Feasibility assessment and investment-proposal optimization for an NZEB

Nikolaos Alexandros Kritikos

Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

Supervisor: Prof. Carlos Augusto Santos Silva

Examination Committee

Chairperson: Prof. Jorge de Saldanha Gonçalves Matos
Supervisor: Prof. Carlos Augusto Santos Silva
Member of the Committee: Prof. José Manuel da Silva Chaves Ribeiro Pereira

November 2017

Dedicated to the human capacity for willpower and perseverance.
For it is truly remarkable what a human can eventually achieve.
(e.g. finishing this Thesis)

Acknowledgements

The current work is the result of copious amounts of personal effort. Yet, nonetheless, it would not have been achieved without the insightful contribution of some significant people. Therefore I would like to thank:

Professor Carlos Augusto Santos Silva for providing me with the opportunity to execute this Thesis and the further support along the way.

Professors José Manuel Da Silva Chaves Ribeiro Pereira and Viriato Sérgio de Almeida Semião for introducing me better to the concept of Heating Ventilation and Air Conditioning and intriguing me further into it.

Mr. Manolis Androulakakis for providing relevant information regarding civil engineering projects and bringing me in contact with

Mr. Charalambos Tzanakis for providing extensive initial insight in the building envelope and thermal equipment type, sizing and further nuances

My father Theoktistos Kritikos and his business partners (notably mr. Stelios Loulourgas) for providing extensive market-information and prices regarding building constructions.

Lastly, but definitely not least, I wish to thank deeply professor Duarte de Mesquita e Sousa for his contribution in making my curricular—and extra-curricular—experience here absolutely enjoyable!

Oh, and Lisbon. For being so beautiful…

Resumo

Com o conceito de Near Zero-Energy Building sendo fortemente apoiado pela União Européia ainda não encontrando suficiente aceitação do mercado, o trabalho aqui está focado em identificar quais parâmetros-chave tornariam atraente um tal conceito de investimento. Três locais em diferentes regiões climáticas são escolhidos com 3 diferentes níveis de isolamento e seu desempenho térmico é simulado através do software EnergyPlus. Para cada conjunto de descobertas, um sistema altamente eficiente de geração fotovoltaica no local, bomba de calor, produção de água quente e armazenamento térmico é dimensionado de forma econômica e o custo final, as emissões e os resultados do conforto interno são comparados entre eles e contrastados com os atuais convencionais sistema de calor e água quente. É escolhido o ótimo arranjo de equipamentos térmicos e o impacto do custo e das emissões é avaliado para novos edifícios e reformas. Os resultados finais indicam a rentabilidade de um sistema de construção mais eficiente e seu impacto significativo na redução das emissões de CO2 do setor de construção.

Key-words: energia, residência, NZEB, EnergyPlus

Abstract

With the Near Zero-Energy Building concept being strongly supported by European Union yet not meeting enough market uptake already the work here is focused on identifying which key parameters would make such a concept investment-attractive. Three locations on different climatic regions are chosen with 3 different levels of insulation and their thermal performance is simulated through the EnergyPlus software. For each set of findings a highly efficient system of on-site PV generation, heat pump, hot water production and thermal storage is cost-optimally sized and the final cost, emissions and indoor comfort results are compared among them and contrasted to a nowadays conventional heat and hot water system. The optimal thermal-equipment arrangement is chosen and the cost & emissions impact of it is assessed for new buildings and renovations alike. The final results indicate the profitability of a more efficient building system and its significant impact in curbing CO_2 emissions from the building sector.

Key-words: energy, residence, NZEB, EnergyPlus

Contents

List of Tables

List of Figures

List of Charts

List of Abbreviations

ASHRAE: American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CAPEX: Capital Expenditures
DHW: Domestic Hot Water
EU: European Union
HP: Heat Pump
HVAC: Heating, Ventilation and Air-Conditioning
LEED: Leadership in Energy and Environmental Design
NPV: Net Present Value
NZEB: Near Zero-Energy Building
OPEX: Operational Expenditures
PV: Photovoltaic
TS: Thermal Storage

Foreword

This thesis focuses on the energy consumption and emissions of residential buildings. The purpose is two-fold: on the one side, buildings are one of the most energy-consuming/emitting sectors of human activity (thus an intervention here is crucial in order to fight Climate Change) and on the other side, a residence is one of the most important type of buildings since it is one's shelter, sanctuary, where one finds safety and comfort from the everyday world. Thermal comfort is essentially a human right (as cold can threaten human lives) and upon discovery of the fact that—beyond the high emissions—many households cannot afford completely their energy bills, a decision was made to approach this issue through the work here.

Thus, the effort to develop a building design/system that is thermally comfortable, environmentally friendly and affordable, is recognised on a European level and the concept of Near Zero-Energy Building is explored and supported for the last few years, yet without definitive progress so far. Admittedly, the building sector is a diverse, multi-disciplinary field of very high complexity from design, to construction, to operation of a building. Therefore the effort to optimise a building from comfort, carbon footprint and cost simultaneously is quite some work, if done properly. For that reason severe approximations and assumptions will have to be performed here for the majority of the building, while only the most crucial elements will be integrated into a multi-parameter model that will be optimised.

At the extent to which all these approximations and assumptions are made, the end results of the work here can in no way be considered definitive and completely representative of reality. A large margin of error is expected naturally but within the scope and resources of a Master's thesis, this is the best that can be achieved. To conclude, the work performed here is considered to be only a "scratching of the surface", a mere "reconnaissance" of what lies in the field and if there exists a prospect of such a "trifecta" solution for the residential sector.

Upon completion of the work here what is expected are indicative comfort-, emissions- and cost-values (allowing for the identification of the best design/system) and the discovery of the highest-priority bottle-necks / key-points in the process of creating the "perfect" NZEB.

1. Building sector in Europe

Buildings are an important part of the human life. It is where we can protect ourselves, our loved ones and our property from the threats of nature and other beings. It is where we can shape and control the environment in order to facilitate specialized processes and where we can personalize the space in a way that reflects better our world-view and welcomes us, a place we can call home.

Therefore, evidently, creating and "operating" buildings is a complex, multi-disciplinary process combining various fields of science and engineering. Undoubtedly energy is one of the key resources for a well-built and mostly a well-functioning building. Today—in the era of sustainable-energy scarcity, global energy-oligopoly and extensive energy-poverty—it is more urging than ever to assure a sustainable, accessible and affordable way of providing the necessary energy to the end-users.

In this context European Union is driving a lot of effort and initiatives within the building sector regarding affordable energy sufficiency and lower emissions. In the following chapter some key-points of this sustainability conundrum are highlighted in effort to adequately *chart* the full extent of the building sector and familiarize sufficiently before the *case-cracking* begins.

1.1. Current consumption, energy mix and emissions

1.1.1. The European situation

At 2014 in Europe *the building sector accounted for about 40% of the total final energy consumption and 36% of total emissions in EU* [1]. While the magnitude is impressive, the building sector refers to any kind of buildings. Yet, as stated previously, the specific interest of the current research is on the housing sector. Thus, households form the 24.8% of final energy consumption, i.e. 263.3 Million tons of oil equivalent (Mtoe) [2].

The energy consumed in households is distributed among different primary sources and final uses. For 2014 the exact distribution is illustrated in the Charts 1 and 2 below:

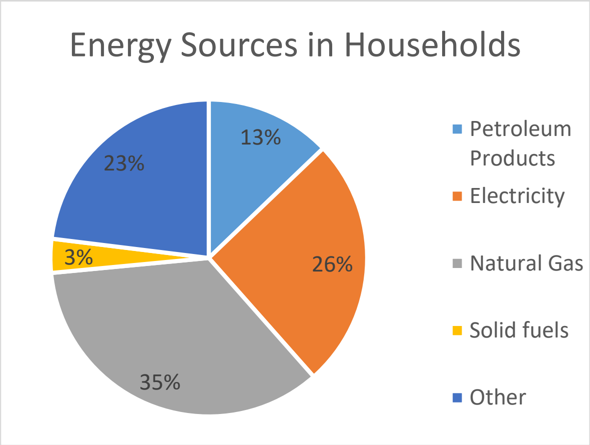


Chart 1: Energy mix of Households (2014)

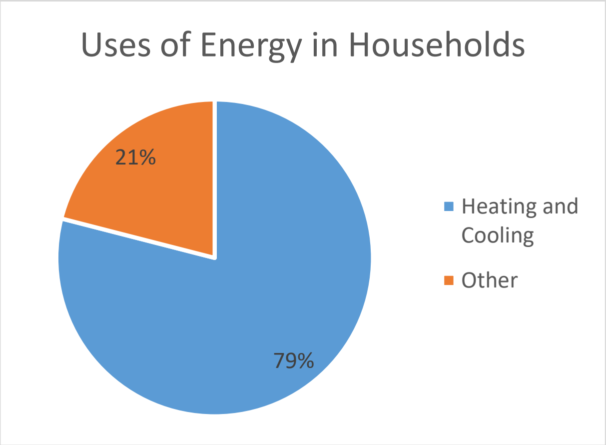


Chart 2: Uses of Energy in Households (2014)

[3], [2]

It becomes profound that the majority of energy consumed in buildings regards heating and cooling. By *heating and cooling* it is not explained explicitly which "uses" of energy are included. Space heating/cooling (i.e. the thermal conditioning of air in a building's spaces) naturally fits the definition but it is not clear whether other forms of "heat" are included such as hot water production and cooking[1]. Regardless, heating and cooling is the majority of energy consumption in households and as it appears from Chart 1 it is mostly covered from fossil fuels. This notion is further backed by more sources claiming *84% of heating and cooling is still generated from fossil fuels* [3].

The (primary) energy sources of Households consist of petroleum products, natural gas and electricity to a portion of 64%. With the electricity energy-mix in Europe being up to 47.6% from combustibles back at 2014 [4], this practically means the energy input of European households is at least 60% fossil-fuel based, i.e. heating and cooling of households in 2014 consumed 125.6 Mtoe of fossil fuels.

Proceeding to some rough calculations, the certain (able to be calculated from the stats above) emissions~~ per household~~ are calculated at a minimum of 729.72 Mt of CO2 and consist as below in Chart 3:

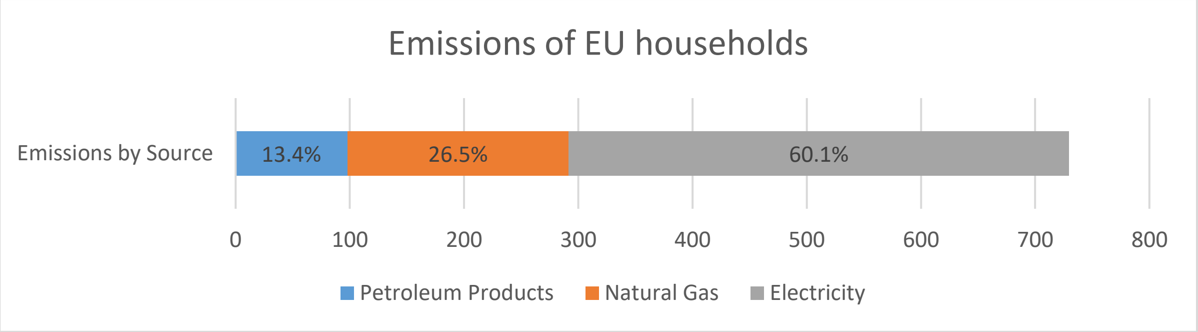


Chart 3: Amount of CO2eq emissions from EU Households and percentage by source, 2014

[5], [6]

The calculated value is very close (~87%) to the one found from other sources: 846.19 MtCO2 (in 2014) [7]. Combining the findings it concludes that heating of households is responsible for the release of 660.44 MtCO2 in the atmosphere in 2014. The heating required in households is a low-temperature heat which means that it can be easily derived from various primary or “waste heat” non-fossil sources. Therefore, a significant potential of de-fossil-ising the household heating needs exist, reducing simultaneously the greenhouse gas emissions and the financial expenditures of the sector.

