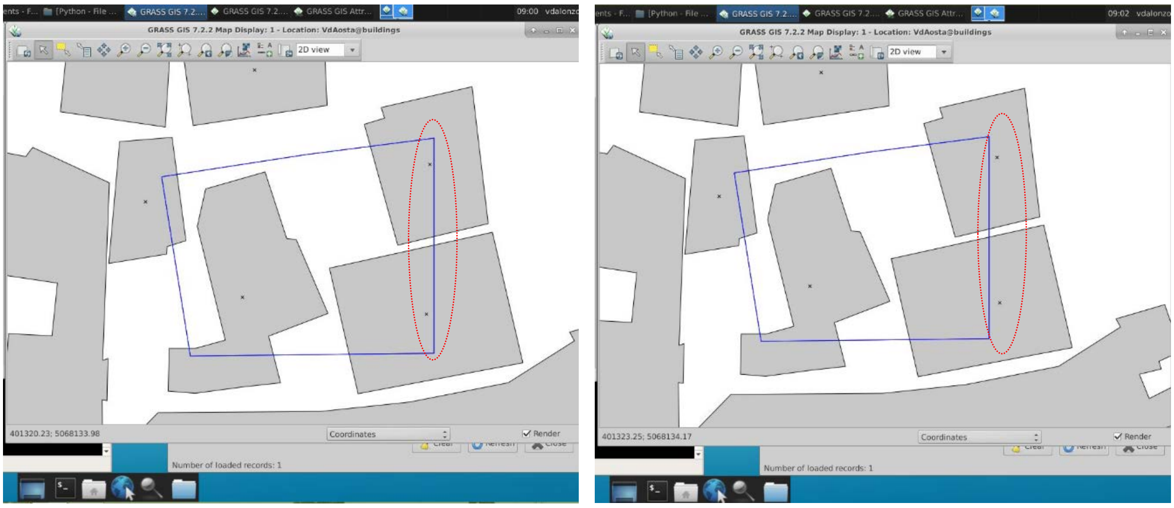

Figure 3.8: Example of geometrical fix: moving the centroids of buildings between census tracts with and without population. Source: Thesis 2019.

The polygon layer used for extracting the considered buildings was available as well on the regional GeoBrowser; all the shapefiles of “civil” buildings (i.e. not industrial) were downloaded and merged in one single layer using a Python script. These buildings were considered as they have prevailing residential use since the actual information on the mix of functions hosted in the buildings was not available at the building level. This layer was used to calculate the different surfaces of the considered buildings: from the footprint of the shapefile (deemed as the gross surface), the net surface was calculated applying a reduction coefficient of 0.83 (Provincia Autonoma di Bolzano 2013). Then, another reduction factor equal to 0.75 (Provincia Autonoma di Bolzano 2013) was applied to obtain the heated surface of the buildings. The same reduction factor of 0.75 was used to calculate the heated volume starting from the gross volume of each building. In the beginning, the residential buildings were considered as entirely heated, since the information on the real occupation of the buildings was not available for each building.

Furthermore, a point vector layer on the historic built-up areas available from the Regional Spatial and Landscape Plan (accessible on the same regional GeoBrowser) was used to gather some information on the period of construction of the buildings. In particular, a buffer of 50 m was created around these points and all the buildings that fell within the buffer were marked as “oldest” buildings[4]. For the calculation of the solar gains of the buildings, DSM map was used as input data (together with the vector file of buildings) for GRASS GIS r.sun module (Hofierka, Suri, and Huld 2007) to estimate the mean direct solar radiation on the vertical surface of the buildings, over the heating season. In particular, the incidence angle (i.e. the slope value) was forced to be equal to 90 degrees to reproduce the vertical surfaces. Then, a weighted sum was performed to

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[4] See „Relazione illustrativa“ of the Regional Spatial and Landscape Plan (Regione Autonoma Valle d’Aosta 1998).

assign a greater value at the longer sides of the buildings per each month, avoiding to consider the sides of a possible courtyard as relevant as the external sides of the building.

B ***Source***	***Data***	***Scale***	***…used for***
Region VdA – Tourism website and GeoBrowser; OpenStreetMap	Tourist (hotels, B&B, camping, residence, etc.) and service (hospitals, schools, swimming pools, ice rinks, etc.) buildings	Building	Characterisation of function of buildings

Data on tourist buildings are collected from the regional tourism website ('Dove dormire | Valle d'Aosta' n.d.). This information was then integrated with the data on tourist and service buildings (hospitals, schools, swimming pools, ice rinks, etc.) and other kind of non-residential buildings (agricultural, garage, industrial, military, monument, public, religious, sport, transport, etc.) collected from OpenStreetMap (OSM) ('OpenStreetMap' n.d.). These data were used for better characterising the function of the buildings and exclude the non-residential buildings from the analysis.

C ***Source***	***Data***	***Scale***	***…used for***
Region VdA – Environmental Agency (ARPA)	Temporal dataset of temperatures from 75 official weather stations	Region	Estimation of HDD

To integrate the climatic local conditions into the analysis and compute the losses due to the building envelope transmission, the Heating Degree Days (HDD) were estimated starting from the hourly data for the air temperature of 75 official weather stations provided by the Regional Environmental Agency (ARPA). HDD are measurements designed to quantify the amount of energy needed to heat a building. They are defined in relation to a base temperature; as base temperature were considered 20°C for the estimation of HDD. The monthly and annual HDD for each weather station were computed. A multivariate linear interpolation of HDD values was then performed using the following independent variables: weather station elevation, mean solar irradiation, slope orientation, sky-view factor, number of shadow hours. In this way, HDD values for each buildings' position were obtained. The variables have been selected, through a feature selection, seeking the highest correlation of HDD with other raster data (e.g. slope, land use, other geomorphological features).

D Source	Data	Scale	…used for
ISTAT – National Census 2011	Number of residential buildings per age, total heated surface per age, number of permanently occupied flats and total flats	Census tract	Characterisation of age and occupation level of buildings

Some outputs of the last Italian Census on population and buildings carried out in 2011 were acquired from ISTAT (ISTAT 2011). In particular: (i) number of residential buildings per period of construction; (ii) heated surface with different fuels per period of construction; (iii) number of permanent occupied and total flats per period of construction. Of course, all Census data are aggregated at the census tract level. These data were used mainly for providing information and “constraints” to characterise the building stock when the information at the building level was missing. For instance, since the information on the real occupation of the buildings was not available, it was derived statistically to respect the percentage obtained from ISTAT data on permanently occupied and total flats in each census tract per period of construction. As well, Census data was used to compare the heated surface values between the vector data of buildings and ISTAT data, looking at the aggregated values per census tract. When the difference was substantial, the polygons and other information (i.e. OSM data) were checked to find the reason for this discrepancy and correct it.

E Source	Data	Scale	…used for
Region Lombardia – CENED dataset	Age, energy performance (U-values) and geometrical features of certified buildings	Building	Estimation of age and energy performance of buildings

Since it was not possible to gather the information on the period of construction nor the energy consumption data for each residential building of Valle d’Aosta, the CENED+2.0 dataset (Infrastrutture Lombarde S.p.A, n.d.) was used to estimate the age and the energy performance of the residential buildings. This dataset collects all the Energy Performance Certificates (EPC) of the buildings performed in the Lombardia Region (NW of Italy, adjacent to Valle d’Aosta) since October 2015 and it is freely available as open data. A similar dataset is not available as open data for the certified buildings of Valle d’Aosta. Among CENED certificates, only those concerning the entire buildings (not apartments) and relating to buildings located in the climatic zone F were selected. The latter selection choice was done because more than 70% of the municipalities of Valle d’Aosta are located inside this climatic zone. The procedure of using the CENED dataset to estimate the age and the energy performance of VdA residential buildings will be explained in Section 3.5.1.

F **Source**	**Data**	**Scale**	**…used for**
Region VdA - Energy Agency (COA Energia)	Mean energy performance (kWh/m² year) per age of buildings, total energy consumption per fuel of residential sector	Municipality, Union of Municipalities	“Calibration” of estimation of space heating demand

From the Energy Agency of Valle d’Aosta (i.e. COA Energia Finaosta s.p.a.), two aggregated datasets were gathered concerning the housing sector of the Region: (1) total energy consumption (thermal and electrical) in 2015 per fuel and Union of Municipalities (*Unités des Communes*)[5]; (2) average value of the energy performance of the building envelope (in kWh/m^2 year) per period of construction of the buildings at the municipal level. These latter values were estimated by COA Energia starting from Census 2011 and EPC data collected in the Valle d’Aosta region but they were available only at municipal scale. The two aggregated datasets were used to adjust the estimated space heating demand of the buildings to consider the possibility of partially heated buildings, as we will see in Section 3.5.1.

3.4 Second part of Methodology

As already introduced, the presented SDSS aims also to connect the energy planning and the spatial planning fields using the framework of the Strategic Environmental Assessment (SEA), for the coordination of energy planning and spatial planning goals so that they are consistent and working towards the shared vision of sustainable energy transition. The second part of the methodology is also divided into some steps (see Figure 3.4) and it was developed mainly during the Ph.D. visiting period at the Newcastle University (UK), working with Paola Gazzola, who is a senior lecturer in Planning at the School of Architecture, Planning and Landscape.

The process started from the collection of information about European and national policies, strategies and related targets for the energy transition towards a low-carbon future (see also Sections 1.1.1 and 1.1.2). This so-called “secondary data” are listed in the following lists, divided in mid-term (until 2030) and long-term (until 2050) objectives.

2030 – European targets

Climate and Energy Framework 2030 (European Commission 2016):

- At least 40% reduction in greenhouse gas (GHG) emissions, compared to 1990 levels;
- At least 27% in the share for renewable energy;
- At least 27% improvement in energy efficiency.

2030 – Italian targets

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[5] http://www.regione.vda.it/link/comunita_montane_i.aspx

National Energy Strategy (Ministero dello Sviluppo Economico 2017):

- 28% of production from renewable energy sources on the basis of gross final consumption;
- 30% reduction in energy consumption compared to the trend level;
- 39% reduction in CO_2 emissions compared to the level of 1990.

2050 – European targets

Energy Roadmap 2050 (European Commission 2011):

- Reduction of GHG emissions by 80-95%, when compared to 1990 levels;
- Reduction of energy demand by 41%, when compared to 2005-2006 peaks;
- High share of renewable energies in gross final energy consumption (75%).

All the European scenarios indicate as well that the electricity will play a more relevant role than in the current situation; in particular, its share in the final energy demand is expected to almost double to 36-39% in 2050. This turn in favour of the electric energy will also contribute to the decarbonisation of the transport system and of the heating and cooling (H&C) systems. Most scenarios at European level also indicate that electricity prices will rise until 2030 and then follow a downward trend.

2050 – Italian targets

National Energy Strategy (Ministero dello Sviluppo Economico 2017):

- Energy efficiency: reduction of primary consumption from 17% to 26% compared to 2010;
- Production from renewable energy sources should reach the level of at least 60% of gross final consumption;
- Increase of the electrification process, which is expected to almost double, to at least 38%.

The energy efficiency measures in buildings are seen as they can open the way to a rethinking of the urban planning and management processes, given that about 70% of the energy consumption occurs in urban contexts. Consequently, the single building can become the nucleus of a wider strategy for renovating the territory. Moreover, the observable trend in energy consumption towards a relevant role of the electricity will also contribute to the achievement of the energy efficiency objectives, through the diffusion of efficient supply systems such as the heat pumps for heating and cooling the buildings.

After the pre-analysis on the “secondary data”, the first step was to analyse the possible impacts on the environmental components of SGE and other energy sources for the thermal supply of the buildings. Then the objectives of the Regional Energy and Environmental Plan (REEP), on one side, and of the Regional Spatial and Landscape Plan (RSLP), on the other side, were compared to highlight possible conflicts, gaps or need to improve the connection with new objectives. The third step concerned the formulation of site-specific strategic objectives for the case study taking into account the outputs of the previous two analyses. In the end, the last step was the development of alternative scenarios for the regional energy system of Valle d'Aosta. All these analyses will be described in detail in Sections 3.5.4, 3.5.5 and 3.5.6.

3.5. Data Processing

In the subsequent sections, the steps of the data processing are explained in detail, divided into the main methodological phases of SDSS as illustrated in Figure 3.3. It is worth to mention that almost all the data processing was done using open-source software (i.e. GRASS GIS, QGIS, R, and Python) and following a spatially-explicit approach, for pushing the integration of the spatial dimension in the energy analyses. To briefly introduce the following sections, the data processing started with the spatial estimation of space heating demand of the building stock. Then, two analyses performed in the framework of the GRETA project but preparatory for other Ph.D. investigations are described, with the links at the more in-depth explanations: the spatially-explicit financial feasibility analysis of SGE and the spatial suitability analysis of SGE installations. For what concerns the second part of the methodology, firstly the environmental assessment of the use of SGE was performed. Then, the energy planning and spatial planning objectives of the current regional planning system were compared, and finally some sustainable energy scenarios for the Valle d'Aosta were developed.

As already stated, the first part of the methodology concerns the characterisation of the residential existing building stock from the thermal energy viewpoint. Indeed, in order to evaluate the use of shallow geothermal energy (SGE), it is necessary to start from the energy demand that must be satisfied with this technology. This is because the geothermal energy is tightly linked to the energy demand, especially if compared to other RES. For this reason, the thermal energy demand needs to be well described and consequently, the residential building stock must be characterized from the energy viewpoint (GRETA project 2018b). Within the Ph.D. thesis, a method was developed to estimate the required values (above all, mean height and volume) when this information is not available for every single building (see also Figure 3.5).

The renewable sources used for the electricity production can be stored or relocated; for them, it is possible to estimate a maximum theoretical potential. For example in the case of solar photovoltaic, this potential would depend on the total surface that can be covered with PV panels. Instead for SGE, given the limited possibility of storage or transfer it to a network, the maximum theoretical potential is less suitable. This potential is difficult to define because it depends, in addition to the properties of the ground, on the depth reached by the probes and therefore is variable. On the other hand, by setting a maximum probes' length, the relative potential may not be representative, since it may indicate an amount of energy that can not be locally exploited and therefore it is not relevant for the planning process (GRETA project 2018d). Therefore, concerning SGE the constraint for the potential estimation is not dimensional (as for the PV systems) but rather technical/operational. In particular, it is given by the plant solution that optimises the size of the installation according to the thermal demand of the building to be supplied.

3.5.1 Spatial Evaluation of Space Heating Demand of Buildings

As we saw, the knowledge about the space heating demand of buildings becomes essential for the estimation of SGE feasibility and should be based on real consumption data (e.g. data collected by the energy utilities that deal with the distribution of natural gas, LPG, heating oil, electricity, etc.). However, in the case of large case study such, as the Valle d'Aosta region, the information on real energy consumption is often difficult to gather. Other alternatives are possible (depending on the availability of data):

1. To use the data contained in the Energy Performance Certificates (EPC) of buildings that estimate the annual energy demand per square meter of the certified buildings. Nevertheless, the information provided in EPC may be partial and not sufficient to fully characterise the thermal demand, as it would be necessary to define also which part of the building is continuously used, which one is temporarily used (e.g. holiday houses) or is completely unused. In addition, in order to use EPC information, this data must be collected in a systematic way and must be geo-referenced.
2. To follow the "archetypes-approach" that, according to the literature review on BSA, is usually adopted in the "bottom-up" models (see also Section 2.2.2). It identifies different building typologies and it analyses some representative buildings in order to assess the energy performance of the entire building stock (Corrado, Ballarini, and Corgnati 2012). For each reference building, some simulations are then required in order to calculate the space heating demand, according to the dimensional features and the period of construction of the buildings. It was decided not to use the "archetypes-approach", but instead to develop a methodology for the estimation of the needed value for each building considered as a single unit.

For the Valle d'Aosta case study, it was not possible to gather data on energy consumption for each building neither to access the information on the single energy certificates. In order to evaluate the space heating demand, the energy performance parameters coming from EPC of the buildings contained in CENED dataset (Infrastrutture Lombarde S.p.A, n.d.) were used after a selection process (see Section 3.3.1-E). This was done assuming that similar residential buildings in Lombardia and Valle d'Aosta will have similar thermal characteristics, as they are located in the same climatic zone of Italy.

To avoid the inclusion of errors due to data input procedure into CENED dataset, some outliers were excluded from the analysis, i.e. all those buildings whose values of (i) ratio between dispersing surface and volume (S/V ratio) and (ii) efficiency of the heating system were lower than the 2nd percentile and higher than the 98th percentile. All the buildings with a value of the heated surface less than 20 m^2 were also excluded from the analysis because considered too small. From this filtered data, the thermal transmittance value (U-value) was calculated for each certified building (see the formula in Box 3.1). The U-value represents the overall heat loss coefficient through the building envelope to the external environment by conduction.

Then, thanks to a Python script, the age and the U-value of a "CENED" building was assigned to the most similar building of Valle d'Aosta. The similarity was defined in terms of total heated surface and S/V ratio for the same period of construction. Punctual data on the historic built-up areas has also been integrated into the script, assigning the oldest construction period present in the census tract (i.e. before 1918 or 1919-1945) to the buildings that fell in the buffer of 50 m around these historic areas (see Section 3.3.1-A and Figure 3.5). Thus, the Python code was designed to include in the analysis the following constraints: percentage of buildings per period of construction at the census tract level and the number of buildings falling into the buffer of 50 m around the historical points.

The space heating demand of the building stock of Valle d'Aosta was calculated computing a simplified energy balance between the energy losses, due to climatic conditions and geometrical features of the buildings, on one side, and the internal and solar energy gains, on the other side. For computing the space heating demand of each building, the "*Simplified procedure for assessing the energy performance for heating the buildings*" described in Annex 2 of Italian Ministerial Decree 26/06/2009 (Ministero dello Sviluppo Economico 2009) (Box 3.1) was followed. This procedure was later updated by the technical standard UNI/TS 11300-1:2014 (UNI Italia 2014). The heating season for the case study was established according to the same MD 26/06/2009 that for the climatic zone F sets the heating period from the 15th of October to the 15th of April.