---

[1] In “*An EU strategy for heating and cooling*”, 2016, activities such as *hot water production* and *process heating* are included in contained the analysis.

1.1.2. The Greek situation

In Greece the situation of energy sources and uses in households deviates from the average European case due to climatological, cultural and energy-related differences. In 2014 the total final energy consumption was 15.52 Mtoe, 24% of which (3.78 Mtoe) was spent on households. As a matter of fact there has been a quite sharp increase in residential energy consumption in 2015 reaching 4.40 Mtoe. [8]. Details can be seen below in Charts 4 and 5:

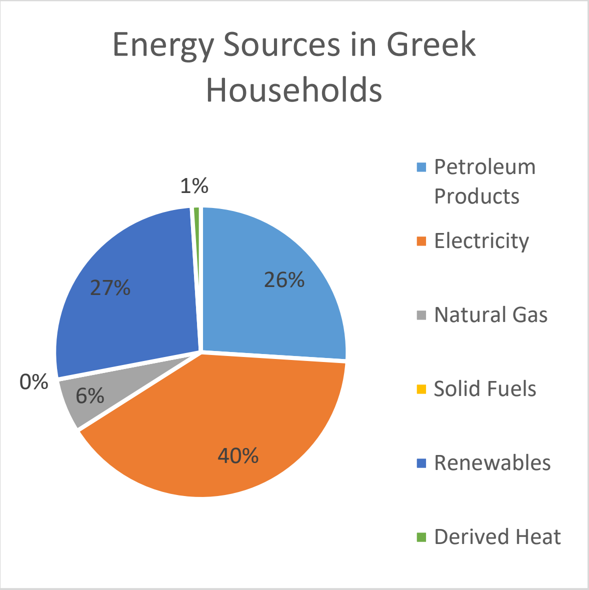


Chart 5: Energy mix of Greek households (2013)

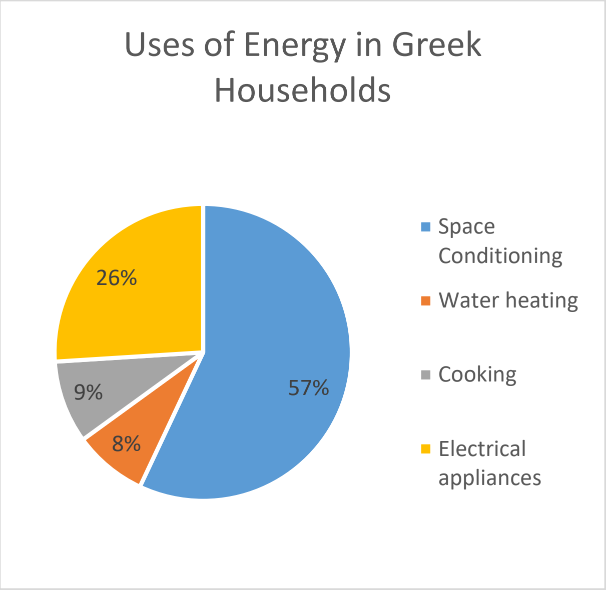


Chart 4: Uses of Energy in Greek households (2013)

Based on the primary fuels for electricity production in the country (only 24% Renewables in 2013) [5] the Greek households end up being fossil-fuel-based on a minimum of 62%. Thus, overall they accumulate a consumption for “heating and cooling” of 1.80 Mtoe of fossil fuels for the coverage of their energy needs in 2014 (and 2.10 Mtoe in 2015).

Emission-wise, the household sector yields the following volume and shares by final energy source, show in Chart 6:

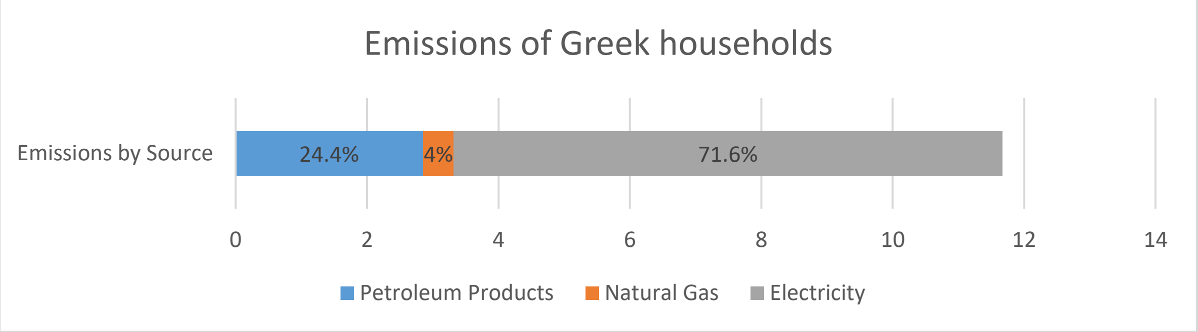


Chart 6: Amount of CO2eq emissions from Greek Households and percentage by source, 2014

[8], [9], [6]

Once more, the values calculated are similar (~80%) to ones found from sources: 14.65 $MtCO_2eq$. As a measure of comparison the total emissions of Greece in 2014 were 92.26 Mt CO2eq, i.e. household sector is responsible for about 16% of total national emissions [7].

So far some key conclusions can be derived for both Europe and Greece specifically. To begin with, heating and cooling of spaces has by far the highest consumption of energy in households and so it is identified as the key intervention-field in reducing energy consumption and emissions in the residential sector. Secondly, a simple shift from petroleum and natural gas to grid-electricity for the covering of the needs will not yield a reduction in emissions since electricity is as well fossil-fuel based. Therefore only an increase in energy efficiency of heating and cooling in households or a direct implementation of renewables on the dwelling can yield the desired results.

Taking these conclusions a step further—towards the goal of establishing an NZEB—optimizing the heating and cooling of the building upon renewable sources is a critical step. Yet merely that is not enough. Even though “nearly-zero” is not explicitly quantitatively-defined throughout Europe [10] its final dependence on non-self-produced energy (fuels and grid electricity) has to be very low and the 21% of energy required for appliances will still have to be domestically produced to a large extent (until the NZEB “limit” is reached). Overall, it becomes already profound that an NZEB is a technical challenge since the need for energy storage both in thermal and electrochemical (battery) form is necessary.

1.2. Policies, development goals and means of achieving them

European Union desires to be a frontrunner on various economic, social and sustainability issues. The strategic plan of EU aiming to address these goals is the famous “Europe 2020”. One of the five main headline targets is Climate and Energy under which are set the famous 20-20-20 goals for year 2020: 20% reduction in carbon emissions (vs 1990 levels), 20% of EU energy production be from Renewable Sources and 20% improvement in energy efficiency. [11]

Currently, buildings in EU are responsible for 40% of energy consumption and 36% of CO2 emissions [1] while heating and cooling (including buildings and industry) accounts for 50% of EU energy consumption [3]. From these facts heating and cooling in buildings is a key field in the long-term battle against climate change and energy dependence of the European Union. Zooming down to the scope of this thesis—energy consumption in households—as it occurred previously, the domestic sector accounts roughly for 25% of EU energy demand and 15% of EU emissions.

For that reasons various regulation, legislation and EU directives have been composed in an effort to promote policies that will facilitate reaching the designated goals. A lot of documentation exists on the matter yet the most resourceful were deemed to be “Energy Performance in Buildings Directive”, “Energy Efficiency Directive”, “Clean Energy for all Europeans” and “A European Strategy on Heating and Cooling” along with its accompanying Commission Staff working document.

Common ground can be found in all documents, indicating a clear direction of EU intentions and policies accordingly. To begin with the social aspects of the matter**,** addressing energy poverty in EU is a key goal. In 2014 on average households had to pay 6% of their total income in order to cover their energy needs. 11% of EU households could not meet their total heating demands. For the lowest households the share of energy expenditures was up to 9% of total, increased by 50% since 10 years ago. Therefore the mandate for Member States is clear: *energy efficiency is the best way to address energy poverty* and *the clean energy transition should benefit all Europeans including the vulnerable and energy poor* [12], [13]. *Affordable heat and cool is even more important for those who spend more time in their houses for reasons of bad health, disability, age or lack of employment* [14]. Overall, energy cost is a controversial issue for end users as although gas and oil prices have fallen more than half, since 2013 and 2014 respectively, *retail electricity prices have risen about 3% a year since 2008* [12]. The general image of energy costs, as depicted above, defines an imperative goal for affordable access to reliable, clean energy.

A second point of congruence among the documents is the importance of “clean energy”-buildings in a decarbonised EU economy. *Buildings are crucial to achieving the Union objective of reducing greenhouse gas emissions by 80-95 % by 2050 (compared to 1990)* [15] and thus *investment in a clean energy building stock can drive the transition to a low-carbon economy* [12]. *To achieve our [EU] decarbonisation objectives, buildings must be decarbonized* and this entails—along with new low-carbon buildings—an extensive renovation of the existing building stock. As a matter of fact *75% of the Europe’s buildings are inefficient, being constructed with minimal or no energy performance requirements in building codes and their great majority will remain in use beyond 2050* [13]. Therefore no significant reduction in carbon emissions can be achieved in the building sector unless along with new low-carbon buildings the existing ones are renovated in a level of similar performance.

Coming to the means of provision of energy to the building sector, it is unanimously mentioned through the documents that application of demand-response must be supported for it holds key advantages in the operation of the electricity grid. Demand response is considered a great assistant in improving energy efficiency as it allows more stakeholders to take action and through management of consumption achieve energy savings additionally in generation and transmission/distribution. Therefore *conditions for, and access to, demand response should be improved* and can be done so in the form of price signals or building automations [15]. Automation is key in this as *the automatic management of energy demand in buildings allows consumers to take part in demand response* [13]. Beyond that, the New Electricity Market design, another flagship project of EU, *will further create a level-playing field for demand-side participation in the market* [12]. This comes partly as a technical necessity *since electricity generation […] will reach about half of the EU's electricity generation mix, mainly from variable sources like wind and sun* and thus *market rules must be adapted to facilitate this development, to manage variability and ensure security of electricity supply* [12]. The same argument is made elsewhere as well, concluding *supply and demand must become more flexible, through wider use of demand reduction, demand response mechanisms and energy storage* [13].

Furthermore on the buildings' energy sources, it is made clear that small-scale, distributed generation, consumer-owned points is a rising trend, welcomed and supported by EU for its various benefits. *Member states* [should take measures] *in order to encourage distributed energy generation* [15]. *In recent years, investments in renewable generation assets represented over 85% of generation investments, most of them at lower voltage levels, notably at the level of distribution grids. The new proposals aim to further consolidate this trend, for example by removing obstacles to self-generation* [12]. Self-generation in specific is of special interest in the New Energy Market Design for its key-attributes in various aspects. The current policy-direction aims to *make it easier for consumers to generate their own energy, store it, share it, consume it or sell it back to the market – directly or as energy cooperatives* [12]. Moreover to cost-containment, "pro-sumption" (production and consumption) *can lower energy system costs e.g. solar PV can meet peak demand for electricity for air conditioning. Generating and consuming electricity locally can also reduce losses to the system and increase its resilience* [13]. Overall, self-generation greatly facilitates the implementation of demand response and real-time price signals which both boost the electricity grid, technically and economically.

Demand-wise it is of particular interest indeed the issue of addressing (peak-) loads for space cooling in summertime. Currently residential space cooling is rather low (1.6 Mtoe per year) *but is growing fast. Several studies indicate that this is likely to increase significantly in the future mainly to satisfy unmet demand for thermal comfort and partly because of more extreme weather types with warmer summers, driven by climate change. Projections even indicate 'exponential' growth.* Although so low (~2%) and mainly considered a "comfort service", space cooling becomes imperative in warmer climates. Indeed, *If some negative effects of climate change happen, cooling may become a more wide-spread necessity or be perceived more and more as such*. Currently *space cooling shows clear peaks in Mediterranean countries* hitting its maximum at Greece, being 9% of total heating and cooling needs (in Malta and Cyprus it is even higher, at 19% and 33% respectively) and in such extreme cases *negative impacts on health are also apparent as a result of excess heat during summer time* [14]. For the reasons above it is considered that *priority should be given to strategies which enhance the thermal performance of buildings during the summer period* [16] and thus corresponding measures (such as the PV self-production for meeting air-conditioning peak-demand mentioned previously) shall be investigated and implemented accordingly.