The performed energy balance considers the building system only from the space-heating point of view, therefore the energy demand values for the domestic hot water (DHW) use and for the cooling were not taken into account. In Valle d'Aosta, the energy consumption due to the cooling of buildings represents a very little part of the total energy use (Regione Autonoma Valle d'Aosta 2012), since its particular position inside the Alps.

In the pre-processing phase, the residential buildings were considered as entirely heated; at this point, the occupation degree of the buildings was derived statistically to respect the percentage obtained from Census data (ISTAT 2011) on occupied and total flats (see Section 3.3.1-D). In particular, an occupation ratio of the buildings in each census tract per each period of construction was calculated and multiplied for the estimated thermal demand. This "occupied" value of thermal demand was then used in the following steps of the methodology to avoid as much as possible the overestimation of the thermal energy demand.

The Census 2011 did not explicitly survey the buildings used as holiday houses and it was not possible to gather other data at regional scale concerning this topic. Therefore, the buildings could not be divided into permanent and occasional houses and they were considered all as entirely inhabited, and so heated. Another hypothesis, due to the lack of information, was to consider the buildings as entirely residential. Actually this is not true, especially inside the historic parts of towns and villages, but it was not possible to internally divide the buildings among different functions (residential, commercial, offices, etc.). Consequently in general, the heated surface of the residential buildings and the relative space heating demand were overestimated (this issue will be discussed in Section 4.1.1).

All the previous analyses were performed continuously combining data processing in R or Python and joining the outputs with vector data in GRASS GIS and QGIS, and vice versa. The developed procedure, based on Annex 2 of DM 26/06/2009, can be divided into three main steps:

1) Estimation of U-value for each selected building of CENED dataset;
2) Running the Python script for the match between CENED and VdA buildings;
3) Estimation of space heating demand (Qh) of VdA buildings using the U-value assigned to each building from CENED dataset.

The formulas listed in Box 3.1 were used to perform these estimations.

Within the obtained dataset of Valle d'Aosta buildings, only the features with a not null value for the period of construction and U-value were selected. At this point, almost 6.33% of the total buildings were excluded from the analysis. Afterwards, other buildings were excluded since their estimated heated surface was less than 25 m^2 and/or they have a value of heated volume less than 75 m^3. In the end, around 41,700 features were considered in the subsequent analyses. As introduced in Section 3.3.1-F, from COA Energia, the aggregated data on the average value of the energy performance of the building envelope (in kWh/m^2 year) per period of construction and municipality was gathered. For each of the resulting buildings, a "fixed" value of specific space heating demand (in kWh/m^2 per year) was obtained modifying the estimation using the average value per period of construction and municipality provided by COA Energia, to consider the possibility of partially heated buildings.

After the spatial estimation of space heating demand, according to Table 3.6, the demand of the residential buildings was matched with the geothermal energy potential estimated for the whole Valle d'Aosta region. The maps of the geothermal potential were performed within the GRETA project for the three pilot areas and are available on the WebGIS of the project. Moreover, the residential buildings located in areas defined as not suitable for the installation of geothermal plants were excluded from the next analysis, in order to avoid the overestimation of the feasible SGE plants in Valle d'Aosta (as explained in the following Section 3.5.3).

Box 3.1: Formulas used to perform the simplified energy balance of the residential buildings of Valle d'Aosta. Source: Thesis 2019.

$EP_i = (Q_h/S_h)/\eta_g$ (kWh/m^2)
where:
EP_i = energy performance index for heating the building
Q_h = space heating demand of building (kWh)
S_h = heated surface (m^2)
η_g = average energy efficiency

Therefore:
$Q_h = EP_i*\eta_g*S_h$ (kWh)

At the same time
$Q_h = ((H_t+H_v)HDD)/1000 - f_x(Q_s+Q_i)$ (kWh)
where:
H_t = losses coefficient for transmission (W/K)
H_v = losses coefficient for ventilation (W/K)
HDD = heating degree days (K) [ARPA temperature dataset, see Section 3.3.1]
f_x = coefficient for reducing the utilization of free gains (0.95) [MD 26/06/2009]
Q_s = solar energy gains (kWh)
Q_i = internal energy gains (kWh)

$H_t = S_d*U_m*b_t$ (W/K)
where:
S_d = dispersing surface (m^2) [geometrical features, see Section 3.3.1]
U_m = mean transmittance value (W/m^{2}K) [CENED dataset, see Section 3.3.1]
b_t = correction factor for heat exchange (0.8) [MD 26/06/2009]

$H_v = 0.34*n*V_n$ (W/K)
where:
n = numbers of air exchanges (0.3) [MD 26/06/2009]
V_n = heated volume (m^3) [geometrical features, see Section 3.3.1]

$Q_s = 0.2*I_s*S_w$ (kWh)
where:
I_s = solar irradiance on vertical surfaces (Wh/m^2) [GIS GRASS r.sun, see Section 3.3.1]
S_w = surface of windows (m^2)
with $S_w = (1/8)*S_h$ (Fichera et al. 2016)
where S_h = heated surface (m^2)

$Q_i = (\omega_i*S_h*h)/1000$ (kWh)
where:
ω_i = free internal gains (4 W/m^2) [MD 26/06/2009]
S_h = heated surface (m^2) [geometrical features, see Section 3.3.1]
h = number of hours of the heating season [MD 26/06/2009]

3.5.2 Spatial Financial Feasibility of Shallow Geothermal Energy

The spatial analysis of the financial feasibility for the use of SGE was aimed at assessing the financial convenience of the installation of a shallow geothermal plant compared to the use of “mainstream” technologies, i.e. natural gas or heating oil boiler with an air conditioning system (ACS), in case of cooling would be required. Thanks to the procedure implemented within the GRETA project, it was possible to assess the financial and economic feasibility of a selected technical solution in each specific location. This was done considering different variables dependent on the position: the geological characteristics of the ground, the legislative and environmental constraints, the solar radiation, the site-specific thermal demand, the position and power of other existing geothermal plants (GRETA project 2018b).

The financial analysis started from the space heating demand of the buildings (see the previous Section 3.5.1 and Table 3.6) for computing the dimensioning of the SGE plant for each residential building. The consequent step was the financial evaluation of these plants compared to the above-mentioned conventional technologies, using some economic indicators (especially the Discounted Payback Period – DPP and the Levelized Cost Of Energy – LCOE). For each building, SGE plant was also combined with solar rooftop photovoltaic (PV) panels and with national subsidies for increasing the energy efficiency of buildings to investigate the effects of these two elements on the financial performance of the system.

The analysis required some hypothesis and assumptions mainly because of the lack of spatially distributed information, the computational constraints and the simplifications needed to effectively address this complex issue. The most important assumptions implemented in the analysis performed for the Valle d’Aosta region were the following (GRETA project 2018c):

- The geothermal heat pump will cover the entire space heating demand of the buildings (i.e. no auxiliary systems were included in the analysis);
- The costs of installation of an SGE plant are higher than those of the conventional plants;
- To calculate the installation costs of SGE plant for each building, according to (Lu et al. 2017), the capital cost estimation for the plants took into account a 40% increase of the estimated costs for excavation and heat pump (HP);
- The national incentives have been applied in a single solution;
- The PV panels’ surface was calculated from the annual sum of the solar radiation incident on the roof, using r.sun module of GRASS GIS (Hofierka, Suri, and Huld 2007).

The spatial evaluation of the technical and financial feasibility of SGE in Valle d’Aosta was carried out for closed-loop and open-loop solutions assuming to cover the energy demand of the residential buildings and to replace the fossil fuels within the heating system, as much as possible. Just to briefly cite it, the closed-loop systems (or Ground Source Heat Pumps – GSHP) exchange the thermal energy with the ground due to a heat-carrier fluid circulating in the pipes. While, the open-loop systems (or Ground Water Heat Pumps – GWHP) exchange the thermal energy with the groundwater, by extracting it with two or more wells.

GSHP is a mature technology that is increasingly used in buildings for space H&C and domestic hot water production. Recently, technological advances have led to an increase in energy efficiency of these systems, making them more attractive for heating systems in buildings (Miglani, Orehounig, and Carmeliet 2018). In terms of CO_2 emissions, GSHP ranks also higher than all fossil fuel-based boilers and the air-source heat pumps. Further details about the different types of SGE plant, the methods used in the analysis and all the assumptions considered can be found in the deliverables of the GRETA project concerning WP5 activities: (GRETA project 2018b) and (GRETA project 2018c).

3.5.3 Spatial Suitability Analysis of SGE installations

The spatial suitability represented the last step for accomplishing the spatially explicit analysis of the technical, financial and environmental feasibility for the use of SGE to cover the thermal demand of the residential buildings in Valle d'Aosta (see Table 3.6). This analysis aimed to estimate the maximum number of SGE systems that can occur at the same time, minimizing the risk of interferences among different installations or between SGE plants and some environmental components. In general, the space suitability analysis for closed/open-loop systems detected and excluded (GRETA project 2018c): (i) water protection areas, (ii) areas close to the water bodies (rivers and lakes), (iii) areas too close to roads and buildings, (iv) areas interfering with the thermal plume of the already existing plants. If the area of the pertinence of the buildings was available, a further constraint was applied: (v) SGE installation must be inside this area. The distance requirements set for the analysis were: the minimum distance of an SGE plant from its building is at least 1m, while the maximum distance from the building is less than 36m. For the closed-loop systems, the minimum distance among the installations was assumed of 7m, while for the open-loop systems the minimum distance was 10m.

For the case study, the analysis of the spatial suitability did not consider the area of the pertinence of the residential buildings because this data was not available at the regional scale for the Valle d'Aosta. Instead, it included the water protection areas and a buffer around existing buildings and water bodies. In addition, the thermal plume of the existing SGE plants has been computed (GRETA project 2018c) and the potential new SGE systems must not interfere with their thermal plumes. LCOE values of the geothermal systems (computed in the financial analysis, see the preceding Section 3.5.2) have been used to give priority to the buildings that can install the system: specifically, buildings with lower

LCOE had higher priority in the use of this technology. As well as before, further details about the method developed for the spatial suitability analysis can be found in the deliverables of the GRETA project concerning WP5 activities: (GRETA project 2018b) and (GRETA project 2018c).

3.5.4 Environmental Analysis of SGE use

As already stated, the second part of the methodology is carried out in the framework of Strategic Environmental Assessment by following some analytic steps; the first of them was the analysis of the possible impacts on the environmental components of SGE and of other thermal renewable sources for the energy supply of the building stock. This analysis was done assessing the main impacts with qualitative measures for three criteria: magnitude (low-medium-high), time (short-long term), space (direct-indirect impact). The environmental components are those considered in SEA Directive 2001/42/EC (European Parliament 2001) plus some other elements useful for our analysis. Specifically, they are air quality, climate change, surface and groundwater, snow and ice, land use, underground, protected areas and habitats, biodiversity, landscape, cultural and architectural heritage, noise, waste, radiation, energy efficiency, renewable energy, sustainability, and cost of the source.

In Table 3.7 this analysis is represented, where the impacts of the different energy sources are evaluated in a qualitative way with a four-colour scale (from red = negative impact to dark green = positive impact). Some prevention/mitigation measures for the detected impacts are also suggested. The main references for the impacts assessment of SGE and other thermal renewable sources are: (Hähnlein et al. 2013), (Kurevija, Vulin, and Krapec 2011), (Sanner et al. 2003), (Cataldi 2001). Some notes useful to better interpret the following table:

- the magnitude of SGE impact often depends on the size of the plant;
- the solar thermal source is often not able to replace other fuels for heating the building but only for DHW service;
- the use of biomass may have indirect impacts on climate due to its emissions if it is not considered carbon-neutral.

Table 3.7: Qualitative analysis of possible impacts on the environmental components of SGE, solar thermal and biomass. Source: Thesis 2019.

	env.components: **fuels:**	**NSGE**	**magnitude**	**time**	**space**	**mitigation/ prevention**	**SOLAR TH.**	**magnitude**	**time**	**space**	**mitigation/ prevention**	**BIOMASS**	**magnitude**	**time**	**space**	**mitigation/ prevention**
ENVIRONMENT (SEA Directive)	**Air quality**	🟩	high	long	dir.		🟩	medium	long	dir.		🟥	medium	long	dir.	right filter system
	Climate change	🟩	high	long	indir.		🟩	medium	long	indir.		🟧	low	long	indir.	switching to other RES
	Surface water	🟥	variable	long	dir.	right plant sizing	🟩	high	long	indir.		🟧	low	long	indir.	switching to other RES
	Groundwater	🟥	variable	long	dir.	right plant sizing	🟩	high	long	indir.		🟧	low	long	indir.	switching to other RES
	Snow and ice	🟩	high	long	indir.		🟩	high	long	indir.		🟧	low	long	indir.	switching to other RES
	Land use	🟩	medium	long	dir.		🟥	medium	long	dir.	avoid ground-mounted installations	🟧	medium	long	dir.	coordination with forest planning
	Underground	🟥	variable	long	dir.	right plant sizing	🟩	high	long	indir.		🟧	low	long	indir.	switching to other RES
	Protected area and habitats	🟩	high	long	indir.		🟥	medium	long	dir.	avoid ground-mounted installations	🟧	medium	long	dir.	coordination with forest planning
	Biodiversity	🟥	variable	long	indir.	right plant sizing	🟥	medium	long	dir.	avoid ground-mounted installations	🟧	medium	long	dir.	coordination with forest planning
	Landscape	🟩	high	long	indir.		🟧	medium	long	dir.	right plant positioning	🟧	medium	long	dir.	coordination with forest planning
	Cultural and arch. heritage	🟥	variable	long	dir.	right plant sizing	🟧	medium	long	dir.	right plant positioning	🟧	low	long	indir.	switching to other RES

	env.components: fuels:	NSGE	magnitude	time	space	mitigation/ prevention	SOLAR TH.	magnitude	time	space	mitigation/ prevention	BIOMASS	magnitude	time	space	mitigation/ prevention
	Noise	🟧	variable	short	dir.	drilling phase as fast as possible										
	Waste	🟧	variable	short	dir.	right disposal of waste material	🟥	medium	long	indir.						
	Radiations															
ENERGY (EU strategies)	**Efficiency (energy eff. of plants using the source)**	🟩	high	long	dir.		🟩	high	long	dir.		🟩	medium	long	dir.	
	Renewable (clean and carbon-free energy source)	🟢	medium	long	dir.		🟩	high	long	dir.		🟢	medium	long	dir.	
	Sustainability (contribution to sust. develop.)	🟩	high	long	indir.		🟢	medium	long	indir.		🟩	medium	long	indir.	
	Economic benefit (cost of the energy source)	🟩	medium	long	dir.		🟢	low	long	dir.		🟩	medium	long	dir.	

3.5.5 Comparison among Energy Planning and Spatial Planning Objectives

After the assessment of the possible impacts on the environmental components of SGE and of other thermal renewable sources, the comparison among the current energy planning and spatial planning objectives of Valle d'Aosta was performed. This analysis was aimed at identifying possible gaps to be filled in the coordination of these goals so that they will be consistent and working towards the shared vision of the energy transition for the case study. In the first step, the objectives of the Regional Energy and Environmental Plan (REEP), on one side, and of the Regional Spatial and Landscape Plan (RSLP), on the other side, were analysed and compared to highlight conflicts or need to improve the connection with new objectives.

Concerning the energy plans and policies implemented in the Valle d'Aosta region during the last years, the main energy objectives for 2020 are included in REEP (Regione Autonoma Valle d'Aosta 2012) and can be summarised as follows:

- Targets for installed power and energy production from renewable energy sources: 14.8% on total thermal consumption and more diversified electrical production; new targets in the Monitoring Report: production from RES + 4%, the share of RES production on the total consumption 86.1%.
- Targets for the reduction of energy consumption: 7% concerning the thermal consumption and 6.6% concerning the electrical; new target in the Monitoring Report: total consumption -1.1%.
- Target for the energy renovation of civil buildings: 4% per year.
- Target for energy efficiency: the increase in different sectors.
- Target for the thermal energy production from heat pumps (the plan refers to all the different types of heat pump, not only the geothermal one): 4 thermal GWh (of which 1.28 GWh of renewable energy).

Concerning the spatial strategies implemented in Valle d'Aosta, RSLP is not really recent since it was developed in 1998 (Regione Autonoma Valle d'Aosta 1998). However, the main energy-related and buildings-related objectives addressed in the plan are:

- The improvement of technologies for the reduction of energy consumption and the increase of energy self-sufficiency.
- The energy production from renewable sources in the scattered settlements.
- The completion of the natural gas distribution system in the central valley area.
- The increase of energy saving, diversification of energy sources, functional renovation of infrastructures and completion of distribution networks.
- The refurbishment of settlements, mainly through the renovation and reuse of the existing building stock.

- To ensure correct transformations in the areas that may be refurbished or targeted for new interventions.

In Table 3.8 the comparison among the objectives set by the two plans is reported, and the points of correspondence, conflict or need to improve the connection with new objectives are highlighted.

Table 3.8: Comparison among energy planning and spatial planning objectives of Valle d'Aosta. Source: Thesis 2019.

		REGIONAL SPATIAL and LANDSCAPE PLAN (1998) – Energy and buildings-related objectives [without term]					
		reduction of energy consumption and increase in self-sufficiency	production from RES in settlements	natural gas distribution in central valley area	energy saving, diversification of sources, completion of distribution networks	renovation and reuse of existing building stock	correct measures in areas to be refurbished or targeted for new buildings
REGIONAL ENERGY and ENVIRONMENTAL PLAN (2012) – Specific objectives (by 2020)	targets for installed power and energy production from RES	☑	☑	☒	☑	indirect	☑
	targets for reduction of energy consumption	☑	indirect	Indirect	☑	☑	☑
	targets for increase in energy efficiency in different sectors	☑	indirect	☑	☑	☑	☑
	reduction of CO_2 emissions	☑	☑	☒	☑	indirect	☑

3.5.6 Development of Energy Scenarios

In order to develop alternative energy scenarios for the case study, after comparing the objectives and reporting the possible conflicts or space to improve the connection between energy planning and spatial planning, the following step was the formulation of "our" strategic energy-driven objectives. The main contrast found in the objectives' comparison was the willingness to improve the network for the distribution of natural gas, not only in the central valley (as reported in Table 3.7) but also in the smaller settlements located in the secondary valleys, according to RSLP (Regione Autonoma Valle d'Aosta 1998). This objective was in contrast with the targets for increasing energy production from RES and reducing CO_2 emissions. Therefore, our objectives were more focused on the replacement of all fossil fuels, including the natural gas, for the thermal supply of the residential building stock.

The other goals are in line with those defined in the plans, above all concerning the reduction of energy consumption and the increase of energy efficiency. Specifically, the formulated objectives are:

- The increase of energy saving, improving the efficiency of production plants and distribution systems;
- The diversification of energy sources due to the substitution of fossil fuels in the heating systems (especially LPG and heating oil, partially natural gas);
- The reduction of energy consumption thanks to the refurbishment of the residential building stock;
- The increase of the energy self-sufficiency of cities and towns with more production from local RES;
- The reduction of CO_2 emissions due to the substitution of fossil fuels in the heating plants.

Considering all the previous analyses, the final part of the Ph.D. methodology is the development of sustainable scenarios for the energy system of Valle d'Aosta, along the energy transition path toward the vision of a *Smart Energy Region*. In Figure 3.9, a schema about the construction of these scenarios is represented. Later in the thesis section about the results (Section 4.4), the different scenarios will be described more in detail with all the criteria considered (environmental, economic, spatial, etc.) and the discussion about their effects on the energy demand and CO_2 emissions in the case study area.

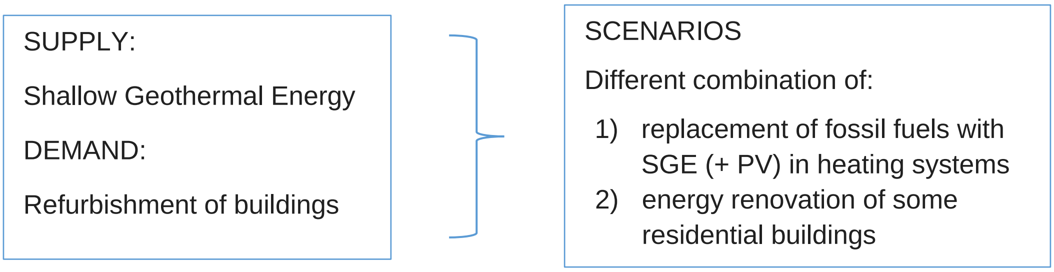

Figure 3.9: Shaping sustainable scenarios for the regional energy system of Valle d'Aosta. Source: Thesis 2019.

Points 1) and 2) of Figure 3.9 were deemed as the driving forces that will influence the development of the regional energy system in the future. Therefore, diverse combinations of these two drivers shaped the developed scenarios, together with the factors considered during the analysis in the first part of the methodology. These aspects are:

- Thermal demand of buildings - ENERGY
- CO_2 emissions of fuels - ENVIRONMENT
- Costs of HS replacement and refurbishment of buildings - ECONOMY
- Spatial suitability of SGE systems - ENVIRONMENT
- Coupling SGE and PV - ENERGY

CHAPTER 4

4 Results and discussion

In this chapter, the main results of the Ph.D. thesis are presented and their implications for the integration of energy planning and spatial planning discussed. To briefly introduce them, the main outputs of the PhD project are: (i) the spatial evaluation of the space heating demand of each residential building of the case study, without using the "archetypes approach"; (ii) the development of a method for the integration of data from different sources and for its estimation if missing at the building level; (iii) the development of a methodology that can be applied at different scales and potentially in every kind of context; (iv) the connection between energy planning and spatial planning fields, using SEA as a methodology for strategic decision-making processes. Although the outputs of the developed methodology refer to a region, the same results can be obtained at different scales and not only for alpine contexts but potentially for every kind of territory given the replicability of the method.

4.1 Spatial Evaluation of Space Heating Demand of Buildings

Thanks to the pre-processing and processing of data presented in Chapter 3, the space heating demand of each building defined as residential in the Valle d'Aosta region was estimated. For the considered number of buildings (41,700), the total estimated thermal demand is around 1,960,000 MWh (1,960 GWh) per year. The output is expressed both in terms of overall thermal demand of the buildings in MWh per year and in space heating demand of the buildings in kWh/m^2 per year. These last values allowed us to classify the building stock also according to some energy classes, as it is represented in the example in the following Figure 4.1. While Figure 4.2 illustrates an extract of the output of the estimation of the construction period of the residential buildings in Valle d'Aosta.

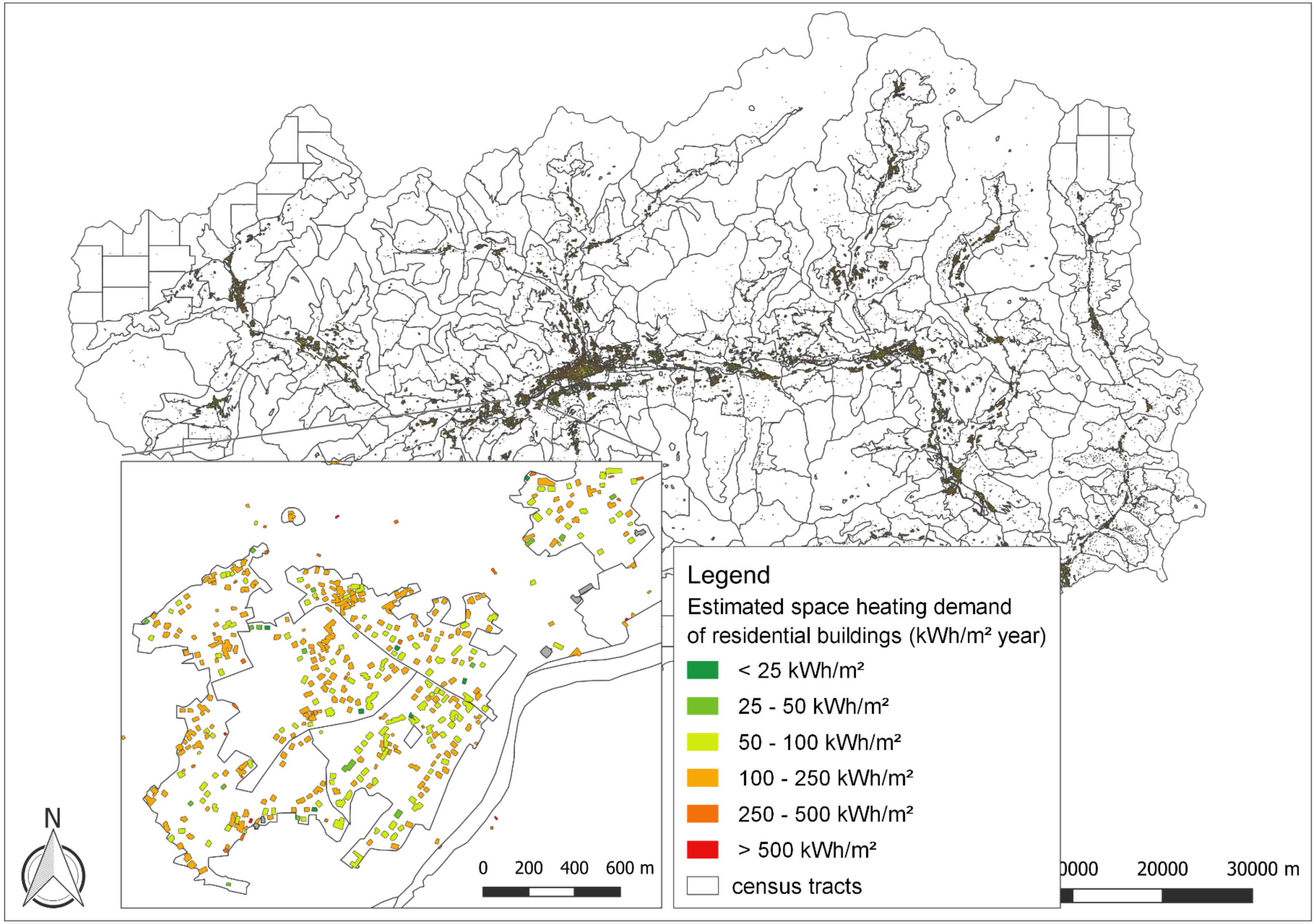

Figure 4.1: Map of classes of space heating demand of buildings in kWh/m^2 per year; in the zoom an extract of Saint Maurice village in Sarre municipality. Source: EURAC for GRETA project, Thesis 2019.

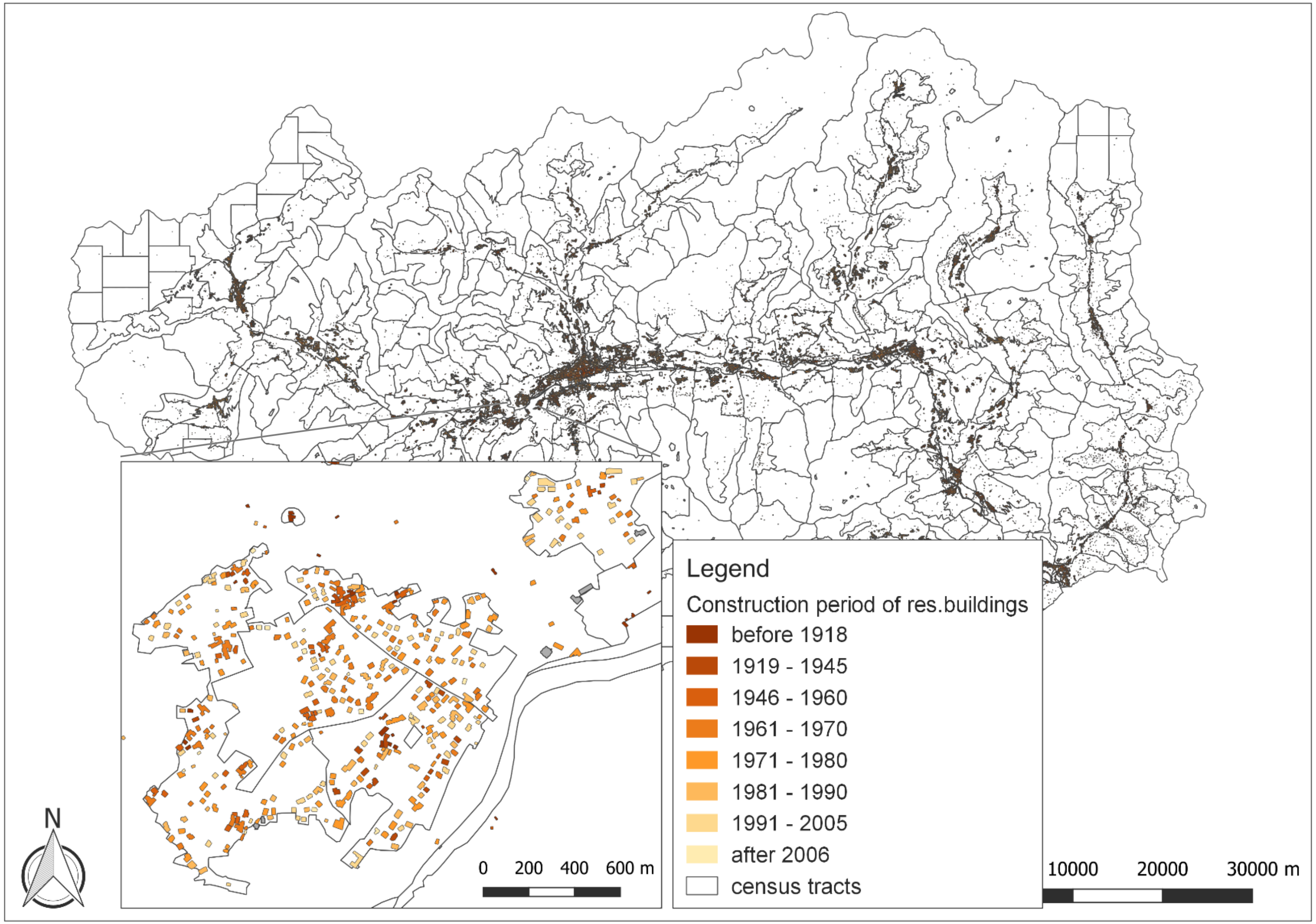

Figure 4.2: Map of period of construction of buildings; in the zoom an extract of Saint Maurice village in Sarre municipality. Source: EURAC for GRETA project, Thesis 2019.

This output of the Ph.D. methodology is also published in the WebGIS of the GRETA project. Indeed, the map of the space heating demand and the map of the period of construction of the residential buildings in Valle d'Aosta are available at the following link: http://greta.eurac.edu/maps.

4.1.1 Strengths, Weaknesses and Future Developments

As described in Section 3.3.1-F, from the Energy Agency of Valle d'Aosta (called COA Energia), two aggregated datasets concerning the housing sector of the Region were gathered: (1) the total energy consumption (thermal and electrical) in 2015 per fuel and Union of Municipalities (*Unités des Communes*), estimated from several national and regional statistics; (2) the average value of the energy performance of the building envelope (in kWh/m^2 year) per period of construction of the buildings at the municipal level. Once the space heating demand of the residential building stock was estimated with the developed methodology, it was possible to compare the predicted total thermal demand with the total thermal consumption of the Region in 2015, obtained by excluding the values of the electrical consumption in the (1) dataset provided by COA Energia.

Generally, the heated surface of the residential buildings and consequently the space heating demand were overestimated. This occurred mainly because of two reasons. Firstly, the information on the real occupation of the buildings was not available at the building level and it was derived statistically to respect the percentage obtained from Census data (ISTAT 2011) on occupied and total flats per census tract (see Section 3.3.1-D). Secondly, due to the lack of information about the mixed use of the buildings (residential, commercial, offices, etc.), they were considered as entirely residential since it was not possible to internally divide them among different functions. However, the sum of the thermal demand values after applying the "occupation ratio" calculated from ISTAT data per period of construction of the buildings (see Section 3.5.1) is equal to almost 54% of the total estimated demand. This high percentage of unused buildings is confirmed by the Monitoring Report of REEP (Regione Autonoma Valle d'Aosta 2018), according to which almost half of the residential building stock in Valle d'Aosta is empty or not permanently occupied.

If we imagine applying an average efficiency factor, which may range between 0.8 and 0.9, to the estimated occupied thermal demand, it is possible to calculate an estimated thermal consumption of the occupied buildings and compare this value with the one provided by COA Energia. This comparison between the estimated occupied thermal consumption and the total thermal consumption of the residential sector from COA data confirmed the overestimation of our values. Of course, the difference between the two consumption values decreases with the increase of the mean energy efficiency applied. The percent difference between our estimated thermal consumption and the thermal consumption of COA data ranges from around 9% to 23% and it may be also due to other reason, like the way of using the heating system by the residents. Indeed, it was not possible to consider the operation schedule of the heating plants neither the information on whether some parts of the buildings are never heated all along the year was available. All the discussed values are summarised in the following Table 4.1.

Table 4.1: Comparison between estimated values of thermal demand and consumption and the "official" data of thermal consumption. Source: Thesis 2019, Monitoring Report of REEP.

Thermal demand or consumption of buildings	***mean energy efficiency***	***MWh year***	***Data source***
tot estimated thermal *demand*		1,960,000	our estimation
occupied estimated thermal *demand*		1,065,000	our estimation
occupied estimated thermal *consumption*	0.80	1,331,250	our estimation
	0.85	1,252,940	
	0.90	1,183,330	
tot thermal *consumption*		1,082,000	COA Energia

Furthermore, due to the "adjustment" performed by using the other dataset provided by COA Energia (i.e. the mean energy performance of buildings in kWh/m^2 per period of construction and municipality), the estimated values of the space heating demand in kWh/m^2 per year were modified to be consistent with the official values in average at the municipal level. Considering the total heated surface of the analysed residential building stock, the average space heating demand is around 140 kWh/m^2 year. According to the H2020 Hotmaps project, which recently performed an extensive BSA for all the European countries (Pezzutto et al. 2018), the average value of space heating demand for the Italian residential building stock is 114.7 kWh/m^2 year. The particular location of the case study inside the Alps may be the reason for the higher space heating demand of the buildings, due to the cold climate.

Referring to Section 3.1.2, where the case study was presented with some data about the regional building stock, in the following Figures 4.3 and 4.4 the results of our estimation are compared with the above-mentioned data, in particular for what concerns the period of construction and the mean space heating demand of the buildings. Regarding the first comparison, one can see that the estimated values are very in line with the ones included in the Monitoring Report of REEP (Regione Autonoma Valle d'Aosta 2018). This is probably due to the fact that both the estimations were done starting from data of the last national Census (year 2011). While as regards the space heating demand, the number of buildings in the energy class between 100 and 250 kWh/m^2 year and in the last one (above 500 kWh/m^2 year) was overestimated while the amount of buildings in the three more efficient classes (below 100 kWh/m^2 year) was underestimated. Whereas, the estimated values are in line with REEP ones for the energy class between 250 and 500 kWh/m^2 year.