Now, narrowing down to more technical aspects of the building's performance, some common highlights can be clearly discerned. Initially**, smart technologies** (as in metering and operations) are in position to *make it possible for consumers—if they chose to do so—to control and actively manage their energy consumption while improving their comfort* [12]. Specifically *at least 80 % of consumers* *should be equipped with intelligent metering systems by 2020* along with individual meters for heating, cooling and hot water in the case of multi-apartment or multi-purpose buildings by end of 2016, if it is technically and economically viable [15]. To conclude *Smart grids, smart metering, smart homes and buildings, self-generation and thermal and electrical and chemical storage need to be promoted by a modern market design* [13].

Energy Storage is evidently a key-player in the field, especially in the form **of thermal storage**. A pivotal point in the potential synergies in the energy system is the integration of Heating and Cooling with the electrical network. Such a development *will reduce the cost of the energy system – to the benefit of consumers. For example, off-peak electricity can be used to heat water in lagged tanks which can store energy for days and even weeks* [13]. The advantages of storage are even more impactful in case of higher renewables in the electricity grid: *storage has many essential benefits within a renewable based energy system. It is central to enable the forecast integration of massive amounts of variable renewable electricity and can help stabilise the grid and ensures security and reliability of electricity supply* [14]. Furthermore, in a smaller scale *combination with thermal storage increases the efficiency of CHP as heat production can be stored rather than curtailed if not needed at that moment* [13]. Eventually, thermal storage is a rather sensible medium of storage since *thermal storage is around 100 times cheaper than electricity storage.* Overall short-term (e.g daily thermal storage) is a commercially proven technology useful for peak-load shifting, reduction of the H/C equipment's size, providing rapid energy reserves, avoiding the losses of frequent on-off switching of the equipment and allowing higher electrical output in CHP units when heating demand is lower. Especially for Cooling, it is even more useful as cooling demands vary significantly more during the day than heating demands. [14]. To conclude, the benefits of storage—and thermal in specific—are significant in technical terms for the electricity grid as well as financial terms for the energy market, making it a critical element for the, sustainably, deeper integration of renewables to our energy system and thus an actual chance of fighting climate change.

A final decision-making issue that affects greatly the implementation of solutions for all the aforementioned issues is the "split-incentives" problem. This describes the condition upon which the owner and the user (tenant) of the building are different persons. Therefore, *incentives are 'split' in the sense that property owners have little incentive to invest if the tenant pays the energy bill* [13] and no action takes place. For that reason EU mandates member states that *obstacles to the renovating of the existing building stock based on a split of incentives between the different actors concerned should also be tackled at national level* [15].

A problem arising jointly with the split incentives issue is the lack of information of owners about the various benefits of new more sustainable heating and cooling technologies. Indeed in the market is deemed to exist *a lack of trustworthy information, lack of skilled workers or doubts on the possible benefits* [12]. The information issue about the users in specific seems to be *that comparison of prices between solutions, as well as information on how their existing system performs, is not easily available for most consumers. This leads them to continue using older, less efficient technologies* [13] . This issue is so profound that Commission mandates a "Consumer Information and empowering programme" requesting that *Member States shall take appropriate measures to promote and facilitate an efficient use of energy by small energy customers, including domestic customers* proposing among others the mere provision of relevant information [15].

The lack of knowledge-proliferation about sustainable solutions extends beyond the end-users, to the lack of skill of the professionals on the energy market as well. Apparently, *lack of expertise and training affects all sectors. Too few professionals have the required expertise in energy efficient construction and in efficient and renewable energy technologies* while essentially *installers are the "market makers"* *for many technologies* [13]. As a remedy to this impediment *Commission will provide platforms for sectors and workers to adapt skills to the needs of clean energy transition* [12] and Member states should also *provide appropriate resources to support training and certification programmes which improve and accredit skills for energy efficiency* [15].

Beyond these common points above each document has its specific focus and valid arguments on its designated domain. To begin with, the Energy Efficiency Directive focusing in energy efficiency in general states that *investment in energy efficiency has the potential to contribute to economic growth, employment, innovation and a reduction in fuel poverty in households, and therefore makes a positive contribution to economic, social and territorial cohesion* in order to underline the—admittedly high—importance of energy efficiency in general. Therefore it *proposes an integrated approach […] to tap all the existing energy saving potential, encompassing savings in the energy supply and the end-use sectors,* pointing out the need of high efficiency in the consumption points as well. Regarding the building sector specifically it states that Member States shall establish a long-term strategy for the *renovation of the national stock of residential and commercial buildings, both public and private* including details regarding statistics of the national building stock, proposals of cost-effective approaches, policies and measures to support deep-renovations and evidence based estimates of expected energy savings. Such an explicit, none-excluding command for improvement in the energy efficiency of buildings indicates the necessity of this development as well the support it's expected to have from Member States and EU alike. [15]

The second document in research "Clean Energy for All Europeans" is one of the latest reports of European Commission and regards the transition to a clean (low-carbon) energy system and how this can benefit the economy and most importantly the European Citizens: *It is equally important to ensure that the transition to a clean energy system will benefit all Europeans. All consumers - not forgetting the vulnerable or energy poor - should feel involved and reap the tangible benefits of access to more secure, clean and competitive energy, which are the Energy Union's key objectives*. For that reason the document sets 3 distinct goals: Putting energy efficiency first, Achieving global leadership in renewable energies, providing a fair deal for consumers. Seeing how these goals relate to Clean Buildings it is stated that *clean energy buildings are about much more than saving energy: they increase living comfort and quality of life, have the potential to integrate renewables, storage, digital technologies and to link buildings with the transport system. Investment in a clean energy building stock can drive the transition to a low-carbon economy*. Proposing an ambitious target of 30% efficiency by 2030 the focus is quickly shifted to the core part of the report: the energy market should be empowering consumers, which for citizens means *better information, possibilities to become more active on the energy market and be more in control of their energy costs.* In order to facilitate and allow this, along with the goals and measures presented above, the Commission summons an *initiative on accelerating clean energy innovation. This initiative sets out a range of specific measures to improve the regulatory economic and investment environment for innovation in clean-energy technologies and systems.* [12]

In the third document the focus culminates from energy efficiency and clean energy in general into heating and cooling specifically. "An EU strategy for Heating and Cooling" *provides a framework for integrating efficient heating and cooling into EU energy policies by focusing action on stopping the energy leakage from buildings, maximising the efficiency and sustainability of H&C systems, supporting efficiency in industry and reaping the benefits of integrating H&C into the electricity system.* The vision set through the document is rather explicit: *To achieve our decarbonisation objectives, buildings must be decarbonized. This entails renovating the existing building stock, along with intensified efforts in energy efficiency and renewable energy, supported by decarbonized electricity* *and district heating. Buildings can use automation and controls to serve their occupants better, and to provide flexibility for the electricity system through reducing and shifting demand, and thermal storage*. The arguments above conclude ambitiously as *a smarter and more sustainable use of heating and cooling is within reach as the technology is available. Actions can be deployed rapidly, without prior investment in new infrastructure, and with substantial benefits for both the economy and individual consumers.* The document thus concludes on “tools and solutions” among which emphasis is given in promoting renewable based heating solutions and supporting the proliferation of Renewable-CHP systems. [13]

So far from the information and proposals contained in the EU-related documents mentioned above a clear picture can be formed of what is expected from the building sector in this “new era”:

- Addressing the energy poverty within European Union
- An EU-wide decarbonised building stock (through appropriate new buildings and renovations)
- Broad application of flexibility and demand-response
- Further deployment of Renewable-based Distributed Energy Sources
- Management of summertime space-cooling (peak-) loads in specific
- Implementation of automation and smart systems as a mean of facilitation
- Support of self-generation
- State-level resolution on the split-incentives barrier
- Deeper engagement of consumers in the energy market
- Better information of consumers on available sustainable technologies (for H&C)
- Better training of energy market-professionals on these technologies
- Acceleration on clean energy innovation
- Reduction of energy losses from buildings
- Improving short- and long-term performance of H&C systems (sustainability)
- Integrating the Heating and Cooling network to the electricity grid
- Application of thermal storage
- Preference on renewable-source heating and CHP solutions

Further ahead than the accumulation of these attributes the “profile” of a building after year 2020 is clearly defined in the famous Energy Performance in Buildings Directive of the European Union. The directive *promotes the improvement of the energy performance of buildings within the Union, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness*. Core goal of the EPBD is the proliferation *of the ‘Nearly zero-energy building’* as the eventual sole standard of buildings’ energy performance. According to EPBD *‘Nearly zero-energy building’ means a building that has a very high energy performance* […]. *The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby*. It becomes quickly apparent that “Energy Performance” is the key element in the practical definition of the NZEB. Therefore the Directive dictates Member States shall come up with a standardised methodology of calculating the energy performance of an existing or expected building and also come up with some "minimum energy performance requirement” for each building, achievement of which classifies the building as an NZEB and thus is acceptable.

Therefore the issue now transfers to the explicit definition and quantification of which these minimum energy performance requirements are. In Article 4 of the directive it is clearly stated that *the minimum energy performance requirements for buildings or building units are set with a view to achieving cost-*

optimal levels. Focusing now on what is considered “cost-optimal”, it is defined as *the energy performance level which leads to the lowest cost during the estimated economic lifecycle, where: (a) the lowest cost is determined taking into account energy-related investment costs, maintenance and operating costs […] and disposal costs, where applicable; and b) the estimated economic lifecycle is determined by each Member State. It refers to the remaining estimated economic lifecycle of a building where energy performance requirements are set for the building as a whole […].*

Theoretically, the Member State shall proceed through a specific process/methodology proposed by the EU, calculate the minimum energy performance requirements (always based on cost-optimality) and then express them in a transparent manner that *shall include an energy performance indicator and a numeric indicator of primary energy use, based on primary energy factors per energy carrier*. In compliance to that, based on the current progress of national definitions on NZEBs, Member States are setting national NZEB guidelines described as a maximum of kWh/m^2 per year for heating and cooling (the energy performance indicator), the share of renewable energy and indicators regarding the envelope performance, CO_2 emissions, technical system performance etc. [10].

Currently though, a bit less than half of EU States have not finalised yet their NZEB definition so no regional minimum energy performance requirements are issued (Greece and Portugal included), in order to be used for the design of the current building. For that reason, the methodology to be used in the current case study will be to begin from EU’s proposal for definition of the regional guidelines: calculating and deciding based directly on cost-optimality.

The Directive provides (in its Annex III) a simple, rather intuitive, *comparative methodology framework* in order to identify the cost-optimal levels: upon definition of a building type (based mostly on functionality and location/climate-conditions) a variety of energy efficiency measures shall be proposed to the reference building (in this case study a multi-apartment residential block). Then the final and primary energy needs shall be assessed for the “conventional” reference building and each one occurring from the various energy efficiency improvements (individually or in combination). Finally a cost-estimation technique shall be chosen (e.g. Net Present Value) and applied for every improved-energy-efficiency scenario allowing thus to compare cost-wise the cases and rank them in order of cost-effectiveness, concluding eventually to the identification of the cost-optimal ones (top few).

The make-or-break point of this methodology is deemed to be the accurate assessment of energy performance/needs. For that reason in Directive’s Annex I is proposed a *common general framework for the calculation of energy performance of buildings.* There, some key-parameters are indicated to be taken into consideration when MSs’ will be designing the methodology. In brief they include the actual thermal characteristics of the building, technical installations (heating/cooling, hot water, lighting, ventilation and any other heat-emitting elements), climatic-solar conditions and indoor climate goals. In addition to those the positive influence of other elements shall be taken into consideration such as: renewable- or CHP-based heating and electricity production systems, district-network sources and natural lighting.