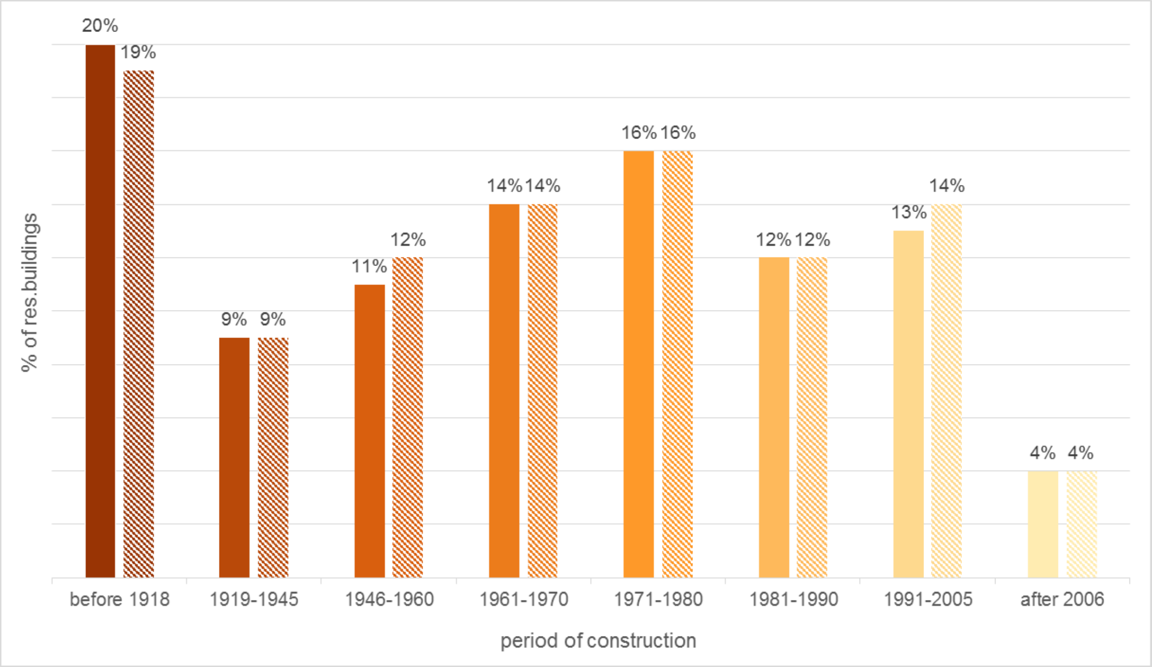

Figure 4.3: Period of construction of residential buildings, the comparison between estimation values (left, solid fill) and "official" data (right, pattern fill). Source: Thesis 2019, Monitoring Report of REEP.

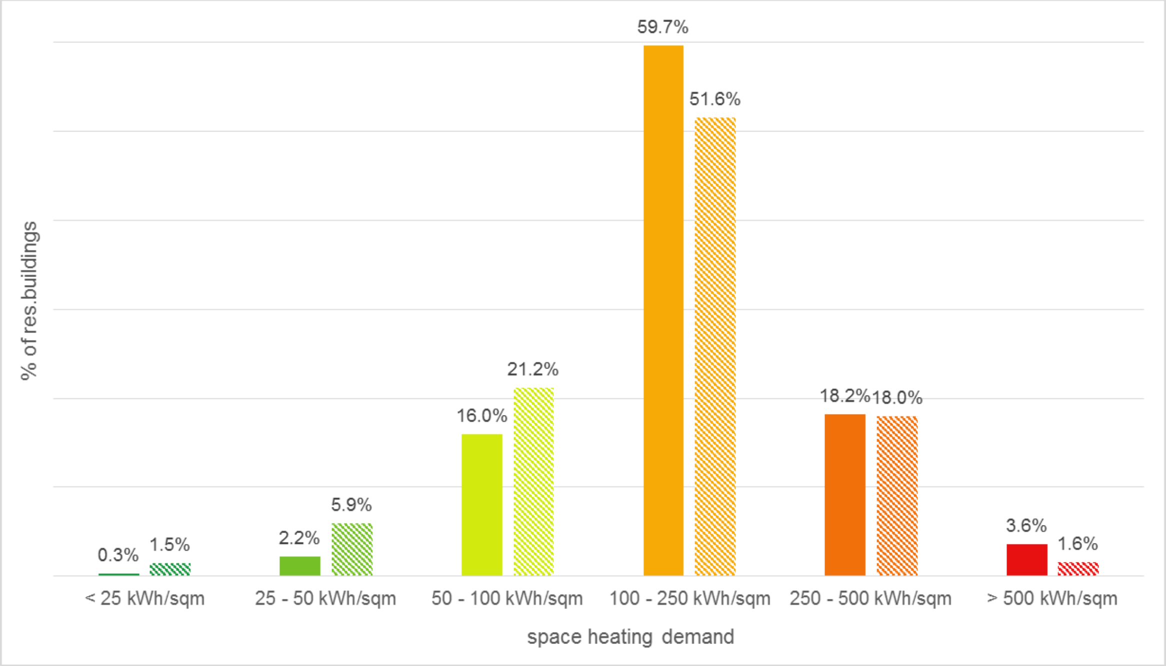

Figure 4.4: Space heating demand of residential buildings, the comparison between estimation values (left, solid fill) and "official" data (right, pattern fill). Source: Thesis 2019, Monitoring Report of REEP.

Concerning Figure 4.4, it is worth to mention that the data provided by COA Energia takes into account also the more recent buildings, built between 2011 and 2015 (Regione Autonoma Valle d'Aosta 2018), whose number and characteristics were estimated starting from EPC for new construction. While the latest available data for the estimations was the Census data that are updated at 2011. These new residential buildings considered in the COA dataset have to be certainly counted inside the more efficient energy classes, thanks to the mandatory energy regulation in place for some years. This may be one reason for the underestimation of the number of buildings with a space heating demand smaller than 100 kWh/m^2 per year. Furthermore, the distributions of the energy performance within the two datasets of Valle d'Aosta and Lombardia were supposed to be similar (for the same climate zone). Since the raw data of COA Energia was not available, it was not possible to verify that the two distributions are actually similar. So, the difference between our results and COA data can also be related to a different distribution of the energy performance of buildings in Valle d'Aosta.

In conclusion, even though the resulted overestimation of the space heating demand is supposed to be up to 23%, a compromise between the degree of generalisation of the building stock analysis and the willingness to consider the specificities of each building was found, when proper data are available. The trade-off between accuracy and simplicity of thermal demand estimations is a common issue among the "bottom-up" building stock models (see Section 2.2.2), as recently pointed out by (Brøgger and Wittchen 2018). They also reported on the so-called performance gap, which occurs when there is a large difference between the predicted theoretical energy demand and the actual consumption of buildings.

This difference can be ascribed to (i) the users' behaviour inside the building, (ii) the lack of information about the energy performance of the heating systems or (iii) the "rebound effect", where technical innovations do not lead to a decrease in energy consumption because the increment of efficiency tends to be balanced out by growing consumption (Droege 2014). Furthermore, the quality of the results reflects the precision of the input data; the more reliable and detailed the input data are, the more realistic and case-specific will be the energy estimation. Indeed, although the assumptions required by this kind of analysis at the building level may increase the uncertainties of results, at the same time the uncertainty of input data may cause bigger uncertainties than those involved by simplifications in the methodology (Frayssinet et al. 2018).

Additional data that I would suggest to collect and spatialize at the building level are: (a) information on energy retrofit measures already implemented, (b) real number of residents in the building, (c) number of dwellings not occupied or used as holiday houses, (d) commercial or other kind of activities located in the building. As future developments of the Ph.D. thesis on the estimation of the space heating demand, some issues should be addressed: (A) taking into account the users' behaviour within BSA since it is demonstrated to have influence on the energy consumption; (B) better validating the estimation of the space heating demand by including and combining measured data on the energy consumption at the same level of analysis; (C) assessing the impact on the thermal demand of different energy refurbishment measures applied to the buildings; (D) adding the calculation of DHW and electricity energy demand to the space heating one.

4.2 Spatial Financial Feasibility of Shallow Geothermal Energy

As introduced in Section 3.5.2, the evaluation of the technical and financial suitability of SGE closed and open-loop solutions for covering the energy demand of the buildings and replacing, as much as possible, fossil energy sources within H&C systems was done by means of some economic indicators, i.e. mean Discounted Payback Period – DPP and technology-related Levelized Cost Of Energy – LCOE. The financial comparison was performed between SGE plants and conventional technologies (natural gas and heating oil boilers). For each residential building SGE plant was also combined with solar rooftop photovoltaic (PV) panels and national subsidies for increasing the energy efficiency of buildings.

The applied subsidies in this analysis were taken from the Italian Ministerial Decree 16/02/2016 (GSE 2016); when applied, 65% of the capital costs for the whole closed/open-loop SGE system was subtracted. As described in Section 3.5.2, roof areas where the annual solar direct radiation was greater than the 75th percentile of the distribution of the direct solar radiation were considered covered by a PV system (1 KW for 7 m^2). When rooftop solar PV systems have been implemented, their contribution was evaluated by means of an LCOE of 0.09 € (E Vartiainen, G Masson, and C Breyer 2015) for each kWh produced. In this way, PV investment costs were taken into account although they were not directly considered in the calculation.

For the Valle d’Aosta region, all the possible combinations were considered and compared (GRETA project 2018c), as in the following list:

1. Closed-loop (GSHP) with both subsidies and rooftop PV systems;
2. Closed-loop without subsidies and with rooftop PV systems;
3. Closed-loop with subsidies and without rooftop PV systems;
4. Closed-loop without subsidies nor rooftop PV systems;
5. Open-loop (GWHP) with both subsidies and rooftop PV systems;
6. Open-loop without subsidies and with rooftop PV systems;
7. Open-loop with subsidies and without rooftop PV systems;
8. Open-loop without subsidies nor rooftop PV systems.

It is worth mention that the number of open-loop plants was very lower than the number of closed-loop plants due to the smaller extension of the open-loop input dataset. The results of the financial analysis for the case study area showed that there is a clear positive influence of subsidies over LCOE values for SGE closed-loop systems (in Figure 4.5, a and b versus c and d). In general, the combination of natural gas boiler and air conditioning system (ACS) was always more convenient than the combination of heating oil boiler and ACS. Considering that the conditions were supposed to be the same, this result is justified by the higher annual costs for the systems with heating oil boiler plus ACS, especially due to the high cost of the heating oil fuel. The same output was recorded for SGE open-loop examples. All these results and further information can be found in one deliverable of the GRETA project (GRETA project 2018c).

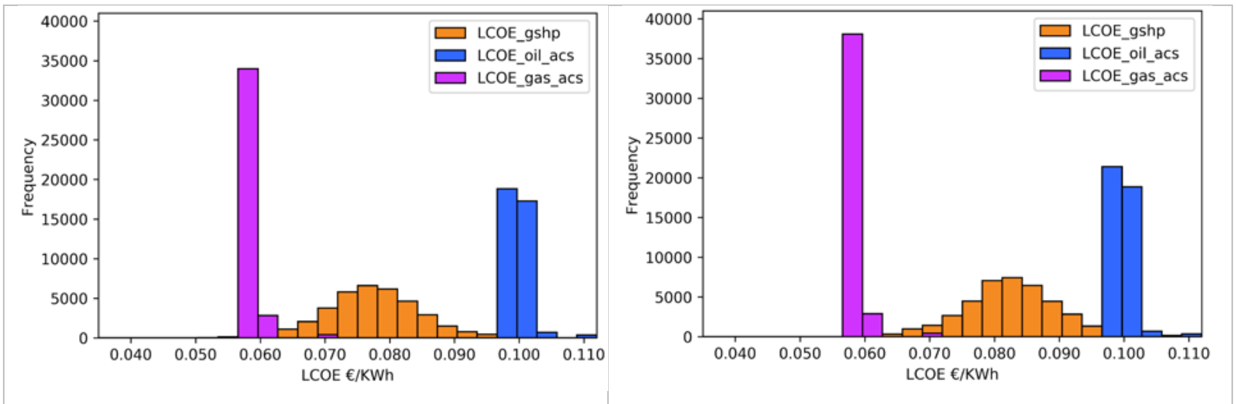

Figure 4.5a: *including* solar rooftop PV systems, *excluding* subsidies.

Figure 4.5b: *excluding* both solar rooftop PV systems and subsidies.

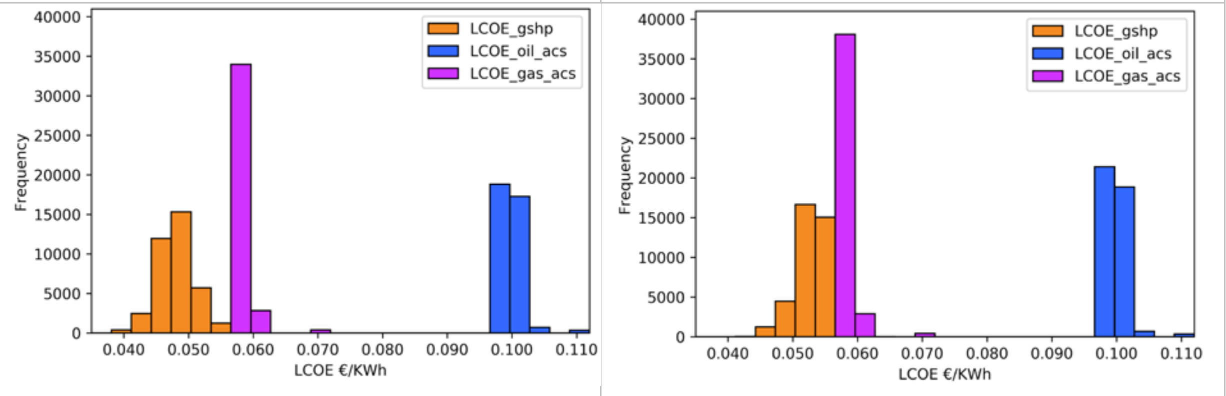

Figure 4.5c: *including* both solar rooftop PV systems and subsidies.

Figure 4.5d: *excluding* solar rooftop PV systems, *including* subsidies.

Figure 4.5: LCOE (€/kWh) histograms for natural gas boiler plus ACS (gas_acs, in violet), heating oil boiler plus ACS (oil_acs, in blue), and the four closed-loop SGE cases (in orange) for Valle d'Aosta: without subsidies and with PV systems (Figure 4.5a), without subsidies nor PV systems (Figure 4.5b), with both subsidies and PV systems (Figure 4.5c), with subsidies and without PV systems (Figure 4.5d). Source: EURAC for GRETA project.

The results underlined the importance of Italian subsidies for the financial convenience of geothermal HP plants. Indeed in case of their lack, the combination of natural gas boilers and ACS was usually associated with a lower LCOE (that is more convenient). The coupling use of geothermal HP with solar PV systems also resulted to have a positive influence on DPP and LCOE values of SGE systems. However, the real discriminant factor was constituted by the application of subsidies, since solar PV systems were only able to produce a small reduction of both LCOE and DPP values (see Figure 4.6). As already said, an extensive discussion about the outputs of the spatial-based financial analysis and more details on the assumptions considered in the analysis can be found in one deliverable of the GRETA project (GRETA project 2018c).

As well as before, these outputs are published in the WebGIS of the GRETA project at the following link: http://greta.eurac.edu/maps. The following Figure 4.6 represents one of these maps, where the heating system with the minimum value of LCOE for each building is identified. In addition, the web-tool mentioned in Section 3.3 allows the user also to assess the main financial figures, comparing the different heating systems.

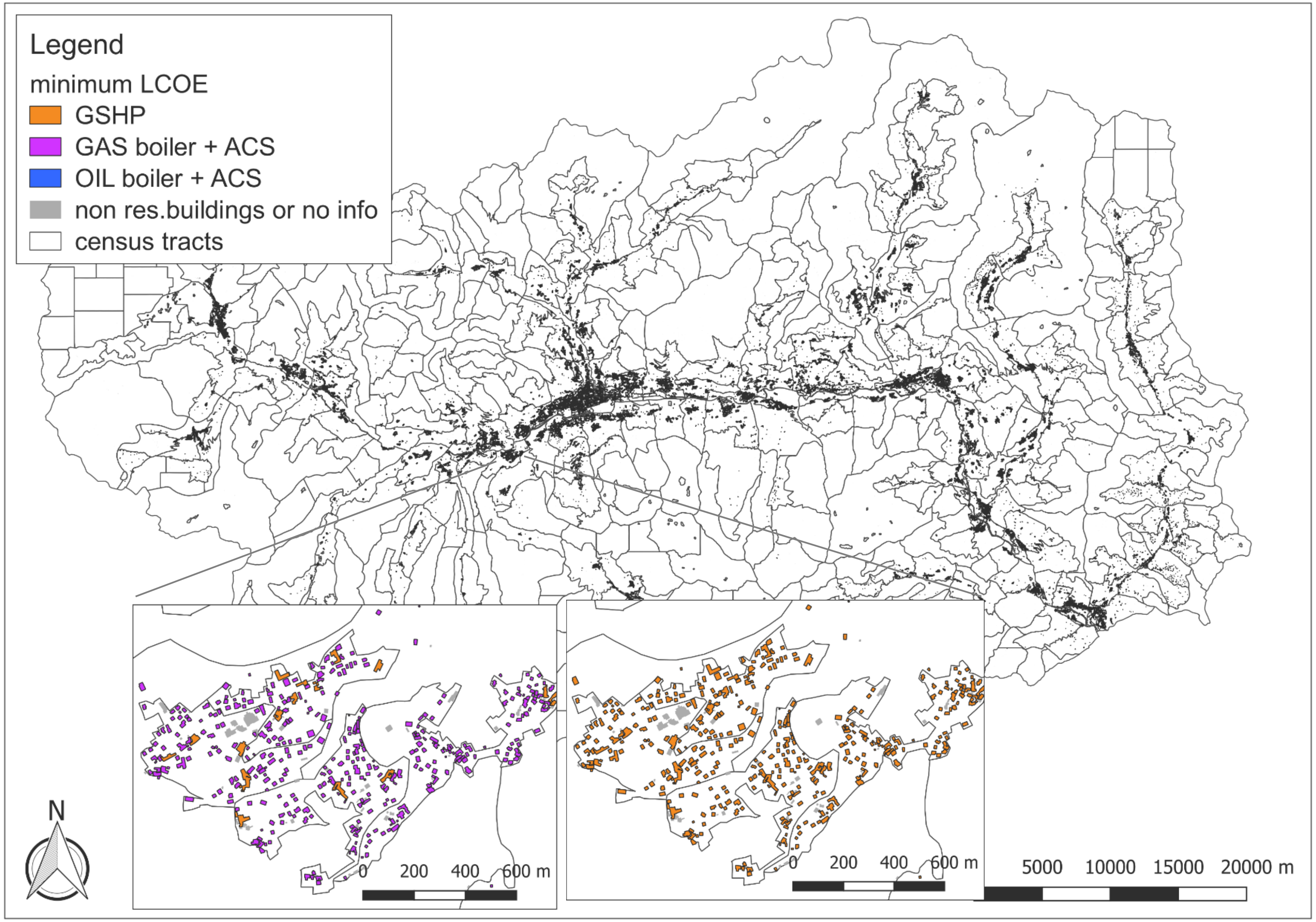

Figure 4.6: Map of the minimum LCOE value per building considering the combinations GSHP and PV (left), GSHP and PV plus subsidies (right); in the zooms an extract of Aymavilles municipality. Source: EURAC for GRETA project, Thesis 2019.