Furthermore, apart from key-parameters and final criteria the Directive highlights some details in the final composition of the buildings. *For new buildings, Member States shall ensure that, before construction starts, the technical, environmental and economic feasibility of high-efficiency alternative systems […] is considered and taken into account*. This includes Decentralised, Renewable-based energy sources; cogeneration; district heating/cooling and heat pumps. The same applies to the existing buildings, they all should undergo major renovations and consider initially the same solutions as above. The proposal of these solutions in specific, along with the acceleration of renovations initiative of the Directive, aim at an eventual decarbonisation of the building stock by mid-century. For that reason strong emphasis is given once more to the Technical Building Systems. *Member States shall, for the purpose of optimising the energy use of technical building systems, set system requirements in respect of the overall energy performance, the proper installation, and the appropriate dimensioning, adjustment and control.* The system requirements should cover at least the heating, hot water, air-conditioning, large ventilation or any combination of such systems with, additionally, encouragement of introduction of intelligent metering systems. All of the above always under the scope of technical, financial and functional feasibility.

Eventually the Directive sets a deadline for the implementation of NZEB concept on the new buildings: beginning from 2021 all new buildings must be NZEBs while the deadline is set 2 years earlier for new public buildings, since 2019. For the existing stock of buildings that shall be refurbished, their post-refurbish requirements shall be close to NZEBs (based on cost-optimality once more) and the renovation rate is proposed from the Energy Efficiency Directive to be *3% of the total floor area* [per year] *of heated and/or cooled buildings owned and occupied by its central government* while no clarifications are set for the renovation of private buildings.

Overall the EPBD provides some clear yet flexible guidelines for Member States to design some straightforward, easy-to-implement requirements for the building sector that will allow to achieve a functional and cost-effective decarbonisation. Yet even though the goals, key-points and guidelines are rather clear, eventually the question remains: how do we get there? A transition to a new-era building sector through constructions and renovations requires inevitably a significant amount of capital that the average building owner does not seem to have. The financing of all these proposed actions and measures is a pervading issue in all researched documents, without exception.

The issue begins with lack of personal finance for the execution of energy efficiency improvements. It is true that *substantial benefits for both the economy and individual consumers, provided that (household) consumers can afford to invest or have access to the finance needed to do so.* Indeed *owners often do not undertake cost-efficient renovations because […] have financing constraints.* The same condition applies to Small and Medium sized Enterprises, while their energy demand is significant *they often have fewer resources and less access to finance to make improvements*. [13]. The public sector's facilities (hospitals, schools, offices etc.) face the same problem as here too *upscaling of investment […] also depends on availability of private finance and private energy service companies offering innovative mechanisms, such as energy performance contracting*[2] [12].

The adversity of the condition continues to the unfavourable financial decision-makers themselves. In the current market *despite the compelling economic rationale, there are few attractive financial products for building renovation* and even with these few the *financial institutions often remain reluctant to provide financial products due to perceived risks.* Eventually, as the Energy Efficiency Financial Institutions Group concludes, even *project promoters and investors still need to understand and trust that energy cost savings lead to additional available cash-flow and better energy performance leads to higher asset values* [13]. Therefore the lack of proper information among

---

[2] *'Energy performance contracting' means a contractual arrangement between the beneficiary and the provider of an energy efficiency improvement measure, verified and monitored during the whole term of the contract, where investments (work, supply or service) in that measure are paid for in relation to a contractually agreed level of energy efficiency improvement or other agreed energy performance criterion, such as financial savings.*

In an energy performance contract the beneficiary of the energy service avoids investment costs by using part of the financial value of energy savings to repay the investment fully or partially carried out by a third party. [15]

financial institutions (i.e. commercial funding sources) creates a lack of third-party finance that could compensate the lack of personal funds and thus unlock the energy efficiency uptake in buildings.

For the reasons above the EU takes a strong stance of resolution against the scarcity of financial sources. To begin with *In view of the importance of providing appropriate financing and other instruments to catalyse the energy performance of buildings and the transition to nearly zero- energy buildings, Member States shall take appropriate steps to consider the most relevant such instruments* and then *the Commission shall assist, where appropriate, upon request Member States in setting up national or regional financial support programmes with the aim of increasing energy efficiency in buildings* [16]. In the effort of Member States to *establish a long-term strategy beyond 2020 for mobilising investment in the renovation*, a specific measure proposed is that *Member States should encourage the use of financing facilities.* These facilities could be designed to draw funding from EU sources and institutions, national/fiscal sources, emission-tax schemes etc. and also encourage additional private investment (through their reliability). Containing now the capital means these facilities can become hubs of high-quality good-practice output through application of e.g. *criteria ensuring the achievement of both environmental and social objectives for the granting of funds, use of innovative financing mechanisms (loan guarantees, […] energy performance contracting, grants, subsidised loans and dedicated credit lines, third party financing systems) reduce the risks of energy efficiency projects and allow for cost-effective renovations even among low and medium revenue households,* link with agencies of quality control, *provide technical assistance, promote the energy services market and help to generate consumer demand for energy services.* Strong emphasis is paid to *use, where appropriate, energy service companies, and energy performance contracting to finance renovations* [15]. As observed, the expertise and tools of the private sector are highly valued and expected to have a great impact in the transition to a clean and cost-effective building sector. Additionally to this centralised type of administrating the issue, more market-level resolutions are proposed such as facilitating *the aggregation of small projects into investible packages* and to *encourage retail banks to offer products adapted for renovation of privately rented buildings (e.g. deferred mortgages, term loans) and disseminate best practices, also in relation to tax treatment of renovation.*

For the satisfaction of the proposals and solutions above there are mentioned distributed in the bibliography various institutions and organizations capable of providing—direct or indirect—financial support, aggregated in the list below:

- European regional Development Fund;
- PPP on European Energy-efficient buildings;
- European Investment Bank initiative: EU sustainable energy financing initiative;
- Marguerite fund: 2020 European Fund for Energy, Climate change and Infrastructure;
- Joint European Resources for micro to medium enterprises;
- Energy Efficiency Finance Facility
- Competitiveness and Innovation Framework Programme
- European Bank for Reconstruction and Development
- European Energy Efficiency Fund.
- Structural Funds and the Cohesion Fund
- European Structural and Investment Funds
- Horizon 2020 research and innovation programme
- European Fund for Strategic Investments

To conclude, lack both of own-capital and of third-party finance as well creates a tough blockade on the progress towards the sustainability goals of the building sector. EU takes great care in mapping this impediment and devising measures over it but still it seems to be the first and foremost reason that measures are maybe being studied but rarely adopted. For that, cost-optimality makes great sense as a priority in the designing of solutions.

Overall, in this chapter key documents of the European Union have been reviewed in an effort to identify what are EU's goals and intentions from the building sector in the times ahead. A wide range of attributes has been managed to be identified and now, keeping these in mind, the process can proceed with the design of the case study building of this thesis under the arising guidelines.

1.3. Sustainability challenges

The aimed transformation in the building sector is no small endeavour. As seen previously large research and coordination of actions exists on behalf of EU in order to facilitate this. Beyond the definition of key-goals and some of their relevant impediments a lot more barriers and challenges exist in the field of implementing energy efficiency and in the sustainable-building design and construction in general. So far the strongest barriers can be summarised in the following types:

- Lack of information / communication about the applicability and potential of energy efficiency improvements in buildings (both on building owners and energy professionals)
- Unfavourable regulatory / policy environments
- Inadequate technology characteristics
- High capital / investment costs
- “Split-incentives”

[14]

This sub-chapter is dedicated to identify and point out any further critical challenges and barriers as clear as possible.

1.3.1. Financial

Real Estate is one of the biggest sectors of every country’s economy. A lot of capital is invested in construction and thus residences are considered strong assets that even participate in the country’s financial system (can be leveraged into loans, set as collaterals etc.). Given today’s financial condition in Europe—a not-so-booming economy—the impact on the construction sector is double: from the one side there is no capital to invest in a new construction and on the other side the subdued economy reflects on housing’s low prices. Construction costs for new buildings in Greece, in specific, range at 1,000 – 1,200 €/m^2 [17], [18] for a fully-finished conventional type of building, i.e. with not significantly high thermal properties. Additional thermal insulation of the envelope etc. will yield even higher prices depending on the chosen interventions.

Then, even if the building is constructed despite scarcity of finance, the real estate sector will have its influence on the financial success of the project. Real estate prices per m^2 vary greatly depending from location to location, building to building even real estate agent to agent. A more statistically reliable idea about the building prices can be obtained from the Greek Government’s “Table of Objective Values for Buildings” an index according to which constructed areas are evaluated on an “objective” and not current-market/speculation value (upon which taxation is applied and other statistical values are calculated). As observed there, the real-estate value of buildings in all major urban areas of the country range from 500 to 8,500 €/m^2 [19]. Therefore, apart from the type of construction, the location of construction also affects the financial viability of the project.

Another critical factor, as in every investment venture, is the time-related financial indexes of the project, i.e. interest rates and cash-flows. For such big investments there usually exists some form of bank lending and thus this plays a critical role in the pay-back of the investment. In the counter-end of time-related expenses comes the steady source of revenue (in case the building is rented to tenants) / the avoided expenses (if one chose to build his/her own-house rather than renting a dwelling). Interest rates in Europe are in rather low levels—given the economic downturn—with Central bank rates near zero or even negative [20] the Monetary Financial Institutions lending rates to companies range at 1.29 – 2.69 % in June 2017 [21]. Yet once more in Greece given the extreme economic conditions the latest weighted average interest rate for loans to companies is around 4.86% in January

2017 [22]. On the other hand rents fluctuate on a wide basis: on the real estate of each area, on the demographics of the tenants, on the overall luxury of the residence etc.

A final significant, distinct cost related to occupancy of a residence is the ongoing utility costs. These are not directly related to the building structure itself like the previous ones but more on the type and intensity of use of it. In this case the most relevant utility bills are the ones of electricity and heating fuel (gas or liquid petrol). In Europe prices fluctuate quite a lot (0.096 – 0.295 €/kWh for electricity and 0.039 – 0.117 €/kWh for natural gas in households 2015) depending on the country [23] and in Greece the prices come at an average minimum of 0.08 €/kWh for electricity [24] and 0.059 €/kWh for natural gas [25] even though only a couple major cities have a gas network with more popular solution being diesel fuel oil at 0.065 – 0.098 €/kWh in 2016 [26]. The heating cost thus can be even bigger as older fuel oil boilers tend to be far less efficient than newer gas boilers. Therefore a consideration that can be made is integrating the energy production assets to the building investment and thus increase the revenue of the building owner by the amount of the, otherwise towards a third company, utility bill.

1.3.2. Environmental

From the environmental perspective, buildings face significant sustainability challenges as well. Even though a building is a static object during its lifetime and thus it “intervenes” with the environment mostly during its construction and decommission, the use of the building from its occupants has a lot of “exchanges” with the environment. Beginning from the core focus of this current analysis, the energy use, electricity and heating in a building come to a large extent from fossil fuels, thus the use of buildings is responsible for a large part of GHG emissions in EU, as mentioned in an earlier chapter. Minimizing these emissions—in a cost-effective manner—is a core objective of the work to be performed further ahead.

Yet greenhouse gases are not the only mass flows towards the environment caused by the human activity inside buildings. Residences (and service facilities) are responsible for a large output of solid and liquid waste (sewage) as a result of human functions. Municipal Solid Waste in Europe (i.e. *waste from households, as well as other waste which, because of its nature or composition, is similar to waste from households* [27]) are produced in great quantities, on average a 476 kg/capita each year (ranging all the way from 247 to 789 kg/capita in European countries) with 25 % of it being landfilled in 2015 [28]. Recycling varies greatly through member states (as much as from 0 to a bit more than 60%, [29]) and landfill practices are far from sustainable. With most of the solid waste being biodegradable (over 40% in half of Europe) and the majority of the rest recyclable plastic glass and metal [27], there exists a large margin for reduction of solid waste streams from buildings through in-situ management of biodegradables, leaving only recyclables as out-going streams. Various techniques exist for decomposition of organic waste the simplest ones being aerobic composting and vermi-composting. A more advanced and complex technique, anaerobic digestion, allows as well for the production of gas fuel (bio-gas) and therefore poses an even higher advantage of exploitation.

Lastly the liquid effluents of buildings, commonly “sewage”, are another stream of high pollution capability requiring costly treatment before released to the environment. The interesting fact here is that from a building’s total effluents only about 35% of the liquid streams have a high organic and microbial load i.e. require intensive treatment (the toilet flushes), while the rest 65% is what is referred to as “grey-water”, meaning water that with light treatment (cost-feasible in a domestic level) can be reused safely for non-consumption purposes (e.g. flushing the toilet, mopping the floors or watering the plants) [30]. A 65% reduction in the volume of effluents (even though it would increase the concentration of treatable material) allows for a much lower capacity (thus cost) of pipe network and as well treatment infrastructure, making grey-water reuse a more sustainable practice overall.

1.3.3. Living experience

One of the biggest issues and thus impediment in the application of any alternative, more sustainable options is that almost no one wishes the current living standards to be compromised. All the technological advancements the last decades (or even centuries) have raised the bar for living-experience and now that we realise many of them come with dangerous side-effects we are not so keen on rolling back to previous /alternative more sustainable yet "lower" everyday life-quality states. Therefore, a major challenge today is to manage the transition to a sustainable system without compromising significantly our living standards.

The same applies to the building sector as well. The living experience during the occupancy and use of a building is perhaps the sole "success index" of the building, apart from providing shelter and safety. Some of the factors that make living in a building enjoyable are more directly related to the construction/design and energy use of the building, that are of interest in the current work. To begin with it is broadly accepted that there exists a minimum amount of space requirement per occupant. No explicit congruence exists on the matter but various organisations worldwide provide their own suggestions. Most notably, United Nations in a report on overcrowding around the world sets as the limit 20 m^2/occupant [31]. For residential houses, in the U.S.A., it is proposed a minimum area of 15 m^2/occupant, a number of total house rooms at least equal to the number of occupants and no more than 2 persons per bedroom, (data corroborated with work of UK's Office of the Deputy Prime Minister) [32]. The values above provide a reasonable guideline for the design of any residential building, which shall be kept in mind for the building-design phase of this case study.

Yet another important parameter of indoor living quality is the amount of illuminance available in the living spaces. Well-lit rooms improve the functionality and mood of people occupying them and this is specifically true for the penetration of natural sun-light during day-time. This concept known as "daylighting" comes to play more and more important role in the design of buildings nowadays. As a new concept to receive extensive attention on its own there exist no clear regulations. The Leadership in Energy and Environmental Design is a U.S.-based organisation concerned with this topic and issues guidelines regarding the illumination of buildings as minimum illuminance per a portion of total floor area over a designated amount of time per year/usage hours [33]. The aforementioned levels require computer simulation in order to be calculated and no simple rule-of-thumb exists over the issue. Yet on the other side, fenestration allows for a higher influx of solar energy, something that increases cooling loads in summer, and has lower insulation than walls, something that increases heating losses and thus loads in winter. For that reason also a maximum limit of fenestration is proposed for buildings. As stated by ASHRAE the total vertical fenestration area can't be more than 40% of total wall area [34]. The findings above are somewhat helpful, yet not very explicit. Therefore additional attention shall be paid for the fenestration during the design phase of this case study building.

Related directly to the energy use of the building is of course the issue of indoor thermal comfort. According to ASHRAE, the leading organization in building climatisation, defining a comfortable indoor temperature depends on a very broad variety of parameters (season, humidity, light exposure, human activity level, clothing, personal preference etc.) but in general falls within the range of 19.5 – 27.8 °C [35]. In the case of living areas (e.g. living rooms and bedrooms, instead of shops, gyms and bank halls) there should preferably exist the possibility of adjusting freely the temperature so it can match the occasion-to-occasion needs of the occupant.

Lastly, related to the central-equipment installation of the building comes the issue of indoor air quality. Humans and their activities emit by-products in the air that deteriorate the air-quality (water vapour, odours, carbon dioxide and more). For that reason a constant removal of these (through either filtration or exhaustion) is necessary. The simplest method is of course a continuous partial replacement of the indoor air with fresh outdoor air. To ensure that, use of ventilation equipment is necessary and the outdoor air has to be thermally conditioned before introduced inside, with both factors being connected to costs, energy use and emissions and thus deserving careful consideration at design phase. The fresh air influx depends on various parameters just like the setting of indoor temperature. The two key parameters are the number of occupants and their type/level of activity (judging from the type of room) so air refreshment rates are mostly based on that. An easier alternative is a rule-of-thumb designation of "air changes per hour" in the total volume of the indoor space, based on its type/use. Despite, there exists no absolute congruence among the professionals on the field on the minimum/optimal values. It is stated in ASHRAE 62.2 that for houses the ventilation rate should be *7.5 cfm per person plus 1 cfm per 100 square feet,* argued to be up to 3 cfm/100 ft^2 (i.e. 3.54 L/s per person plus 5 to 15 L/s per 100 m^2) [36] with higher requirements for special places like kitchens (minimum 100 cfm of intermittent ventilation or 5 air-changes-per-hour of continuous ventilation) and bathrooms (minimum 50 cfm of intermittent ventilation or 20 cfm of continuous ventilation) [37]. Elsewhere it is stated that the fresh air rate in residences must be 2.5 – 7.5 L/s per person [38]. In general it is considered that a minimum of 4 air changes per hour are necessary in any indoor space [39]. All these guidelines will have to be carefully assessed during the design phase so the chosen size of equipment is adequate yet cost-optimal.

2. Designing a sustainable NZEB

In the previous chapter a general effort has been made to familiarise with the notion of "residential building"; understand what are the goals and intentions of governing bodies from it and what are the main sustainability challenges related to their existence. A lot of insightful material has been uncovered and a good understanding has been achieved regarding some make-or-break points of sustainable building design. Yet all these are general qualities that fit in the entire "residential" or even just "building" sector. Eventually, every building is built upon a request to satisfy some very specific requirements, which in turn define uniquely the design and composition of the building.

It is truly astonishing how many nuances influence the design and composition of one building that in the end it proves that if the designers are deeply committed to creating an optimal building for the occasion, then no two buildings should ever be the same. Beyond the fact that every human is unique and thus if the house correctly represents his/her personality should be uniquely designed as well, there exist more general (yet still more specific) qualifications that affect the final outcome. For example the number and type of occupants affects the size and design of the house (different for two students, or a married couple, or a family of 4). Then it depends the intention of use (different if it is meant to be an everyday residence, or just a vacation house for few days a year). Then comes into place the geographic region it is located based on its climate (of course dwellings in the North of Europe will be much more different than ones in the South) but even in a much smaller scale based on the microclimate (there will be different interaction of the building with its surrounding if it is positioned by the coast in a lush plot hit by sea-breeze rather than 100km away in the middle of an arid, sun-struck field). Even minute differences such as the orientation of the building can affect the final decisions (a house having its largest façade facing towards the equator—e.g. due to plot restrictions—will have different needs than one exposed more to the West or East direction). So far only the "passive" elements of the building are being considered (design, fenestration, building materials, orientation etc.). Expanding the concept of "building composition" to the energy sources and heating/cooling-ventilation equipment, more parameters come into play such as the energy production potential of the location (wind, solar), cost-availability of the related equipment (PV panels, solar-thermal panels, heat pumps, thermal storage tanks etc.), price of competitive energy sources (grid electricity, fossil fuels etc.) and the list goes on. These are only few of the main parameters that affect the design and composition of a residential building [40].

The effort of the work from here on will be to identify and combine all these parameters in such a way that a finished building (structure, HVAC equipment and potential energy sources e.g. PV panels) will form a sustainable, yet coherent and competitive proposal compared to any other alternative, ergo "Feasibility assessment and investment-proposal optimization for an NZEB".

2.1. Designing the building

The design of a building begins with the end in mind: the purpose it is going to serve. Yet here that the building is of residential nature but a financial investment at its core a more business/market driven approach will determine the exact nature and thus the design of the building. The key financial aspect of an investment is to maximise its profitability, i.e. to pay-back the investment quickly and keep creating profits for as much as possible. In the real estate revenues are created through rents so the key goal is to maximise rent extraction. Considering regardless of specific markets, the larger the house (more floor area) the higher the rent so the final size is not of such relevance. The goal thus is to identify the type of use (/building) that maximises rent *per* area. Judging from own experience, in shared-housing cases where a larger area is shared among individual tenants (e.g. a flat on a room by room basis) the rent price can be relatively low for each tenant but cumulatively rather high for entire residence. This is the common case of student housing in flats or dormitories. Students are also a more "privileged" type of buyer since their expenses are considered of high priority (as they are essentially investing on their future selves) so they are a quite robust, reliable market segment in general. For that reason the type of building is intended to be a student dormitory.

Coming to the actual architectural design of the structure, student houses are of quite minimal nature as the average expectation is not a luxurious living but minimising the expenses. Therefore is chosen an arrangement of individual bed- and bath-rooms with common cooking and laundry facilities. Designing more from an energy-optimisation perspective rather than aesthetics, the exposed area (facades) of the building should be minimised thus an as much as possible cube-like lay-out is considered. The dormitory is intended for Southern Europe (initially) so the constant insolation of the Southern facade can be an issue of increased loads in the summer and so absolute minimum fenestration will be applied there. Finally the total capacity of the dormitory is taken as a first estimation at about 30 occupants. Keeping still in mind the minimum fenestration and floor-area per person requirements, further advice is sought from an architect in terms of minimum dimensions for the various rooms and overall experience in building design. Therefore the final layout of the dormitory is concluded as in Appendix A

In brief, each floor features 10 private bedrooms with bathroom, connected by a common corridor with the kitchen and the staircase on the north part of the building. For a total of 3 same floors and one of the occupant rooms being used as the laundry- and crucial electronics installation-room the dormitory has a final size of 695.67 m^2 serving 29 occupants.

2.2. Locating of the building

Choosing the location of the building is highly important for it affects the financial viability of the project in more than one ways, given that construction and real estate markets are highly local. To begin with the structure, the local construction market will determine the investment cost. Then the local real estate will affect the rent prices, thus the revenue cashflows of the building. Usually these two go hand-in-hand since they are highly connected markets. Beyond these parameters, location is strongly related to thermal conditions (and thus heating/cooling needs) as well energy sources. Depending on the regional and local climate the heating and cooling needs will variate accordingly and the local insolation as well wind-potential affect how much energy is available to extract for covering these needs, or alternatively, the local energy market prices (grid electricity and fuels) what the annual cost will be on these utilities.

As the clues indicate above, the final "levelised cost" of "residing" (i.e. rent + energy use) is a function of many location-dependant variables that some are completely non-related to each other. For that reason no "analytical" approach can be taken in order to optimise the choice (and minimise the cost) so a trial-and-error approach will be followed: Initially some locations will be chosen based on their climatic conditions. For reasons of simplicity (as to maintain most variables under a common denominator) all locations will be within Greece. The final selection of locations depend upon the availability of data for the analysis and the degree that they are differentiated climatically. A reasonable differentiation criterion is the use of "hardiness" zones from agriculture. Hardiness zones are Average-Minimum-Winter-Temperature zones of a geographic region, separated in 10 °F (5.6 °C) increments (e.g. for zone 10, AMWT is -1.1 – +4.4. °C; for zone 9, it is -6.7 – -1.1 °C; etc.) and is used to determine the survivability of plants in different locations [41]. This concept relates directly to the Heating and Cooling Degree Days (the sum of degrees the outdoor temperature deviates lower and higher, respectively, from the desired indoor temperature range for all the days of the year) used in estimating thermal needs and size HVAC equipment accordingly, yet it is more detailed as seen in the figures 2 and 3 below. As observed 3 hardiness zones exist in Greece (zones 10, 9 and 8), which coincide with the 3 major official climatic zones of Greece (A, B and Γ as seen in figure 4). Therefore 3 locations shall be chosen for the analysis, one for each zone. Juxtaposing this with the availability of weather data, the exact choice of software comes in place. For the determination of the thermal needs the software EnergyPlus will be used. EnergyPlus utilises specific files of weather data for the extraction of results, found in its own libraries. Browsing through the available data files, ones can be found for the cities of Thessaloniki (hardiness zone 8) and Athens (zone 9). In lack of a weather file on a Greek city of zone 10, the closest alternative to Greece will be considered which proves to be city of *Larnaca in Cyprus* and has an almost identical latitude (i.e. expected solar potential) with city of Chania in Greek island of Crete.