4.3 Spatial Suitability Analysis of SGE installations

As explained in Section 3.5.3, the spatial suitability analysis aimed at estimating the maximum number of SGE systems that can occur at the same time in the case study area, minimizing the risk of interferences among different installations or between SGE plants and some areas with special environmental constraints regarding water resource, i.e. water protection areas and areas close to water bodies. The results showed that 83% of the total thermal demand of residential buildings in Valle d'Aosta can be covered by SGE source, corresponding to 93% of the heated surface.

Imagining to replace only LPG and heating oil boilers (as we will see in Section 4.4.1 about the development of scenarios), that is where SGE can have the greatest environmental and financial advantages, SGE systems would be able to cover around 39% of the total energy demand of the residential buildings in Valle d'Aosta. In Figure 4.7 the output of the spatial suitability analysis is presented for an extract of the residential buildings of the case study. Further information on this analysis can be found in the deliverable of the GRETA project (GRETA project 2018c).

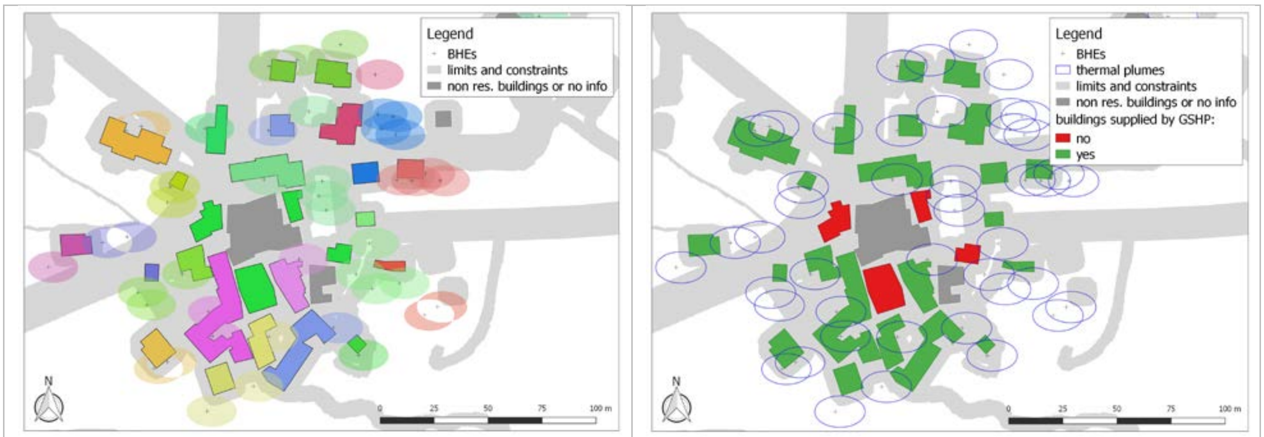

Figure 4.7a: buildings with closed-loop SGE systems and related thermal plumes, calculated considering the energy demand of the buildings. The colours of the buildings and of the thermal plumes are the same.

Figure 4.7b: buildings classified as potentially supplied by closed-loop SGE system or not. Buildings in red cannot be supplied by a closed-loop SGE system for one of the reasons explained in Section 3.5.3.

Figure 4.7: Maps of the spatial suitability for closed-loop plants in Valle d'Aosta; extract of a hamlet in Verrayes municipality. Source: EURAC for GRETA project.

4.4 Development of Sustainable Energy Scenarios

As described in Section 3.5.6, the development of scenarios for the energy system of the Valle d'Aosta region was aimed at suggesting sustainable pathways for the energy transition of the case study toward a *Smart Energy Region*. All the elements considered in the construction of these scenarios were taken from the previous analyses (i.e. space heating demand of buildings, financial analysis and spatial suitability of SGE systems, comparison between energy planning and spatial planning objectives, etc.) and combined with the strategic objectives formulated for the case study area (see again Section 3.5.6).

The basic structure for the construction of scenarios is represented in Figure 3.9, where the two driving forces that will influence the development of the regional energy system in the future were identified in: 1) using shallow geothermal energy for supplying the space heating demand of the buildings, replacing as much as possible the fossil fuels; 2) refurbishing part of the residential building stock for decreasing the thermal demand. Different combinations of these two drivers shaped the developed scenarios, which were then compared through some indicators:

- Heated surface involved [m^2];
- GHG emissions saved [tCO_2 equivalent];
- Costs of replacement of heating system with HP [M€];
- Cost of energy renovation of buildings [M€];
- Electrical consumption for HP utilisation [MWh].

The formulated scenarios were divided into two sections. In the first one, it was imagined that SGE will supply the space heating demand of a part of the residential buildings, partially replacing some fossil fuels, without applying any renovation measures. The buildings considered in the scenarios are those considered in the spatial financial analysis that have a value of estimated space heating demand smaller than 50 kWh/m^2 per year and are located in census tracts where LPG, heating oil and natural gas are used as fuels for the primary heating system.

The value of 50 kWh/m^2 represents also our target for the refurbishment measures (considered in the second scenario section) and is equivalent to the class B in the energy certification system. This threshold was chosen because the buildings below it should be quite efficient (given the medium-low demand) and would be possible to install in them a geothermal HP that works with low temperatures. The information on the fuel for the primary heating system was instead derived analysing ISTAT data of Census 2011 (ISTAT 2011) about the heated surface with different fuels per period of construction of the buildings (see Section 3.3.1-D).

From the considered building stock, the buildings that fell in areas where environmental interferences and hazards for the installation of SGE systems were detected (GRETA project 2018a) were excluded. These areas not suitable for the installation of SGE plants in Valle d'Aosta were: mining areas, cavities, landfills and contaminated sites; evaporites and anhydrides; landslides; karst; multiple and artesian aquifers. A map about the localisation of these areas can be found in the GRETA WebGIS (http://greta.eurac.edu/maps).

4.4.1 Replacement of Heating Systems

In the first section, two different scenarios were developed for the buildings with a value of space heating demand smaller than 50 kWh/m^2 per year:

1. ***S1***: to replace LPG and heating oil plants (that is where SGE can have the greatest environmental and financial advantages) with geothermal HP;
2. ***S2***: to replace some natural gas plants and in particular those where the comparison performed in the financial analysis among DPP values between SGE coupled with PV panels and subsidies versus natural gas boiler and ACS was less than 15 years.

In the S2 scenario, the combination of the geothermal HP with PV panels and subsidies was considered because this is the only combination in which SGE would be economically convenient compared to the natural gas option (see also Section 4.2). Furthermore, in this scenario the geothermal HP is deemed to be used as the primary heating system and the natural gas boiler as the secondary one, to cover the peaks, as the infrastructure for natural gas would remain active even if the heating system changed.

For these two scenarios, the greenhouse gas emissions saved due to the partial replacement of fossil fuels with SGE were calculated by using IPCC emission factors (Joint Research Centre 2017) for the different energy sources (Table 4.2). In particular, the difference was calculated between the emissions of fossil fuel plants (LPG/heating oil and natural gas) and the emissions of the imagined electrical geothermal HP installed to cover the same space heating demand of the buildings.

Mean values for the energy efficiency of the heating systems were taken from the Italian Inter-ministerial Decree 26/06/2015 on the update of national guidelines for the energy certification of buildings (Ministero dello Sviluppo Economico 2015) to convert the total space heating demand of each building in energy consumption (Table 4.3) and then in GHG emissions. The total emissions in Valle d'Aosta in 2010 were taken from REEP (Regione Autonoma Valle d'Aosta 2012) and considered as the starting point for the calculation of the saved emissions.

Table 4.2: Standard emission factors for different fuels. Source: JRC, 2017.

fuel	***emission factors (tCO_2_eq/MWh)***
heating oil, LPG	0.2475
natural gas	0.202
electricity	0.344

Table 4.3: Mean energy efficiency of different heating plants. Source: MD 26/06/2015.

fuel	***mean energy efficiency***
heating oil, LPG	0.82
natural gas	0.95
geothermal HP (SPF)	4.00

The increase in electricity consumption due to the installation of geothermal HP was evaluated as well. Also in this case, the total electricity consumption in the Region in 2010 was taken from REEP (Regione Autonoma Valle d'Aosta 2012) and considered as the starting point. Concerning CO_2 emissions and electricity consumption, one has to bear in mind that the Valle d'Aosta region is already 100% renewable for the electricity production thanks to the hydropower source. Therefore, an increase in the electrical energy use inside the Region would have "negative" effects on the national CO_2 balance but not in the regional context. On the contrary, the Region would use more a local energy source instead of buying fossil fuels from outside (LPG, heating oil and natural gas). In this way, the overall sustainability of Valle d'Aosta would increase in terms of energy self-sufficiency.

Concerning the costs, the capital and operative costs were estimated in the spatial financial analysis (GRETA project 2018c) and used as input in the scenario development. Within the capital costs, the investment for HP and the drilling works were considered; the capital cost estimation took into account a 40% increase of the estimated costs for excavation and HP to overcome the high variability of the analysed cases (see also Section 3.5.2). Within the operative costs, the cost of electricity and maintenance of the system were instead considered.

4.4.2 Renovation of Buildings and Replacement of Heating Systems

For the second section of scenario development, the residential building stock was supposed to be partially refurbished for decreasing the total space heating demand. At the same time, as before, SGE systems were imagined to be installed in the renovated buildings in place of fossil fuel plants. In this case, other two scenarios were developed taking into account the buildings not involved in the previous scenarios, i.e. those with a value of estimated space heating demand greater than 50 kWh/m^2 per year. Indeed, these buildings must be refurbished before thinking to install a geothermal HP system.

In particular, the multi-family houses (MFH) were considered as the buildings with 3, 4 or 5 floors and the single-two-family houses (SFH) as the buildings with 1 or 2 floors and the heated surface between 25 m^2 and 200 m^2. Among these buildings, only those built between 1946 and 1980 that are usually less efficient were took into account. As mentioned, in addition to the energy renovation of the buildings, the replacement of the heating systems with a geothermal HP was considered, as in the previous two scenarios.

The two scenarios were in line with the ones described in the first scenario section but for the buildings with a value of space heating demand greater than 50 kWh/m^2 per year and they were:

3. ***S3***: to refurbish the buildings (MFH and SFH) where LPG and heating oil are used as fuels for the primary heating system and then replace the fossil fuel plants with a geothermal HP;
4. ***S4***: to refurbish the buildings (MFH and SFH) where natural gas is used as fuels for the primary heating system (as before, only when the comparison among DPP values between SGE coupled with PV panels and subsidies versus natural gas boiler and ACS is less than 15 years) and then replace the fossil fuel plants with a geothermal HP.

In these scenarios, the reduction of GHG emissions was calculated as the combination of the emissions saved due to the energy refurbishment measures (lower space heating demand) and those saved due to the replacement of fossil fuel plants with SGE systems. As well as before, the capital and operative costs were estimated with the financial analysis procedure (GRETA project 2018c), this time starting from the lower space heating demand of the buildings. Within the capital costs, the investment for HP and the drilling works were considered; within the operative costs, the cost of electricity and maintenance of the system were instead considered.

In addition, the total investment costs for the energy renovation of the selected buildings were calculated. The data on energy renovation costs (in €/m^2) were taken from the outputs of the iNSPiRE project. iNSPiRE was a 4-year EU-funded project whose main objective was to tackle the problem of high energy consumption in the building sector by producing systemic renovation packages that can be applied to residential and tertiary buildings. The renovation packages developed by the project aim to reduce the primary energy consumption of a building to lower than 50 kWh/m^2 year[6].

It is noteworthy that the buildings considered in these two refurbishment scenarios are equivalent to more than one-quarter of the entire analysed building stock (around 27%). The four developed scenarios are represented in Figure 4.8 and Figure 4.9 and compared through the chosen indicators. While in Figure 4.10, the four scenarios are represented considering the cumulative sum of heated surface (x-axis), GHG emissions saved (first y-axis), and total costs (second y-axis) for each scenario. The buildings were previously ordered according to the ratio between CO_2 equivalent saved and total investment costs; so the first buildings on the x-axis are those where with the same amount of money one can obtain a bigger amount of GHG emissions saved.

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[6] http://inspirefp7.eu/

Figure 4.8a: heated surface involved (m^2) in the 4 scenarios.

Figure 4.8b: GHG emissions saved (tCO_2_eq) in the 4 scenarios.

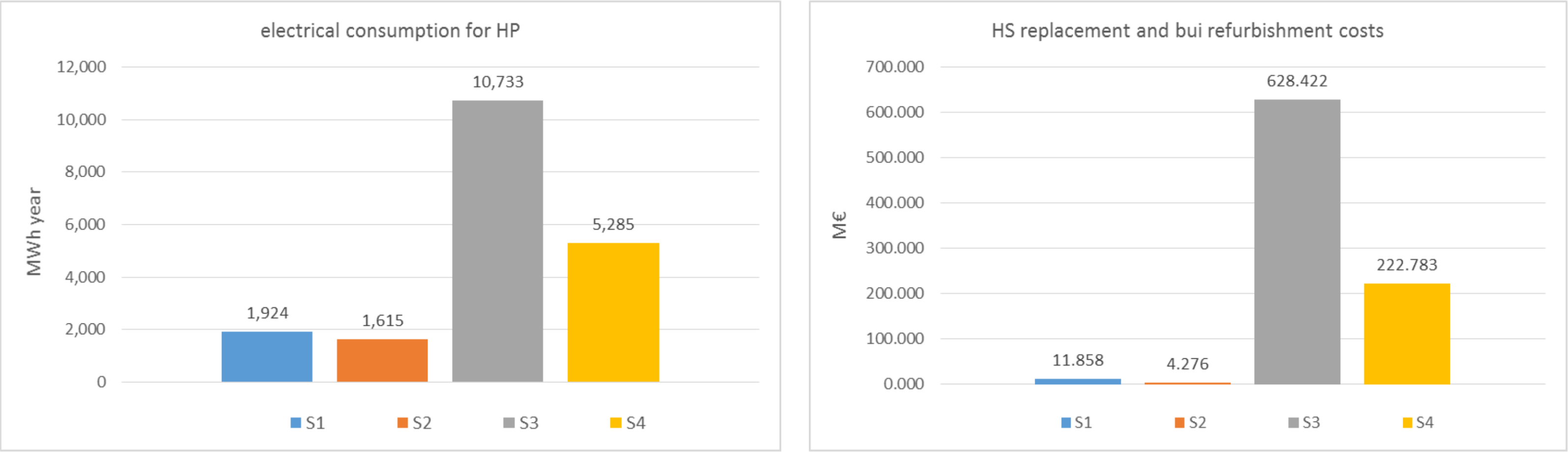

Figure 4.8c: increase of electrical consumption (MWh) in the 4 scenarios.

Figure 4.8d: total costs (building energy refurbishment and/or heating system - HS replacement) (M€) in the 4 scenarios.

Figure 4.8: Comparison among the four scenarios developed for the energy system of Valle d'Aosta. Source: Thesis 2019.

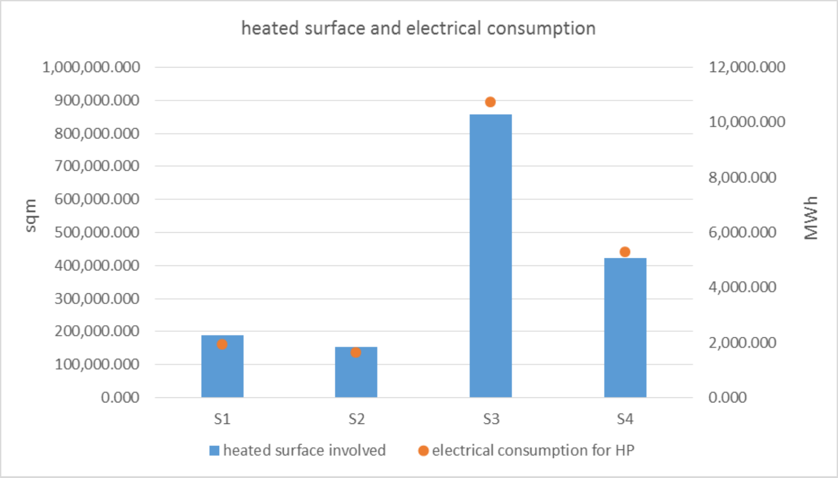

Figure 4.9a: heated surface involved (m^2) and electrical consumption (MWh).

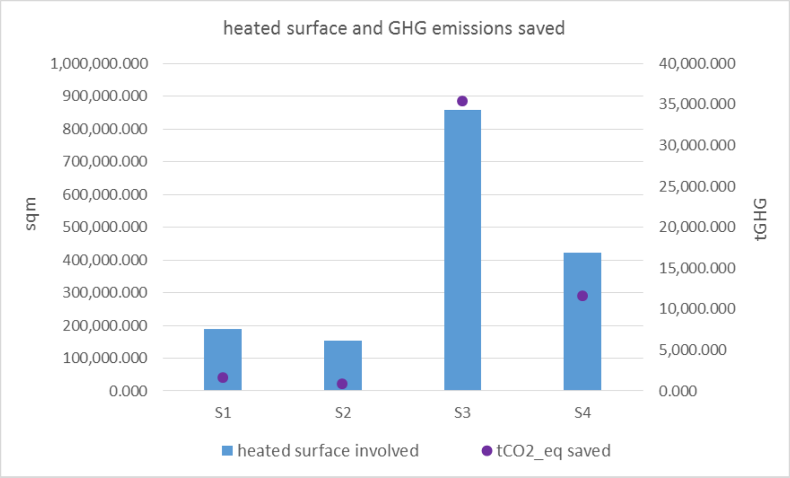

Figure 4.9b: heated surface involved (m^2) and GHG emissions saved (tCO_2_eq).

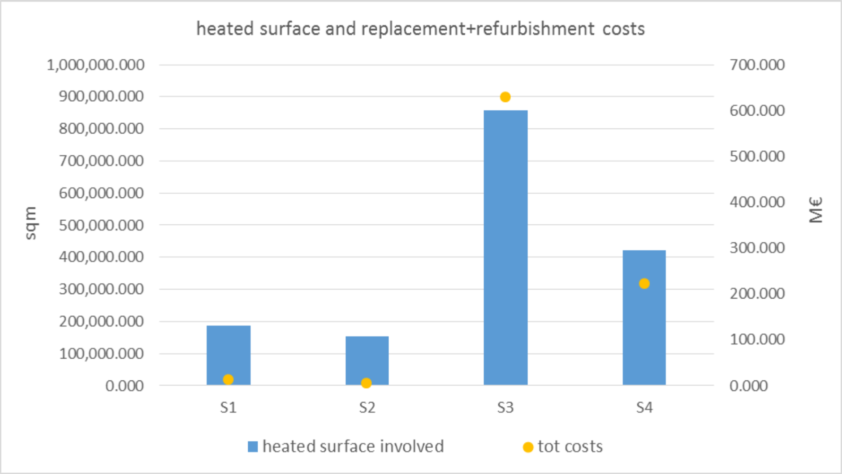

Figure 4.9c: heated surface involved (m^2) and total costs (M€).

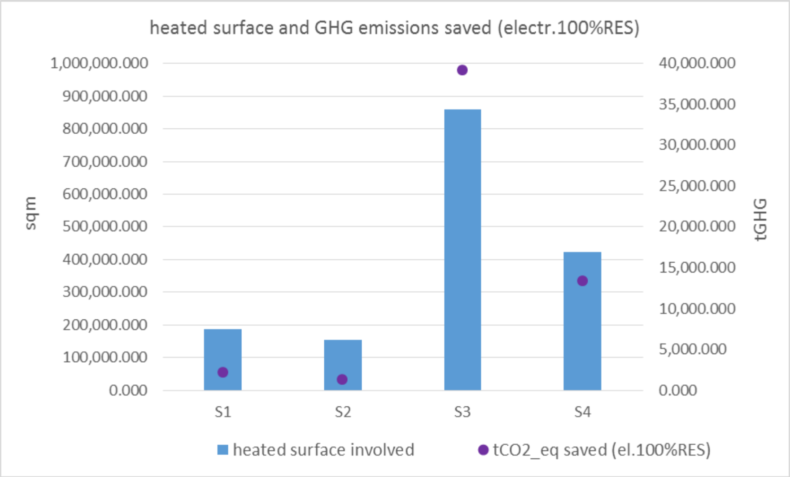

Figure 4.9d: heated surface involved (m^2) and GHG emissions saved (tCO_2_eq) considering the electricity as 100% renewable.

Figure 4.9: Comparison between two indicators for the four scenarios developed for VdA energy system. Source: Thesis 2019.

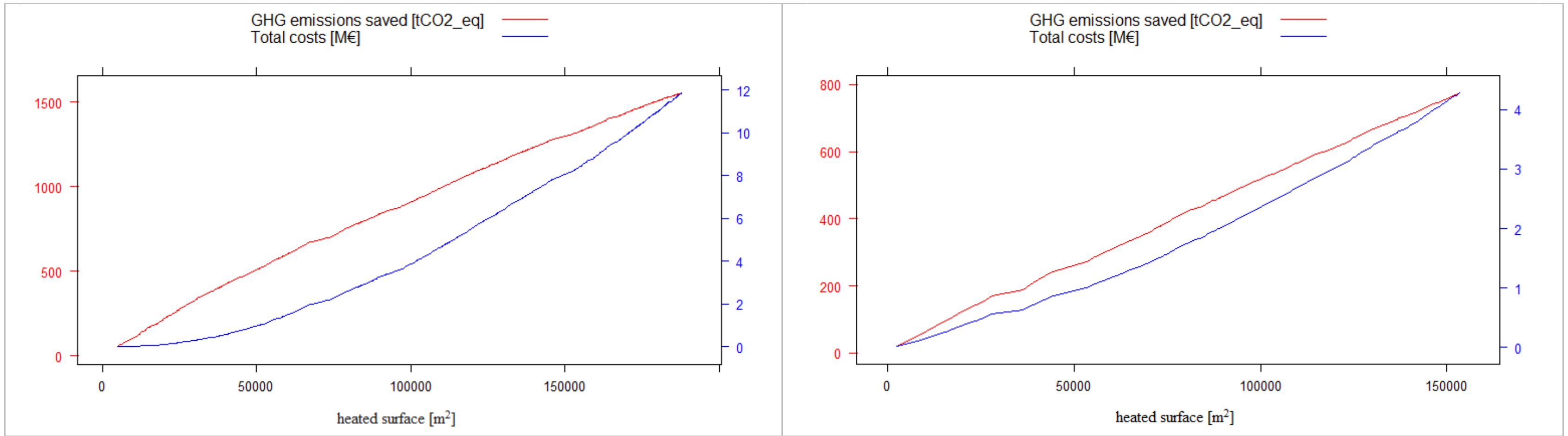

Figure 4.10a: cumulative sum of heated surface (m^2), GHG emissions saved (red, tCO_2_eq) and total costs (blue, M€) for ***S1***.

Figure 4.10b: cumulative sum of heated surface (m^2), GHG emissions saved (red, tCO_2_eq) and total costs (blue, M€) for ***S2***.

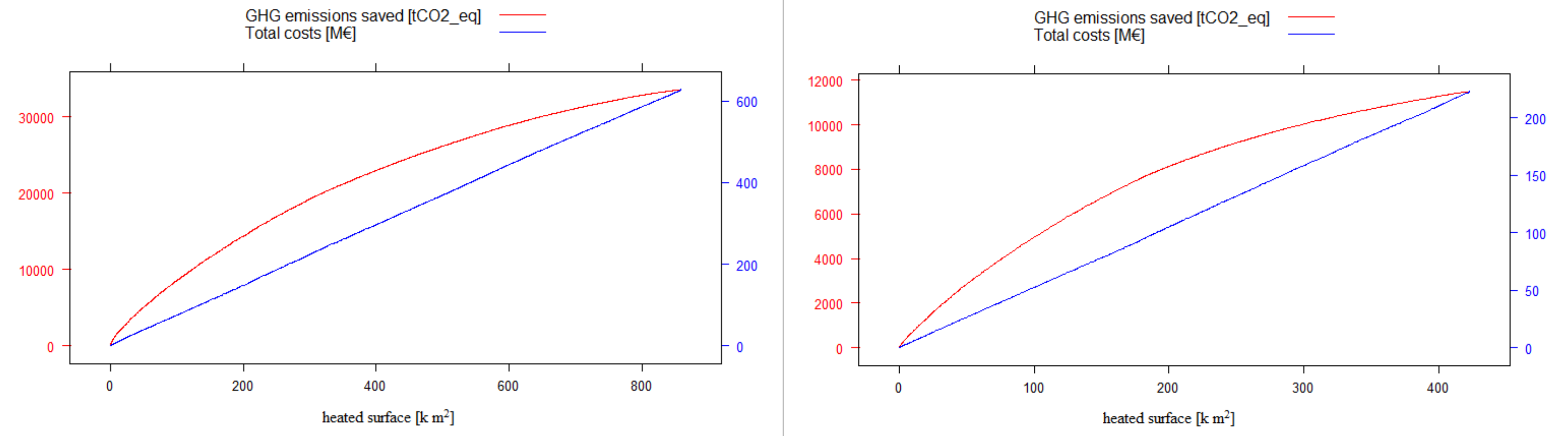

Figure 4.10c: cumulative sum of heated surface (km^2), GHG emissions saved (red, tCO_2_eq) and total costs (blue, M€) for ***S3***.

Figure 4.10d: cumulative sum of heated surface (km^2), GHG emissions saved (red, tCO_2_eq) and total costs (blue, M€) for ***S4***.

Figure 4.10: Comparison among the four scenarios considering the cumulative sums of surface, GHG emissions, and costs. Source: Thesis 2019.

4.4.3 Strengths, Weaknesses and Future Developments

As clearly represented in Figures 4.8, the third scenario is the most impactful in terms of residential heated surface involved, GHG emissions saved, but also increase of electricity consumption and total costs (energy renovation and/or heating system replacement). This is due to the fact that the buildings built between 1946 and 1980, with a value of space heating demand greater than 50 kWh/m^2 per year, and where LPG and heating oil are used as primary fuels represent a relevant part of the analysed building stock (around 21%). Overall, the first two scenarios, which consider the buildings with lower space heating demand, do not have a significant effect on the status quo (in particular on GHG emissions, see Figure 4.8b). While, the second two scenarios are more impactful, also because they involve energy renovation measures for several buildings (about 21% of the total in S3 and about 6% in S4).

Looking at Figure 4.9, one can see that the discriminant factor for the reduction of GHG emissions is the refurbishment of the buildings. Indeed, the electrical consumption increases in each scenario due to the replacement of conventional heating systems (based on fossil fuels but not on electrical machines) with a geothermal HP (Figure 4.9a). Therefore, the contribution to GHG emissions saving given by the modification of the heating system from a fossil one to a renewable one is lightly weakened due to the increased energy consumption. This happens both if Valle d'Aosta is not considered to be already 100% renewable for the electricity production (as already mentioned in Section 4.4.1) (Figure 4.9b) and also if the GHG emissions from geothermal systems are calculated as null (Figure 4.9d). In the latter case, the values of GHG emissions saved in S1 and S2 are a bit higher but not really influential.

What changes in scenarios S3 and S4 is the reduction of the space heating demand (from values above 50 kWh/m^2 per year to this threshold), which clearly has more effect on the cutting of GHG emissions. Despite the fact that, in general, the heated surface and the space heating demand of the residential buildings were overestimated in the studied area (see Section 4.1.1), from this study the energy renovation of the building sector is confirmed to represent a great opportunity for reaching the energy saving targets and the reduction of GHG emissions. Therefore, the replacement of fossil fuels with RES for the heating systems should be combined with interventions aimed at decreasing the space heating demand of the residential building stock. In this way, one will be able to foster a sustainable energy transition (at regional, national and European scale).

Concerning the graphs in Figure 4.10, one can see that the Valle d'Aosta region should intervene with policies and/or subsidies for the replacement of heating systems and the energy renovation of buildings earlier on the buildings where the ratio kgCO$_2$/€ is higher to have the strongest impact on the reduction of GHG emissions. To explain better this recommendation, in Figure 4.11 an example regarding the scenario S3 is represented. In this case, 4% of the residential building stock is supposed to be refurbished yearly (as established in REEP (Regione Autonoma Valle d'Aosta 2012)) and, in the same buildings, the heating system is supposed to be replaced from LPG or heating oil boiler to geothermal HP.

After 5 years, 20% of the heated surface would be renovated and around 12,700 ton of GHG emissions would be saved with an investment of around 125 million euros. After 10 years, with the 40% of heated surface refurbished, the investment would double (around 256 M€) but the GHG emissions saved would be lower than the double (around 21,000 ton). Thus, maybe the best solution (from a financial viewpoint) would be in the middle between 20% and 40% of heated surface renovated. Of course, this is a decision that the policy-makers of Valle d'Aosta should discuss and it also depends on several factors, not only on the financial aspect. However, the proposed SDSS can help during the decision-making process allowing to analyse from various viewpoints the different alternatives and also to localise where is better to address the energy measures. Indeed, as shown in Figure 4.12, thanks to the spatial-based approach, it is possible to specify also which buildings represent the 20% or 40% of the heated surface with the best ratio between GHG emissions saved and investment costs.

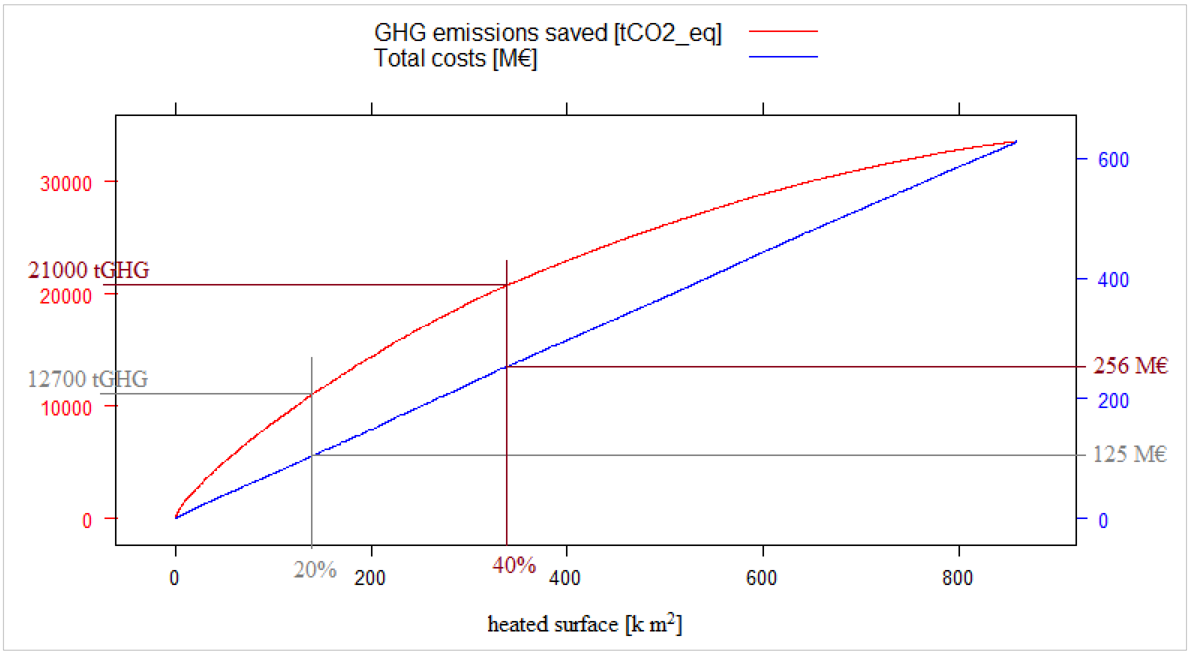

Figure 4.11: Example from S3; GHG emissions saved and total costs imagining to intervene (with HS replacement and building refurbishment) yearly on 4% of the heated surface for 5 or 10 years. Source: Thesis 2019.

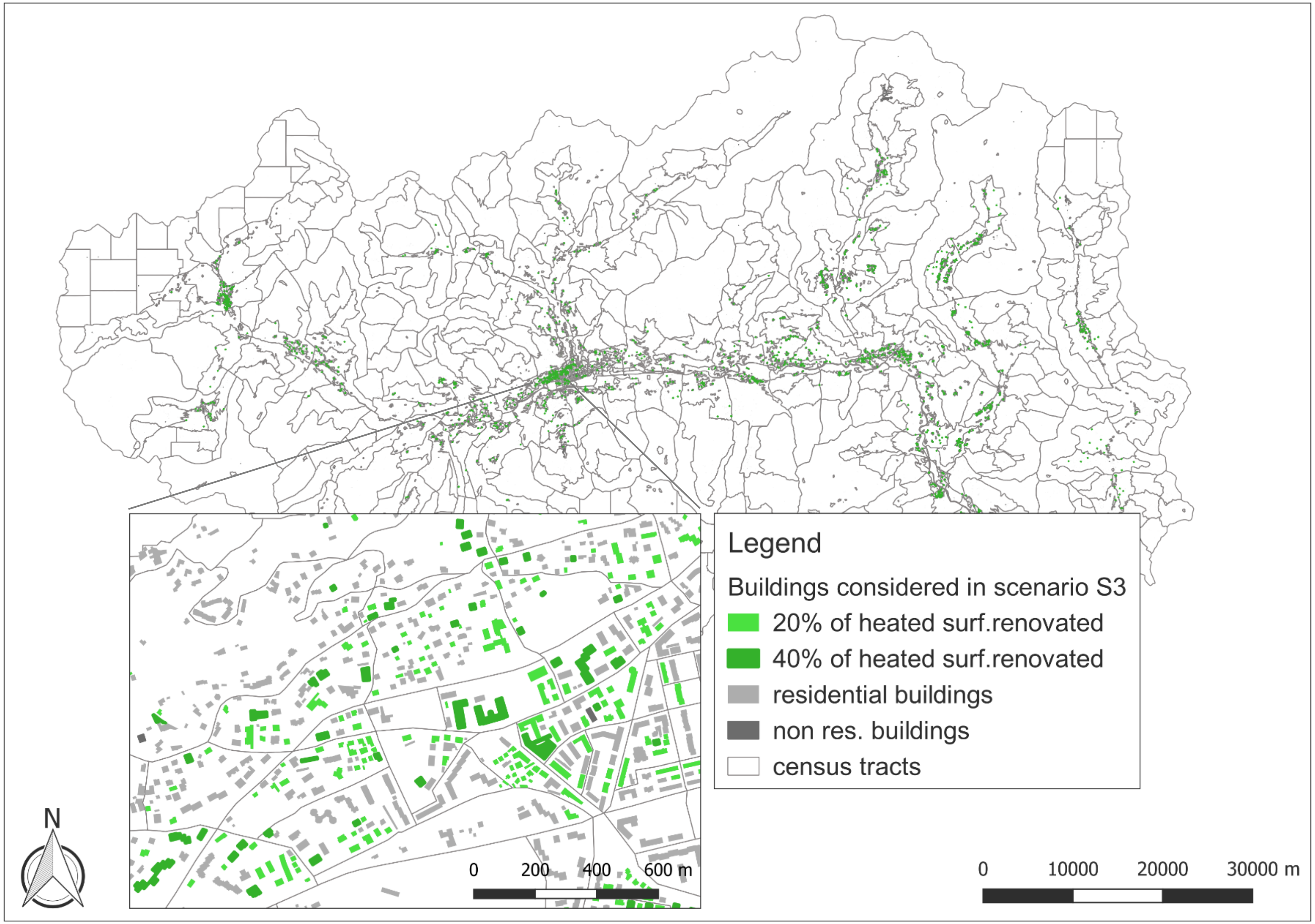

Figure 4.12: Example from S3; map of buildings ordered by $kgCO_2\_eq/€$ and included in the 20% and 40% of the heated surface involved. In the zoom an extract of Aosta municipality. Source: Thesis 2019.