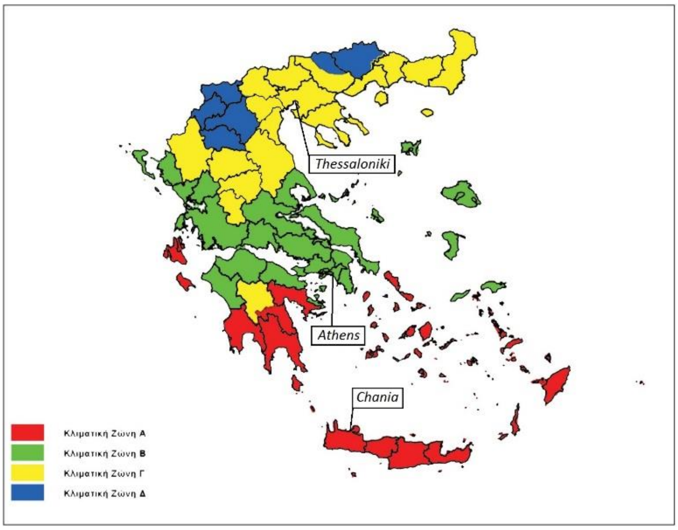


Figure 1: Climatic Zones of Greece [101]

2.3. Assessing the energy needs of the building

2.3.1. Passive design of the building

To begin with it is common knowledge that the highest energy- and cost-saving potential is in the energy that was never spent in the first place, i.e. energy use and losses reduction is the most impactful improvement. Assuming an already rational use of energy (while as well it is beyond the scope of the current work) then minimization of losses in the building is the key issue at hand. A higher-insulative building envelope (floor, walls and roof) is a one-time investment that prevents excessive consumption of energy for meeting the thermal needs, thus is an easy feature to cost-optimise based on insulation, fuel prices and intended payback period.

As a matter of fact the European Insulation Manufacturers Association has already performed such a research for entire Europe (various cities) resulting in insulation-level proposals for each city based on cost-optimality of different scenarios (energy prices predictions). Their conclusion is a range of U-values (thermal conductivity) for each building element (roof, walls and floor) based on the "climate"-profile of each city (number of HDDs and CDDs). Therefore, of the 3 chosen locations only Athens happens to be directly within the research. The optimum values suggested for Athens are 1.45 W/m^2·K for floor, 0.27 W/m^2·K for roof and 0.35 W/m^2·K for walls [42]. For the remaining 2 cities the values shall be extrapolated from the HDDs of each city based on a HDD vs optimal wall U-value correlation.

For the calculation of heating and Cooling Degree Days a base temperature is used. This temperature can be arbitrary based on the preferred conditions for the building, case by case. Yet in bibliography, for the purpose of comparability, some standard base temperatures are used. According to European Environment Agency *the baseline temperatures for HDDs and CDDs are 15.5 °C and 22 °C, respectively* [43], therefore these values shall be used to calculate the HDDs for Thessaloniki and Larnaca. An online calculation tool is chosen and first is "calibrated" to ensure the use of similar baseline temperatures. First Athens is chosen and H-CDD are calculated on the basis of 15.5 and 22 °C. Regardless of the difference on the calculation year between the Eurima report and the online calculator, the results came the closest for baseline temperatures of 15.5 and 18.5 °C (deviations of 3.7% and 5.2% respectively). It is possible that a CDD baseline of 18.5 °C is used in the online calculator since in the U.S.A. the temperature of 65 °F (i.e. 18.33 °C) is used as a universal baseline [44]. Thus eventually the set of 15.5 and 18.5 °C will be used in the calculation.

As results are obtained, HDDs/CDDs are for Thessaloniki there are 1,347/932 and for Larnaca 483/1,474 [45]. From the Eurima report can be obtained the recommended U-values for the walls in these cities, approximately 0.27 and 0.45 W/m^2·K respectively [42]. The values proposed from Eurima are considered to be the cost optimal levels of insulation based on regional climatic conditions, energy prices and insulation costs. Yet here a far more detailed approach will be taken, for Greece specifically, and thus these values shall be used only as indications and an approximate starting point for the optimization process to begin.

Coming now to the exact insulation design of the building, heat losses occur from a space through its surrounding surfaces to the adjacent spaces consecutively until they reach the building "envelope" and dissipate to the outdoor environment. Usually the entire residence is thermally conditioned so only the envelope (i.e. surfaces facing outdoors: roof, walls and floor) are of interest. This usually leads to a decision of insulating the entire building's envelope in order to reduce heat losses. Yet, as it can be easily intuitively understood, reducing the size/number of spaces to be heated/cooled reduces proportionally the thermal demands. For that reason, rooms of reduced use (e.g. garages, storage, laundry rooms etc.) can be excluded from the thermal conditioning with no significant impact in the living comfort of the residency's occupants.

Reflecting this upon the current case, the private rooms are designed to have an almost continuous occupancy, while the common spaces (i.e. the kitchen and the staircase) are expected to have a significantly reduced occupancy. The staircase is of much less interest to thermally condition of course, while for the kitchen the level of occupancy can still justify the need for thermal treatment. Yet for the case of the kitchen a special condition applies. As mentioned previously in chapter 1.3.3 the kitchen due to the higher emission of odours from the cooking activity requires a higher ventilation rate. Additionally this air has to be completely extracted and not recirculated to the rest of the rest of the house through the ventilation since this would spread rather than exhaust the odours. Furthermore the high and abrupt thermal loads that occur from the cooking make it harder to stabilize the kitchen temperature through the HVAC system while they also increase the cooling loads in the summer. Given all the reasons above, for the warmer zones of Greece examined here, it makes eventually absolute sense to have a separate non-heated/cooled ventilation system for the kitchen (and the staircase) and thus design the HVAC system and position the required insulation accordingly in order to provide regulated thermal comfort solely for the private rooms. To conclude the envelope insulation is illustrated below in figure 5 as the blue boundaries:

Figure 2: The insulation (blue) and corresponding thermal-conditioning zone.

The exclusion of the staircase and the kitchen is a decision made currently on reasonable assumptions. Upon execution of the simulation and extraction of results it will be determined how acceptable it is in terms of thermal conditions and relevant actions will be taken.

3. Thermal performance simulations and results

3.1. Run Parameters

3.1.1. Run period:

EnergyPlus runs the simulation on a time-step basis and has the ability to choose the simulation run period. While some parameters of the simulation can be designed to change from time to time during the run others are set for the entire run. Based on the design of the PV panels array, the tilt of the panels cannot be varied during the simulation run, yet it is proven that adjusting the tilt throughout the year allows for a much higher capacity ratio and thus return on investment of the PV panels. For that reason the entire year has been separated into 4 periods around 4 key dates—based on the solar zenith: the winter solstice (21 December), the spring equinox (21 March), the summer solstice (21 June) and the fall equinox (21 September). Therefore the simulation periods are defined as: 7 November to 6 February, 7 February to 6 May, 7 May to 6 August and 7 August to 6 November. The tilt of the solar panels has been optimised for yielding the maximum output on these periods.

3.1.2. Schedules:

For the parameters that can be variated during the simulation schedules have to be defined. In the following table 1 can be found the parameters and their values for each time-period:

Kitchens Use	Kitchen Occupancy	Laundry use	Student occupancy	Occupant Activity level	Lights	Electronics use
Fraction	Fraction	Fraction	Fraction	Any Number	Fraction	Fraction
Through: 12/31	Through: 12/31	Through: 12/31	Through: 12/31	Through: 12/31	Through: 12/31	Through: 12/31
For: AllDays	For: AllDays	For: AllDays	For: AllDays	For: AllDays	For: AllDays	For: AllDays
Until: 15:00	Until: 08:00	Until: 08:00	Until: 7:00	Until: 07:00	Until: 18:00	Until: 7:00
0	0	0	1	70	0.1	0.1
Until: 17:00	Until: 09:00	Until: 24:00	Until: 8:00	Until: 24:00	Until: 24:00	Until: 8:00
1	0.4	1	0.9	100	1	0.9
Until: 20:00	Until: 15:00		Until: 9:00			Until: 9:00
0	0.1		0.8			0.8
Until: 22:00	Until: 17:00		Until: 10:00			Until: 10:00
1	0.6		0.7			0.7
Until: 24:00	Until: 20:00		Until: 15:00			Until: 15:00
0	0.1		0.1			0.1
	Until: 24:00		Until: 16:00			Until: 16:00
	0.6		0.2			0.2
			Until: 17:00			Until: 17:00
			0.3			0.3
			Until: 21:00			Until: 21:00
			0.9			0.9
			Until: 24:00			Until: 24:00
			0.8			0.8

Table 1: Schedules of simulation parameters

3.1.3. Materials:

For the software to calculate the thermal performance of the building elements it requires the thermal properties of all the composing parts of the building envelope and interior. While the software has it's own database of common building materials, in the table 2 below follows the list with some specific materials and their properties used in the simulation:

	Red clay hollow brick	Notes/References
Thickness (m)	0.09	[46]
Thermal conductivity (W/m·K)	0.43	[47]
Density gross (km/m^3)	911.4	[46]
Specific heat (J/kg·K)	900	[48]

	ORTHOBlock	
Thickness (m)	0.30	[49]
Thermal conductivity (W/m·K)	0.106	[49]
Density gross (km/m^3)	800	[49]
Specific heat (J/kg·K)	900	[48]

	ORTHOBlock	
Thickness (m)	0.25	[49]
Thermal conductivity (W/m·K)	0.108	[49]
Density gross (km/m^3)	800	[49]
Specific heat (J/kg·K)	900	[48]

	ORTHOBlock	
Thickness (m)	0.10	[49]
Thermal conductivity (W/m·K)	0.419	[49]
Density gross (km/m^3)	875	[49]
Specific heat (J/kg·K)	900	[48]

	YTONG (Aerated concrete) slab/ load-bearing block	
Thickness (m)	0.250/0.350	[50]
Thermal conductivity (W/m·K)	0.16	[50]
Density (km/m^3)	600	[50]
Specific heat (J/kg·K)	880	

	YTONG (Aerated concrete) block	
Thickness (m)	0.125	[51]
Thermal conductivity (W/m·K)	0.13	[51]
Density (km/m^3)	525	[51]
Specific heat (J/kg·K)	880	

	Durosol (Expanded Polystyrene Insulation)	
Thickness (m)	0.02-0.12	[52]
Thermal conductivity (W/m·K)	0.033	
Density (km/m^3)	28	[52]
Specific heat (J/kg·K)	1400	[53]

Table 2: Properties of building materials

3.1.4. Construction:

The materials above—along with others from the database of the software—used in the construction of the case-study compositions are then combined in order to form the various building elements (e.g. external and internal walls, floor and roof slabs etc.). The exact combinations used can be seen below in table 3:

WINDOW double-pane	Ytong 350mm wall (R=2.27)	Ytong 125mm wall	Ytong 250mm slab ground (R=1.61)	Ytong 250mm slab roof (R=2.28)	Ytong 250mm slab interfloor	ORTHOBlock 300mm wall (R=2.91)	ORTHOBlock 100mm wall
CLEAR 3MM	Cement Placter: Sand aggregate - 20mm	Gypsum plaster: Lightweight aggregate - 13mm	Cork tile - 3.2mm	Built-up roofing - 10mm	Cork tile - 3.2mm	Cement Placter: Sand aggregate - 20mm	Gypsum plaster: Lightweight aggregate - 13mm
AIR 3MM	Ytong 350mm	Ytong 125mm	Ytong 250mm	Durosol EPS Insulation 20mm	Ytong 250mm	ORTHOBlock 300mm	ORTHOBlock 100mm
CLEAR 3MM	Gypsum plaster: Lightweight aggregate - 13mm	Gypsum plaster: Lightweight aggregate - 13mm		Ytong 250mm	Gypsum plaster: Lightweight aggregate - 13mm	Gypsum plaster: Lightweight aggregate - 13mm	Gypsum plaster: Lightweight aggregate - 13mm

Brick Insulation wall (R=3.68)	Hollow Brick 90mm wall	Concrete ground floor (low ins R=0.79)	Concrete ground floor (high ins R=1.70)	Concrete roof (low ins R=2.98)	Concrete roof (high ins R=3.89)	Concrete interfloor
Cement Placter: Sand aggregate - 20mm	Gypsum plaster: Lightweight aggregate - 13mm	Cork tile - 3.2mm	Cork tile - 3.2mm	Built-up roofing - 10mm	Built-up roofing - 10mm	Cork tile - 3.2mm
Durosol EPS Insulation 100mm	Standard hollow brick 90mm	Concrete 200mm	Concrete 200mm	Durosol EPS Insulation 90mm	Durosol EPS Insulation 120mm	Concrete 200mm
Standard hollow brick 90mm	Gypsum plaster: Lightweight aggregate - 13mm	Durosol EPS Insulation 20mm	Durosol EPS Insulation 50mm	Concrete 200mm	Concrete 200mm	Gypsum plaster: Lightweight aggregate - 13mm
F04 Wall air space resistance				Gypsum plaster: Lightweight aggregate - 13mm	Gypsum plaster: Lightweight aggregate - 13mm	
Standard hollow brick 90mm						
Gypsum plaster: Lightweight aggregate - 13mm						

Table 3: Construction compositions of the buildings

3.1.5. Zones:

For the execution of the simulation the building spaces must be divided in “zones”. In general “zones” can be identified as spaces / volumes of air that have the same indoor conditions or that their thermal needs need to be assessed individually (e.g. because there is a different unit proving the conditioning in each zone). In the current case the building is separated in 3 different zones: “ZONE ONE”, the main body of the building containing the bedrooms of the residents; “KITCHEN”, the rooms that will be used for the cooking needs of the occupants; and “STAIRS”, the elevator / staircase used to access the building. This division is made since in “ZONE ONE” is the where the air conditioning will be applied, in “KITCHEN” exist severe heat loads due to the cooking appliances, requiring stronger ventilation to abduct this heat and in “STAIRS” the occupation is minimal so is of no interest to thermally condition and thus should be excluded altogether from the HVAC design.

3.1.6. Windows:

Fenestration is another key element of the building's synthesis. While the design / size of the windows is explained in the main report, the exact composition of the windows is of critical importance as well in the thermal performance of the building. Here the windows are double paned, the standard design, with two layers of clear 3mm glass interrupted by an air gap of 3 mm. Another critical element of the window is its frame. Window-frames account for a significant mean of heat / cool leakage to the outdoors so it's preferable if they are included to the simulation. The chosen frame for this case is the standard thermal-interrupted aluminium frame (with a conductivity of 2.5 W/m·K, [54]) with an average width of 10 cm.

3.1.7. Shading:

Shades affect greatly the thermal performance of a building as well since they can prevent solar irradiation from entering the building through fenestrated areas and heating up parts of the facade. In this design shade is provided from parts of the building itself, the balconies. The balconies of the rooms extend by 1.5 m from the facade and are separated from each other with partitions, i.e. every 3.5 m. therefore in the simulation design shading overhangs and fins are added accordingly in order to simulate this behaviour of the building.

3.1.8. People:

The amount of people in the building impacts, of course, the results since people, apart from a heat load themselves affect also the use of equipment and thus even further the heat loads. Additionally the ventilation needed depends on the amount of people as more people means more "pollutants" in the air and thus a higher extraction rate of them is necessary in order to maintain the air quality. Fr the simulation the total amount of people is considered to be 29 while the schedules of their presence in the spaces of the building depends on the space and the time of the day, as described in the schedules section.

3.1.9. Lights:

Lights are necessary for the operation of a building throughout the day. Here lights are assessed for the main rooms and the kitchen. In each bedroom is considered to be ~37 W (including the bathroom) and with the laundry room the lights of ZONE ONE sum up to 1,100 W. In the kitchen, a total of 80 W per kitchen (i.e. 240 W in total) are considered. The use of them is as described in the schedules chapter.

3.1.10. Electric Equipment:

The use of electric equipment is a profound aspect of our everyday lives in our homes. And since—almost—all electricity used is converted to heat eventually and dissipated to the surroundings, the proper assessment of electric equipment is one of the most crucial parameters in the energy simulation. Here are considered four main types of equipment used in the facility. In ZONE ONE it is estimated that each student uses a personal computer of about 100W power and some other equipment (e.g. an office light, a sound system etc.) of a total 50 W. For the 29 people of the residence this accumulates to 4350 W used according to the assumed scheduled of student occupancy and activity in the residence. Additionally, in ZONE ONE, the laundry room operates. It is estimated that on average a person needs a 5-6 kg laundry per week for its clean clothing needs [55] and an average laundry machine consumes about 0.9 kWh per laundry cycle in Southern Europe [56]. Yet a significant amount of this power is for heating up the water and thus it is flushed in the sewer rather than dissipating to the environment. For the laundry in the specific facility the hot water is derived from the building's hot water production system for this reason it is decided to exclude completely (both from the electricity consumption calculation and heat load) the electricity used for increasing the water temperature. As literature illustrates about 90% of a laundry machine's energy consumption is for heating up the water [57] so here the electricity consumption per cycle will be considered as 0.1 kWh. Assigning the laundry in 3 hour slots a time period of 8am to midnight results in an equivalent of 35W continuous electricity consumption. Regarding the kitchen now the main electric consumption here is considered to be the use of stovetops and the refrigerators. For the stove tops is assumed a use in ~25 min intervals of 2 people at a time for lunch (3 to 5 pm) and dinner (8 to 10 pm) as seen on schedules. A stove top is expected to have an average consumption of 1,500 W [58] which results in a 9,000 W consumption from the kitchens. For the refrigerators an average space per person is estimated at 140L of fridge capacity [59], [60] thus each kitchen will need a total of about 1400L fridge space. This translates roughly to a total of 9 (for all kitchens) 500L refrigerators. A high efficiency fridge of such size consumes 325 kWh per year [61] which equals to a 37 W (for all fridges ~340 W) on a 24 hour basis.

3.1.11. Infiltration:

"Infiltration" refers to the unwilling entering of outdoor air into the building. This is a natural phenomenon as no building is completely air-tight and thus due to external winds, thermal effects in the building and other reasons air will always leak indoors. This plays a crucial role as the HVAC equipment will have to compensate for that in order to maintain the desired indoor conditions. There exist various methodologies for calculating the air infiltration but as a design standard it is considered that air leaks into the house at a rate of 0.25 air changes per hour (i.e. a complete replacement of the building's air volume in one hour). This value is used here as well for all spaces.

3.1.12. Ventilation:

"Ventilation" refers to the intended, and sometimes forced through HVAC equipment, renewal of air inside the building for reasons of maintaining the air quality (through exhausting the metabolic gaseous products, e.g. CO2, odours etc. and introducing fresh outdoor air). The ventilation rate is directly proportional to the size of the building, the amount of occupants and their level of metabolic activity. As mentioned in the main report, according to ASHRAE the ventilation need for a building are 3.54 L/s per person plus 5 to 15 L/s per 100 m^2. For a total of 29 people this corresponds to 135 L/s of ventilation for the bedrooms zone, proportional to the occupancy of them. In the kitchen different standards apply as there the emission of gaseous by-products is even higher due to cooking. Therefore here is required either ~50L/s of intermittent air exhaustion or a constant refresh of 5 air changes per hour. Here the option of intermittent 50L/s is chosen, following the kitchen use schedule.

3.1.13. Thermostat setting:

The thermostat is responsible for indicating whether heating or cooling is needed in a space and when not. Thus the H/C needs depend absolutely upon the thermostat setting. The selection of thermostat set points is an issue of controversy as well personal preference. A comfortable indoor temperature depends upon the local climate, the season, the level of clothing, activity etc. and is as well a health issue (e.g. sick building syndrome or legionella propagation) [62]. Hence, no thermostat setting can be assumed with confidence that will serve the comfort needs of its occupants but the simulation standard in general is a minimum of 20 ^{o}C and a maximum of 24 ^{o}C year round, which are the values to be used here as well.

3.1.14. The HVAC system:

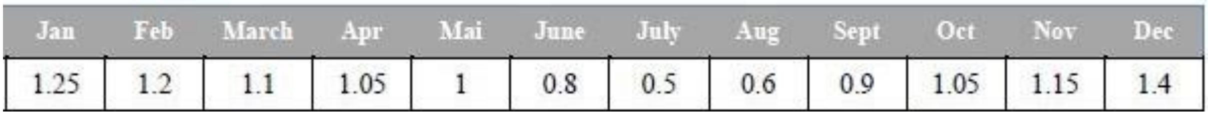
EnergyPlus is a professional piece of software capable of analytically simulating HVAC systems piece by piece of the equipment composition. Yet such an analytical approach is outside the scope of the current work so the option of “Ideal Loads System” is chosen. In practice, the ideal loads system is essentially an ideal piece of HVAC equipment that delivers without losses or technical limitations the heating or cooling required to the designated zone. These results of H/C needs will be extracted and then later processed in a simplistic model in order to define the equipment and energy consumption for their coverage.

3.1.15. On-site electricity generation through PV panels:

Since EnergyPlus has a weather-file database including detailed solar irradiation values it is capable of simulating the performance of an installed PV panel system based on its design characteristics. The choice of PV panels here is made mainly with a purpose of cost optimality/neutrality and secondly with a GHG emissions reduction potential from the operation of the building. The choice of type of the PV panel was performed according to its cost vs efficiency output. A specific model has been identified to be the most promising (see more on the financial part of the main report) with a conversion efficiency of 16.60 – 13.28 % over its 30 year lifetime [63]. Therefore an average value has been chosen of 15% for use in calculations throughout the lifetime of the system. This has been coupled with an inverter of an assumed 90% efficiency.

3.1.16. Hot water use (non EnergyPlus parameter):

The consumption of hater water is one of the biggest (as also proven from the simulation results) energy-consuming operations in households. This is due to the high temperature rise required (Domestic hot water is used at about 50 ^{o}C) and the very high thermal capacity of water (4.187 kJ/kg·K). This makes it one of the most crucial parameters to be simulated as realistically as possible. From the Technical Chamber of Greece are obtained the temperature (50 ^{o}C) and daily consumption (50 L / person / day) standards, while also the average monthly water inlet-temperature for each climatic zone [64]. In an effort to increase the accuracy of the simulation the given “50 L/person/day” value has been questioned as intuitively the consumption of hot water is lower in the summer months. For example in Belgium research has showed a 81 – 114 % variation in the amount of hot water consumption [65] with monthly values as shown below in table 4. This seasonal variation has been integrated in the analysis of hot water consumption in the residence.



Jan	Feb	March	Apr	Mai	June	July	Aug	Sept	Oct	Nov	Dec
1.25	1.2	1.1	1.05	1	0.8	0.5	0.6	0.9	1.05	1.15	1.4

Table 4: Variation of DHW consumption based on month

Yet, additionally to the hot water consumption stated above, in the hot water needs will have to be integrated the consumption for the laundry (as stated previously, the laundry receives directly hot water instead of heating it with its built-in electric resistance). For that, it has been found that an average laundry machine that consumes 60 L per washing cycle roughly half of it is hot water for the washing part [66]. For a suggested washing temperature of 40 ^{o}C, this equals to the necessary thermal energy input to 150L of water daily (for a total of 5 laundries a day as concluded).