In the end, even though in the case study the use of biomass as heating fuel in the residential sector is quite relevant (representing about 48% of the total households and mainly used for the secondary heating system – see Section 3.1.2), the biomass was not considered in the developed scenarios. This choice was done because the use of biomass is widespread in the alpine territories and, at the same time, the amount of harvested biomass is not easily traceable due to the large availability of this resource in private woods. For these reasons, it would not be reasonable to replace the biomass plants with a geothermal HP for the residential heating in Valle d'Aosta, considering also the very low cost of this resource when available in owned woods. This kind of heating systems are supposed to continue to be used as secondary heating plants, for covering the peaks (as it is currently, according to (Regione Autonoma Valle d'Aosta 2013).

This part of the methodology on the scenario development inherited all the limitations of the previous steps, as the starting points are the estimation of the space heating demand of the buildings and the spatial financial feasibility of SGE potential for covering this demand. In addition, the thesis would be an example of how this kind of analysis can support a decision-making process when an energy plan/strategy should be updated or developed. The choice of the criteria to be used to evaluate the scenarios should be done by the local stakeholders and/or decision-makers (as planned in the next steps). Another aspect worthy to be explored is the analysis of the different measures proposed on the basis of their effectiveness in promoting a sustainable energy transition. In this thesis, the focus was not on how to implement the strategic actions for the heating plant replacement and building refurbishment. Even though this is not the focus of this work, it can certainly be a next step.

The future developments of the Ph.D. thesis on the formulation of sustainable energy scenarios for the case study are:

- ✓ Making the process interactive and more structured as a tool (now is defined more as a methodology);
- ✓ Diversifying the refurbishment interventions for different kind of buildings (dividing them according to relevant criteria) and/or defining an annual refurbishment rate for both the replacement of heating systems and the energy renovation of buildings;
- ✓ Performing a cluster analysis for gathering together similar municipalities (according to relevant criteria) and then develop different scenarios for each cluster;
- ✓ Performing a spatial multi-criteria evaluation of the scenarios (Pohekar and Ramachandran 2004) involving the local stakeholders in the weighting system of the considered variables.

4.5 Integration of Energy Planning and Spatial Planning

4.5.1 Formulation of Coordinated Objectives

In Section 3.5.5, the comparison among the current energy planning and spatial planning objectives of Valle d'Aosta was performed. This analysis was aimed at identifying possible gaps to be filled in the coordination of energy planning and spatial planning goals. The objectives of the Regional Energy and Environmental Plan (REEP), on one side, and of the Regional Spatial and Landscape Plan (RSLP), on the other side, were analysed and compared to highlight conflicts or need to improve the connection with new objectives. RSLP is not really recent since it was developed in 1998; REEP instead was published in 2012 but the Valle d'Aosta Region is intending to update it in 2020 (author's note).

Table 4.4 represents the comparison among the objectives set by the two plans as improved according to our analysis and results presented in the previous sections. If compared with Table 3.8, one can see that the potential conflicts or need to increase the connection between energy planning and spatial planning objectives were solved (in blue in the table). The main contrast found was the willingness to improve the network for the distribution of natural gas in the whole Valle d'Aosta (Regione Autonoma Valle d'Aosta 1998). This objective was in contrast with the targets of increasing the energy production from RES and reducing the CO_2 emissions. Therefore, the “new” spatial planning targets focused on the replacement of all the fossil fuels, including the natural gas, for building a high-efficiency supply system and on energy efficient measures for the existing residential building stock.

Table 4.4: Comparison among hypothetical new energy planning and spatial planning objectives of Valle d'Aosta. Source: Thesis 2019.

		NEW REGIONAL SPATIAL and LANDSCAPE PLAN – Energy and buildings-related objectives (by 2050)					
		reduction of energy consumption and increase in self-sufficiency	production from RES in all the settlements	high-efficiency energy supply (DHN, HP) in all the valleys	energy saving, diversification of sources, increase in energy supply from HP	energy renovation and reuse of existing building stock	energy-efficient measures in areas to refurbish or targeted for new buildings
NEW REGIONAL ENERGY and ENVIRONMENTAL PLAN – Specific objectives (by 2050)	targets for electric and thermal energy production from RES	☑	☑	☑	☑	☑	☑
	targets for reduction of energy consumption	☑	Indirect	☑	☑	☑	☑
	targets for increase in energy efficiency in different sectors	☑	Indirect	☑	☑	☑	☑
	reduction of CO_2 emissions	☑	☑	☑	☑	☑	☑

4.5.2 Integration of Ph.D. Outputs in SEA Framework

As introduced in Section 2.4, according to the European Directive 2001/42/EC (European Parliament 2001) Strategic Environmental Assessment is mandatory for plans, programmes, and policies in different sectors, among those energy planning and spatial planning, for the assessment of their environmental impacts in a medium/long term view. SEA relevance as a way to support the decision-making process in both the energy planning and spatial planning sector is also demonstrated by several studies on the application of SEA in different fields (see Section 2.4.1). Since one of the main purposes of SEA is to integrate sustainability issues in the decision-making process, the energy issues can be easily encompassed into the sustainability aspect. Furthermore, SEA is a flexible framework where key elements can vary and act strategically in the decision-making process to ensure an added-value to the planning process (Multiple Authors 2015).

As we saw in Section 2.4.1, the main steps of SEA procedure can be summarised and represented (Figure 4.13) as follows (Partidario 2012):

1. Definition of sustainable objectives;
2. Formulation of alternatives (or strategic options) with targets and indicators;
3. Scenario analysis (opportunities and risks);
4. Environmental analysis: description of environmental baseline, prediction and evaluation of impacts;
5. Evaluation of scenarios;
6. Conclusions, follow-up measures: measures to mitigate the impacts, establishment of environmental guidelines, monitoring programme.

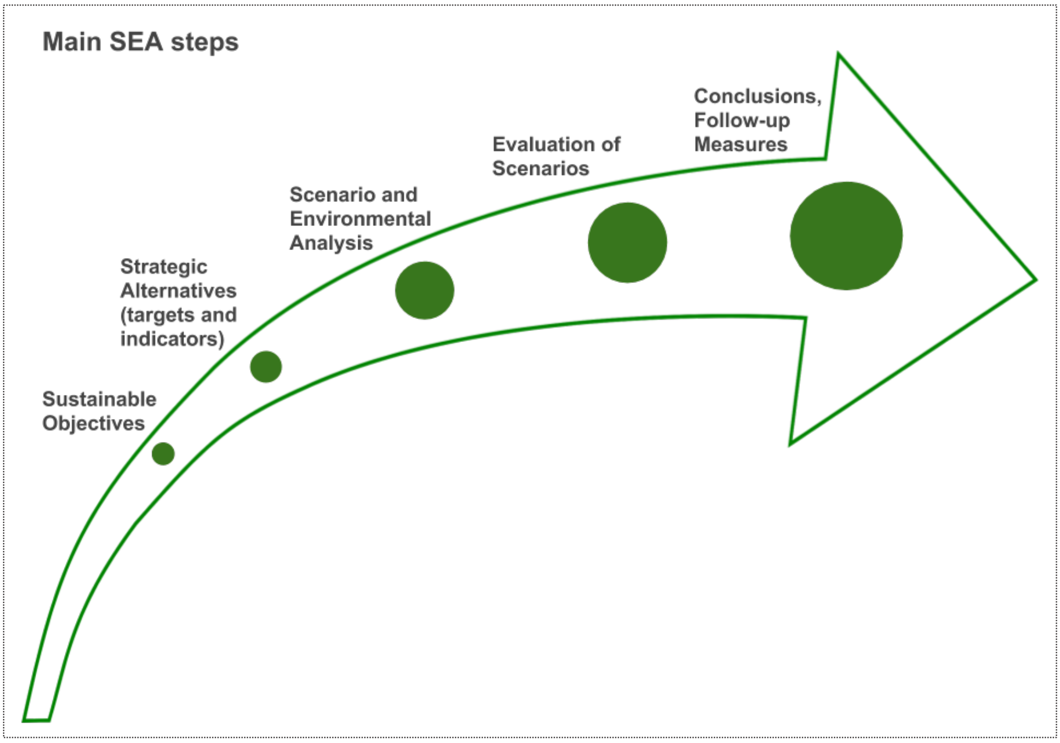

Figure 4.13: Principal phases of SEA process. Source: Inspired by EURAC for GRETA project.

As already stated, in this dissertation SEA is used as a methodology for connecting energy planning and spatial planning fields and for linking the thesis outputs to the energy decision-making process, rather than as an evaluation tool. However, the set of analyses and methods developed within the Ph.D. thesis can support local authorities of the case study in accomplishing some of the tasks requested by SEA Directive. In particular, they can be used to (see also (GRETA project 2018e)):

- identify feasible energy and sustainability targets and indicators, determining whether the objectives of the planned strategic actions are achievable or not;
- describe the energy and environmental baseline, supporting public bodies in overcoming possible data-gaps and/or in defining the context of the strategic actions;
- predict and evaluate the impacts, determining the effects of different energy strategies and alternative actions and highlighting possible mitigation measures;
- mitigate impacts, providing information and data to ensure that the strategic actions are sustainable and their impacts will be minimized.

The spatial resolution of analysis at the building level can aid the decision-makers in identifying different spatial patterns and highlighting local differences, which can require the development of dedicated actions. In our case, the spatial analysis performed at the building level can support the definition of concrete measures to foster both the adoption of SGE systems and the energy renovation of buildings. Particularly, it can be useful to develop incentive schemes and subsidies that effectively promote the favourite scenario, or to estimate the cumulative effects of a large adoption of SGE in the region. The analysis at the building level opens also several options for the evaluation of alternative scenarios, combining information about the available RES, as well as evaluating different refurbishment degrees of the building stock, or different supply system configurations (GRETA project 2018e).

In the following Table 4.5, the effort was made to connect the analysis performed within the Ph.D. thesis and the relative results with the main SEA steps, as listed above. This was inspired also by (Vettorato 2015) and done for emphasising how the developed methodology and the obtained outputs can be integrated into SEA procedure of a future regional plan (energy and/or spatial) of Valle d'Aosta. As one can see, the Ph.D. methodology and outputs can clearly support SEA implementation and be integrated into all its phases. I would like to remind also that the methodology for the integration of data from different sources and for its estimation if missing at the building level can be applied at different scales and potentially in every kind of context.

Table 4.5: Integration of Ph.D. analysis and outputs into the main SEA phases. Source: Thesis 2019.

SEA steps: **Thesis results:**	**1. Definition of sustainable objectives**	**2. Formulation of alternatives**	**3. Scenario analysis**	**4. Environmental analysis**	**5. Evaluation of scenarios**	**6. Conclusions, follow-up measures**
Spatial evaluation of space heating demand for each residential building	• Energy saving • Energy efficiency • Reduction of GHG emissions	Map of space heating demand at the building level				Map of space heating demand
Technical and financial suitability of SGE systems (*GRETA*)	• Diversification of sources for energy supply • Increase in energy self-sufficiency	Maps of LCOE comparison for SGE, natural gas and heating oil systems (*GRETA*)				Maps of LCOE comparison for SGE, natural gas and heating oil systems (*GRETA*)
Spatial suitability analysis of SGE systems (*GRETA*)	• Diversification of sources for energy supply • Increase in energy self-sufficiency considering environmental issues	Map of spatial suitability of SGE (*GRETA*)				Map of spatial suitability of SGE (*GRETA*)
Comparison among current objectives (energy, spatial) and definition of new ones	• Potential conflicts or common objectives between REEP and RSLP • New energy-driven and strategic objectives					New energy-driven and strategic objectives
Development of scenarios for the regional energy system			Different combination of replacement of heating system with geoth.HP & energy renovation of res. buildings			Different combination of replacement of heating system with geoth.HP & energy renovation of res. buildings

SEA steps: **Thesis results:**	**1. Definition of sustainable objectives**	**2. Formulation of alternatives**	**3. Scenario analysis**	**4. Environmental analysis**	**5. Evaluation of scenarios**	**6. Conclusions, follow-up measures**
Assessment of possible impacts on environment of SGE and other thermal RES				Magnitude, time, space of potential eviron. impacts		Magnitude, time, space of potential eviron. impacts
Indicators for analysing the scenarios					• GHG emissions saved • Increase in electricity consumption for geoth.HP • Operative and investment costs for SGE systems • Investment costs for energy renovation of res. buildings	• GHG emissions saved • Increase in electricity consumption for geoth.HP • Operative and investment costs for SGE systems • Investment costs for energy renovation of res. buildings

According to Table 4.5, several thesis outputs can be used to define the sustainable objectives in the first step of the SEA process. These objective may be: increase of energy saving and efficiency, reduction of CO_2 emissions, diversification of renewable sources for the energy supply, increase of energy self-sufficiency considering also environmental issues (in this case maximum density of SGE systems), identification of potential conflicts or commons objectives between energy and spatial plans, formulation of new energy-driven and strategic objectives aimed at a more sustainable planning activity. For supporting the designing of different alternatives with relative targets and indicators (second SEA stage), the suggestion is to take advantage of the maps developed in the Ph.D. thesis, and particularly: the map of space heating demand at building level to identify the priority areas/buildings for energy renovation actions from the thermal viewpoint; the maps of comparison among LCOE values for SGE, natural gas and heating oil systems (performed in GRETA project) to take into account also the financial aspect of possible future interventions; the map of spatial suitability of SGE systems (performed in GRETA project as well) to respect also the maximum density of SGE systems in a certain area.

Different combinations of the two main drivers, identified in replacement of the heating system with geothermal HP and energy renovation of residential buildings, can be useful for the scenario analysis as third SEA step. In the same way, the identification of magnitude, time and space of possible environmental impacts of SGE and other thermal RES can represent an aid in the environmental analysis of different scenarios (fourth SEA phase). The sort of indicators used to analyse the developed strategic scenarios for the regional energy system may also support the decision-makers in the scenarios evaluation step (the fifth one); they are: GHG emissions saved, amount of increase in electricity consumption for geothermal HP use, operative and investment costs for SGE systems, investment costs for energy renovation of part of the residential building stock. In the end, all the thesis outputs described above can contribute to the formulation of conclusions and follow-up actions (sixth and last SEA phase), including measures to mitigate the possible impacts, the establishment of environmental guidelines and the monitoring programme.

As further support element for the future elaboration of strategic and integrated energy and spatial plans, in the following Table 4.6 the thesis results are summarised together with the data required to perform the analysis and the key stakeholders that should be involved in the planning process. Concerning the stakeholders, the “quadruple helix” concept was considered. It individuates the main actors for innovation processes in public authorities, research/academia, industry and citizens/civil society. The most of times, all the four stakeholder categories should be included in the decision-making process about spatially explicit energy transition of their own territory. This highlights also the relevance of social and community groups that may often play a significant role in regional knowledge-based development (Kolehmainen et al. 2016).

Table 4.6: Thesis results, data required for the analysis and key stakeholder categories to be involved in the planning process. Source: Thesis 2019.

Thesis results	Data needed	Key stakeholder category
Spatial evaluation of space heating demand for each residential building	Geometrical features, period of construction, energy features, prevailing function, occupation level, … of buildings; HDD OR real (measured) thermal consumption of buildings	public authorities, academia, industry, civil society
Technical and financial suitability of SGE systems (GRETA)	Hydrogeological features of the ground; environmental, legal and technical constraints for SGE; H&C demand; capital and operative costs of geoth.HP, national subsidies	public authorities, academia, industry
Spatial suitability analysis of SGE systems (GRETA)	Areas of: pertinence of buildings, water protection, buffer around roads and buildings	public authorities, academia
Comparison among current objectives (energy, spatial) and definition of new ones	Plans and strategy documents at different levels (local, regional, national, European)	public authorities, academia, industry, civil society
Assessment of possible impacts on environment of SGE and other thermal RES	Magnitude, time and space of potential eviron. impacts	public authorities, academia, civil society
Development of scenarios for the regional energy system	Outputs of previous analysis; energy renovation costs	public authorities, academia, industry, civil society
Indicators for analysing the scenarios	Outputs of scenario analysis; GHG emissions saved, reduction of H&C demand, increase in electricity consumption for geoth.HP, operative and investment costs for SGE systems, investment costs for energy renovation of buildings, …	public authorities, academia, civil society

4.6 Impacts of Ph.D. thesis

The main impacts of the Ph.D. outputs are: (1) SDSS allows to reach a compromise between the number of input data and the level of detail often required by decision-makers; (2) SDSS can support the decision-makers allowing them to analyse from various viewpoints different energy scenarios and also to localise where is better to address the energy measures; (3) the results at the building level represent a valuable starting point for defining and developing strategies for the energy transition of settlements at different scales; (4) SEA is used as a conceptual framework for connecting energy planning and spatial planning, by coordinating strategic objectives, and linking the thesis outputs to the energy decision-making process.

Concerning the first two points, the developed methodology was able to estimate at the building level for the case study the values needed for data processing, making the results consistent on average with the data available at different scales, i.e. census tract and municipal level. For doing this, a compromise was sought between the degree of generalisation in the building stock analysis and the willingness to consider the specificities of each building, when the data was available. Since one of the aims of the Ph.D. thesis was to define objectives and energy strategies for the entire region of Valle d’Aosta, the selected level of detail was believed as effective. A more in-depth and thorough analysis would be required in order to define implementation measures for specific building categories or sectors.

However, whether the analysis is performed at the building level the decision-makers would have more flexibility in defining and evaluating different spatial and energy strategies. This would give them the possibility to aggregate the outputs at different scales, making the methodology suitable for planning purposes at different levels. Furthermore, SDSS can support the decision-makers allowing them to analyse from various viewpoints different energy scenarios and also to localise where is better to address the energy measures. Here stands the link with the third impact of the Ph.D. project. Indeed, the collection and analysis of data for each building wanted also to represent a linking point between spatial planning (regional or urban) and energy planning processes, by promoting synergies in the definition and development of strategies and scenarios aimed at supporting the energy transition of settlements at different scales (e.g. district, municipality, valley, region).

For doing this, SEA was believed to be an appropriate structure. As we saw, the Strategic Environmental Assessment (SEA) is a procedural instrument useful to integrate environmental and sustainability issues in decision-making processes (Thérivel 2004). Furthermore, it can add value to the decision-making process by enabling plans and policies to incorporate environmental, social and economic considerations. Taking account of these issues is currently central also in the development of energy policies and in the search for more sustainable sources of energy production. Therefore, the use of SEA should be substantial within the energy sector (Jay 2010), given its role in the carbon reduction process. In the Ph.D. thesis, SEA was used as a framework for pushing the integration of the spatial dimension in the energy analyses, by developing strategic objectives and scenarios.

Since the Regional Spatial and Landscape Plan of Valle d’Aosta was drawn up in 1998 (Regione Autonoma Valle d’Aosta 1998), there will be soon the need to update it. What I would suggest to the Regional Administration is to take advantage of the commitment to update also the Regional Energy and Environmental Plan (from 2020 onwards) and coordinate the edit of the two plans using the framework of SEA, in order to integrate in only one planning document spatial and energy sustainable strategies for the future of Valle d'Aosta. From this point of view, this research can represent a support tool for the Regional Administration, since it provides several outputs useful for guiding the decision-makers with insights on the possible different scenarios along the path of energy transition. In this way, Valle d'Aosta can become an example of *Smart Energy Region*, since its high renewable energy potential and commitment to sustainability.

CHAPTER 5

5 Conclusions

In Section 1.3 the research questions that shaped the Ph.D. thesis were presented and discussed. Given the developed methodology and the obtained outputs from the research activities, in this Chapter the main findings and answers to the mentioned questions will be presented.

1) *How to estimate the space heating demand of the residential building stock at the regional scale, as a starting point for developing sustainable energy strategies aimed at the reduction of the thermal energy consumption in the existing buildings.*

In this dissertation, a building stock analysis (BSA) based on a spatially explicit "bottom-up" method (Swan and Ugursal 2009) was developed using open source software (i.e. GRASS GIS, QGIS, Python and R). The first part of the Ph.D. methodology has been designed taking advantage of a GIS environment with the aim to integrate different spatial input data. Particularly, it aimed at estimating the space heating demand of each residential building of the case study, starting from the evaluation of the geometrical features and the estimation of the age of the building stock, without using the "archetypes approach" (Caputo, Costa, and Ferrari 2013). Indeed, although the chosen unit of analysis is the single building, no building archetypes have been implemented. This level of detail has been chosen to better characterize the thermal demand of the whole regional building stock of the case study (Valle d'Aosta), giving the possibility to aggregate the outputs at different scales. This makes the method suitable for regional planning purposes but also replicable in different contexts and at various scales.

The developed methodology for the spatial estimation of the space heating demand of residential buildings is able to estimate at the building level the values needed for the data processing, making the results consistent on average with data available at the other scales. Indeed, in case of unavailability of data at the building level, some analyses have been performed using information at the census tract or municipal level to derive values for the single building. Hence, the methodology has been also developed in order to fill this knowledge gap. For doing this, a compromise was sought between the degree of generalisation in BSA and the willingness to consider the specificities of each building, when the data was available. Since one of the main aims of the Ph.D. thesis was to define objectives and energy strategies for the entire region of Valle d'Aosta, the selected level of detail was believed as effective. A more in-depth and thorough analysis would be required in order to define implementation measures for specific building categories or sectors.

As we saw in Section 4.1.1, in general the heated surface of the residential buildings and consequently the space heating demand were overestimated. This overestimation was calculated to range from around 9% to 23% and occurred mainly because of two reasons. Firstly, the information on the real occupation of the buildings was not available at the building level and it was derived statistically to respect the percentage obtained from Census data on occupied and total flats per census tract. Secondly, due to the lack of information about the mixed use of the buildings (residential, commercial, offices, etc.), they were considered as entirely residential since it was not possible to internally divide them among different functions.

The trade-off between accuracy and simplicity of thermal demand estimations is a common issue among the "bottom-up" building stock models, as recently pointed out by (Brøgger and Wittchen 2018). Moreover, the quality of the results reflects the precision of the input data; the more reliable and detailed the input data are, the more realistic and case-specific will be the thermal demand estimation. Indeed, although the assumptions required by this kind of analysis at the building level may increase the uncertainties of results, at the same time the uncertainty of input data may cause bigger uncertainties than those involved by simplifications in the methodology (Frayssinet et al. 2018).

For trying to overcome this issue, additional data that I would suggest to collect and spatialize at the building level are: (a) information on energy retrofit measures already implemented, (b) real number of residents in the building, (c) number of dwellings not occupied or used as holiday houses, (d) commercial or other kind of activities located in the building. As future developments of the Ph.D. thesis for the estimation of the space heating demand, some other issues should be addressed: (A) taking into account the users' behaviour within the BSA since it is demonstrated to have influence on the energy consumption; (B) better validating the estimation of the space heating demand by including and combining data on the energy consumption at the same level of analysis; (C) assessing the impact on the thermal demand of some energy refurbishment measures applied to the buildings; (D) adding the calculation of DHW and electricity energy demand to the space heating one.

2) *How to integrate the appraisal of space heating demand in the energy planning process of a region in order to elaborate different scenarios for the energy balance between thermal demand and supply, fostering the use of shallow geothermal energy (SGE) that is a renewable source still not well-known and not exploited.*

After the spatial estimation of the space heating demand of each residential building, the financial feasibility and the spatial suitability of SGE for covering this space heating demand and replacing some fossil fuels were evaluated. Both the financial feasibility and the spatial suitability were performed within the GRETA project (GRETA project 2018c). The evaluation of the technical and financial suitability of SGE solutions for covering the energy demand of the buildings and replacing, as much as possible, fossil energy sources within the H&C systems was done by means of some economic indicators, i.e. mean Discounted Payback Period – DPP and technology-related Levelized Cost Of Energy – LCOE. The financial comparison was performed between SGE plants and conventional technologies (i.e. natural gas and heating oil boilers). In some cases, the SGE plant was also combined with solar rooftop photovoltaic (PV) panels and national subsidies for increasing the energy efficiency of the buildings.

The results of the financial analysis for the case study showed that there is a clear positive influence of subsidies over LCOE values for SGE systems. So, the outputs underlined the importance of the Italian subsidies for the financial convenience of the geothermal plants. Indeed in case of their lack, the combination of natural gas boilers and air conditioning system (ACS) was usually associated with a lower LCOE (that is more convenient). The coupling use of geothermal heat pump (HP) with solar PV systems also resulted to have a positive influence on DPP and LCOE values of SGE systems. However, the real discriminant factor was constituted by the application of subsidies, since solar PV systems were only able to produce a small reduction of both LCOE and DPP values. These outputs underline the relevance of proper incentive schemes and subsidies that can improve the financial feasibility of SGE systems, fostering the exploitation of the shallow geothermal resource.

The spatial suitability analysis was aimed to estimate the maximum number of SGE systems that can occur at the same time in the case study, minimizing the risk of interferences among different installations or between SGE plants and some areas with special environmental constraints regarding water resource, i.e. water protection areas and areas close to water bodies. The results of the spatial suitability analysis showed that 83% of the total thermal demand of residential buildings in Valle d'Aosta can be covered by SGE from this point of view, corresponding to 93% of the heated surface.

In order to develop energy scenarios for the case study, the comparison among the current energy planning and spatial planning objectives of Valle d'Aosta was performed. This analysis was aimed at identifying possible gaps to be filled in the coordination of these goals so that they will be consistent and working towards the shared vision of energy transition. Thus, the objectives of the Regional Energy and Environmental Plan (REEP) (Regione Autonoma Valle d'Aosta 2012), on one side, and of the Regional Spatial and Landscape Plan (RSLP) (Regione Autonoma Valle d'Aosta 1998), on the other side, were analysed and compared to highlight possible conflicts or need to improve the connection with new objectives. The main contrast found in the objectives' comparison was the willingness to improve the network for the distribution of natural gas, not only in the central valley but also in the smaller settlements located in the secondary valleys. This objective was in contrast with the targets for increasing energy production from RES and reducing CO_2 emissions. Therefore, the "new" strategic energy-driven objectives for the Valle d'Aosta were more focused on the replacement of all fossil fuels, including the natural gas, for the thermal supply of the residential building stock. They are:

- The increase of energy saving, improving the efficiency of production plants and distribution systems;
- The diversification of energy sources due to the substitution of fossil fuels in the heating systems (especially LPG and heating oil, partially natural gas);
- The reduction of energy consumption thanks to the refurbishment of the residential building stock;
- The increase of the energy self-sufficiency of cities and towns with more production from local RES;
- The reduction of CO_2 emissions due to the substitution of fossil fuels for heating plants.

3) *How to foster the connection between energy planning and spatial planning towards the common goal of sustainable energy transition, helping to fill the gap between the development of plans and strategies and their implementation, thanks to the Strategic Environmental Assessment (SEA) framework.*

To enhance the integration between energy planning and spatial planning, some sustainable scenarios for the energy system of the Valle d'Aosta were developed, looking at the energy transition toward the vision of a *Smart Energy Region*. All the outputs of the previous analyses (i.e. space heating demand of buildings, financial analysis and spatial suitability of SGE systems, comparison between planning objectives, etc.) were combined with the strategic objectives formulated for the case study and used for the construction of the scenarios. The basic structure for these scenarios was shaped by the two driving forces that will influence the development of the regional energy system in the future. They were identified in: 1) using shallow geothermal energy for supplying the space heating demand of the buildings, replacing as much as possible the fossil fuels; 2) refurbishing part of the residential building stock for decreasing the thermal demand. Different combinations of these two drivers shaped the developed scenarios.

These scenarios were divided into two sections. In the first one, SGE is imagined to supply the space heating demand of part of the residential buildings (where the space heating demand is currently lower than 50 kWh/m^2 year), partially replacing some fossil fuels (LPG plus heating oil and natural gas, respectively), without applying any renovation measures. In the second section of scenario development, the residential building stock is supposed to be partially refurbished for decreasing the total space heating demand (where the space heating demand is currently greater than 50 kWh/m^2 year). At the same time, SGE systems are supposed to be installed in the renovated buildings in place of fossil fuel plants. The developed scenarios were then compared through some indicators: (i) heated surface involved [m^2]; (ii) GHG emissions saved [tCO_2 equivalent]; (iii) costs of HS replacement with geothermal HP [M€]; (iv) cost of energy renovation of buildings [M€]; (v) electrical consumption for HP utilisation [MWh].

The results showed that the third scenario (replacement of LPG/heating oil heating systems plus energy renovation of buildings) is the most impactful in terms of residential heated surface involved, GHG emissions saved, but also increase of electricity consumption and refurbishment costs. This is due to the fact that the buildings built between 1946 and 1980, with a value of space heating demand greater than 50 kWh/m^2 per year, and where LPG and heating oil are used as fuels for the primary heating system represent a relevant part of the analysed building stock (around 21%). Overall, the first two scenarios, which consider the buildings with lower space heating demand and only the replacement of heating systems, do not have a significant effect on the status quo (in particular on the GHG emissions). While, the second two scenarios are more impactful, also because they involve energy renovation measures for several buildings (about 27% of the total analysed buildings). Therefore from this study, the energy renovation of the building sector is confirmed to represent a great opportunity for reaching the energy saving targets and the reduction of GHG emissions.

This part of the methodology on the scenario development would be an example of how this kind of analysis can support a decision-making process when an energy plan/strategy should be updated or developed. Indeed, the choice of the criteria to be used to evaluate the scenarios should be done by the local stakeholders and/or decision-makers (as planned in the next steps). Another aspect worthy to be explored is the analysis of the different measures proposed on the basis of their effectiveness in promoting a sustainable energy transition. In this dissertation, the focus was not on how to implement the strategic actions for the heating plant replacement and the energy renovation of buildings. Even though this was not the focus of this work, it can certainly be a further step.

The future developments of the Ph.D. thesis on the formulation of sustainable energy scenarios for the regional energy system are: (a) making the process interactive and more structured as a tool (now is defined more as a methodology); (b) diversifying the refurbishment interventions for different kind of buildings (dividing them according to relevant criteria) and/or defining an annual renewal rate for both the replacement of heating systems and the energy renovation of buildings; (c) performing a cluster analysis for gathering together similar municipalities and then develop different scenarios for each cluster; (d) performing a spatial multi-criteria evaluation of the scenarios (Pohekar and Ramachandran 2004) involving the local stakeholders in the weighting system of the considered variables.

In this dissertation, SEA is used as a framework for connecting energy planning and spatial planning fields, rather than as an evaluation tool. However, the set of analyses and methods developed within the Ph.D. thesis can support local authorities of Valle d'Aosta in accomplishing some of the tasks requested by SEA Directive. In particular, they can be used to (see also (GRETA project 2018e)): (1) identify feasible energy and sustainability targets and indicators, determining whether the objectives of the planned strategic actions are achievable or not; (2) describe the energy and environmental baseline, supporting public bodies in overcoming possible data-gaps and/or in defining the context of the strategic actions; (3) predict and evaluate the impacts, determining the effects of different energy strategies and alternative actions and highlighting possible mitigation measures; (4) mitigate impacts, providing information and data to ensure that the strategic actions are sustainable and their impacts will be minimized.

In the end, the connection between the analyses performed within the Ph.D. thesis, the relative results and the main SEA steps was made. This allowed us to emphasise how the developed methodology and the obtained outputs can be integrated into SEA procedure of a future regional plan (energy and/or spatial) of the case study. The Ph.D. methodology and outputs can clearly support SEA implementation and be integrated into all its phases (see Table 4.5). Since the Regional Spatial and Landscape Plan of Valle d'Aosta was drawn up in 1998, there will be soon the need to update it. What I would suggest to the Regional Administration is to take advantage of the commitment to update also the Regional Energy and Environmental Plan (from 2020 onwards) and coordinate the edit of the two plans using the framework of SEA, in order to integrate in only one planning document spatial and energy sustainable strategies for the future of Valle d'Aosta. From this point of view, the outputs of this Ph.D. thesis can be a support tool for the Regional Administration, since they provide information and results useful for guiding the decision-makers with insights on the possible different scenarios along the path of energy transition.

Providing support for the decision-makers within the energy planning and spatial planning processes looking at the sustainable energy transition of the case study was one of the main objectives of all the research activities performed during the 3-years Ph.D. programme. For this reason, the results of this dissertation want to lay the foundation for further developments of the analysis at regional or valley scale in Valle d'Aosta (or in other contexts). Indeed, the outputs of the Ph.D. thesis can be a starting point for integrating and updating the information collected and the analysis performed during the research project with those already available within the Regional Administration.

As general recommendation for the Regional Administration of Valle d'Aosta, the thesis outputs highlight that one should intervene with policies and/or subsidies for the replacement of fossil-based heating systems and the energy renovation of residential buildings earlier on the buildings where the ratio between GHG emissions saved and investment costs is higher. This in order to have the strongest impact on the reduction of GHG emissions. For this purpose, the proposed SDSS, thanks to its spatial-based approach, can help during the decision-making process allowing to analyse from various viewpoints the different alternatives and also to localise where is better to address the energy measures.

Considering the spatial dimension of a low-carbon energy transition is more than mapping the consequences of policies and strategies, or understanding the implications of different actions for particular places (even if they are very important). Instead, I agree with (Bridge et al. 2013) that the goal for future research in this field should be to understand how the energy transition is *spatially-constituted*. Hopefully, this dissertation goes in this way within the research line on energy transition and sustainable energy planning. It is worth reminding that the developed methodology follows a spatial-based and strategic approach and it was used for analysing an entire region, considering at the same time the specificities of each building as the smallest unit of analysis effective for the planning activity at regional (and urban) scale.

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Credits of the cover image: GEOPLAT (Spanish Technology and Innovation Platform in Geothermal)

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