3.1.17. The HVAC equipment performance (non EnergyPlus parameter):

As described above, the end result of the EnergyPlus simulation will be the heating/cooling needs of the house in thermal terms. Therefore a necessary step intermediates in order to assess the total, final electricity consumption: the conversion of all thermal needs into electricity. This will be achieved through the use of a heat pump for the production of the heating/cooling and hot water loads. The key element in the performance of a heat pump is its coefficient of performance, i.e. the ratio of heating/cooling "produced" versus the electricity consumption. The CoP is a parameter that depends not only on the exact design of the heat pump but also the environmental conditions, mainly the temperature difference that has to be covered between the outdoor and the indoor air. Therefore calculating the "performance" of a heat pump is a dynamic issue and in the market quality indicators for heat pumps exist in the form of Seasonal Energy Efficiency Ratio (SEER) and Seasonal Coefficient of Performance (SCOP) [67]. While a simulation of heat pump's electricity consumption in such a manner would be the most preferable this would over-complicate the simulation model making it—even more—cumbersome and thus an average uniform CoP value will be chosen year-round. Based on the CoP ranges for high-efficiency heat pumps found in literature [68], [69], [70] a CoP=3.5 is assumed for the needs of the simulation.

The heat pump is expected to cover the heating needs in the winter, the cooling needs in the summer and the hot water needs year-round. In an effort of maximising the efficiency and capacity of the heat pump the following configuration will be selected: in the winter, naturally, the useful output of the heat pump is heat and the waste cold, so the "produced" heat will be used to raise the temperature of the indoor air and the hot water. In summer though the useful output is "cold" for the building but heat for the hot water production. Hence, it is chosen to utilise the waste heat of cooling the building for raising the hot water temperature. In this case the final load of the heat pump will be determined by which of the two loads is the greatest at each time.

A final remark regarding the HVAC system is the use of heat recovery in the ventilation system. Given the high volumes of air turnover in the building it requires a substantial amount of heating or cooling to condition the outdoor air accordingly, while the exhausted air is at the desired indoor air temperature. Therefore a Mechanical Ventilation Heat Recovery appliance will be utilised in order to recover much of the valuable heat/cool load of the exhausted air. This indeed proves to be a significant need judging from the amount and level of technological development of air recuperators in the market. Upon brief research a model suitable for the air-flow needs of the residence is found with a remarkable energy recovery efficiency of 84% [71].

3.2. The case-study building compositions:

The simulation is designed to assess 3 different climatic locations in order to identify how the differentiation of this parameter affects the financial aspects of an NZEB. As researched elsewhere (see chapter 2.3.1. in main report regarding Eurima references) different climatic regions require different insulation levels to achieve an overall cost-optimal performance. Within Greece exist 3 main climatic regions that correspond—roughly—to 3 different hardiness zones throughout Europe. Beginning from the Eurima findings, a building composition is put together for each one of the three locations. Yet it is decided to test each location-specific design in all three locations in order to observe the cost optimality of the proposed values from Eurima. The Eurima report proposes a U-value for each one of the building's element: roof, walls and floor, with the U-value increasing in that order. A low U-value is needed for the roof since the hot air gathers there and the temperature gradient to the outdoor is grater yielding in higher losses, while the floor is touching the ground which has a more-stable and closer-to-the-indoor temperature than the outdoor air. For the current design it has been decided to increase the U-value of the roof to the level of the walls since in this specific type of building the forced ventilation is expected to create uniform temperature conditions throughout the indoor air mass, thus the same temperature and gradient (and eventually losses) are expected from walls and roof alike. Eventually the three designs proposed are as in the following tables 5-8:

3.2.1. Design 1: low-insulation for Hardiness Zone 10, location: Larnaca

Eurima derived values: Walls, 0.45 W/m^2·K (R=2.22 m^2·K/W); Floor, 1.45 W/m^2·K (R=0.69 W/m^2·K) (based on HDD/CDD proximity to Athens)

	Exterior Walls	Interior Walls	Ground floor	Interior floors	Roof
Element Name	Ytong 350mm wall (R=2.27)	Ytong 125mm wall	Concrete ground floor (low ins R=0.79)	Concrete interfloor	Concrete roof (low ins R=2.37)
Outside layer	Cement Plaster: Sand aggregate - 20mm	Gypsum plaster: Lightweight aggregate - 13mm	Cork tile - 3.2mm	Cork tile - 3.2mm	Built-up roofing - 10mm
Layer 2	Ytong 350mm	Ytong 125mm	Concrete 200mm	Concrete 200mm	Durosol EPS Insulation 70mm
Layer 3	Gypsum plaster: Lightweight aggregate - 13mm	Gypsum plaster: Lightweight aggregate - 13mm	Durosol EPS Insulation 20mm	Gypsum plaster: Lightweight aggregate - 13mm	Concrete 200mm
Layer 4					Gypsum plaster: Lightweight aggregate - 13mm

Table 5: Design 1, building elements composition

Yet, as explained later on the use of YTONG block is found to be financially uncompetitive thus the use of ORTHOBlock of 250mm thickness is used instead.

	Exterior Walls	Interior Walls	Ground floor	Interior floors	Roof
Element Name	ORTHOBlock 250mm wall (R=2.40)	ORTHOBlock 100mm wall	Concrete ground floor (low ins R=0.79)	Concrete interfloor	Concrete roof (low ins R=2.37)
Outside layer	Cement Plaster: Sand aggregate - 20mm	Gypsum plaster: Lightweight aggregate - 13mm	Cork tile - 3.2mm	Cork tile - 3.2mm	Built-up roofing - 10mm
Layer 2	ORTHOBlock 250mm	ORTHOBlock 100mm	Concrete 200mm	Concrete 200mm	Durosol EPS Insulation 70mm
Layer 3	Gypsum plaster: Lightweight	Gypsum plaster: Lightweight	Durosol EPS Insulation 20mm	Gypsum plaster: Lightweight	Concrete 200mm

	aggregate - 13mm	aggregate - 13mm		aggregate - 13mm	
Layer 4					Gypsum plaster: Lightweight aggregate - 13mm

Table 6: Final Design 1, building elements composition

3.2.2. Design 2: mid-insulation for Hardiness Zone 9, location: Athens

Eurima derived values: Walls, 0.35 W/m^2·K (R=2.86 m^2·K/W); Floor, 1.45 W/m^2·K (R=0.69 W/m^2·K)

	Exterior Walls	Interior Walls	Ground floor	Interior floors	Roof
Element Name	ORTHOBlock 300mm wall (R=2.91)	ORTHOBlock 100mm wall	Concrete ground floor (low ins R=0.79)	Concrete interfloor	Concrete roof (low ins R=2.98)
Outside layer	Cement Placter: Sand aggregate - 20mm	Gypsum plaster: Lightweight aggregate - 13mm	Cork tile - 3.2mm	Cork tile - 3.2mm	Built-up roofing - 10mm
Layer 2	ORTHOBlock 300mm	ORTHOBlock 100mm	Concrete 200mm	Concrete 200mm	Durosol EPS Insulation 90mm
Layer 3	Gypsum plaster: Lightweight aggregate - 13mm	Gypsum plaster: Lightweight aggregate - 13mm	Durosol EPS Insulation 20mm	Gypsum plaster: Lightweight aggregate - 13mm	Concrete 200mm
Layer 4					Gypsum plaster: Lightweight aggregate - 13mm

Table 7: Design 2, building elements composition

3.2.3. Design 3: high-insulation for Hardiness Zone 8, location: Thessaloniki

Eurima derived values: Walls, 0.27 W/m^2·K (R=3.70 m^2·K/W); Floor, 0.59 W/m^2·K (R=1.69 W/m^2·K) (based on HDD/CDD proximity to Rome)

	Exterior Walls	Interior Walls	Ground floor	Interior floors	Roof
Element Name	Brick Insulation 90 mm wall (R=3.68)	Hollow Brick 90mm wall	Concrete ground floor (high ins R=1.70)	Concrete interfloor	Concrete roof (high ins R=3.89)
Outside layer	Cement Plaster: Sand	Gypsum plaster: Lightweight	Cork tile - 3.2mm	Cork tile - 3.2mm	Built-up roofing - 10mm

	aggregate - 20mm	aggregate - 13mm			
Layer 2	Durosol EPS Insulation 100mm	Standard hollow brick 90mm	Concrete 200mm	Concrete 200mm	Durosol EPS Insulation 120mm
Layer 3	Standard hollow brick 90mm	Gypsum plaster: Lightweight aggregate - 13mm	Durosol EPS Insulation 50mm	Gypsum plaster: Lightweight aggregate - 13mm	Concrete 200mm
Layer 4	F04 Wall air space resistance				Gypsum plaster: Lightweight aggregate - 13mm
Layer 5	Standard hollow brick 90mm				
Layer 6	Gypsum plaster: Lightweight aggregate - 13mm				

Table 8: Design 3, building elements composition

3.3. Methodology

The main goal of the current work is to identify the design that will yield the minimum net present value for the construction and coverage of the energy needs of the building ("cost-optimal") for its lifetime (while a building can last up to 100 years, as an investment it is determined to pay back within 30 years, thus the life-cycle time-frame is set in such duration). Always according to cost-optimality, the building must also fulfil the expectations of an NZEB, i.e. have a minimal energy profile and the energy needs be covered to the largest extent possible from low-carbon, renewable sources. Installation of PV panels on-site is considered to be the most viable option, therefore the assessment moves ahead with the intention of maximising the NPV of the PV panels.

A critical decision is made at this point: the production of electricity from PV panels holds a premium position in the energy market and in Greece—as well most places in Europe—it has priority dispatch when surplus exists and is fed back to the grid, with a subsidised price higher than the grip price. Practically this means that any individual can install the maximum amount of PV panels it feels comfortable with investing on, as it is a relatively profit-guaranteed investment given the regulatory conditions mentioned above. Yet this is not the approach chosen here. This is because the input of variable PV electricity in the grid makes it harder to manage and thus if the NZEB solution proposed here is to be applied extensively, this could be at the cost of the grid infrastructure and the distribution operation. Therefore, here the approach taken is that the PV panels are only for self-consumption and any surplus electricity will be "curtailed" and not fed back to the grid. This option eventually will result in an "organically" optimal value based on the price of the PV panel, its life-time efficiency, the cost of grid-electricity and ultimately the balance between the electricity consumption of the building covered vs the surplus electricity to be wasted.

In a further effort to maximise the capacity of the PV panels for a specified area, the arrays' tilt will be adjusted according to season in order to capture the most of solar irradiance. The designed periods are distributed uniformly around the solstices and equinoxes: 6 Nov – 6 Feb – 6 May – 6 Aug – 6 Nov. A random array size is chosen and the tilt is changed every 5 degrees in order to identify the maximum yield for each season. The optimal tilt value is identified and this is the one to be used for the simulation in order to identify the optimal size.

Coming now to the specific building-location cases, the sizing of the PV panels is performed as below: EnergyPlus has the capacity of providing the electricity and heating/cooling consumption as well the PV production in a time-step basis. The chosen time-step here is 1 hour and it is assumed that the energy load is uniformly distributed throughout the entire hour. While the H/C needs will be "buffered" and their coverage is not time dependant, the electricity needs for the use of equipment (e.g. lights, ventilation, electronics, kitchens etc.) will need to be covered instantly, on an hour-to-hour basis as described above. Therefore a calculation is performed on the amount of electricity available from the PV panels after the coverage of the electric equipment needs. This "pre heat-pump" electricity surplus of PV panels is summed daily and then the daily heat-pump electricity need is deducted. The final value will be a surplus or deficit—depending on the H/C load of the day versus the post-electronic-equipment PV-electricity produced—and either PV output will be curtailed or more grid-electricity purchased. While the heating (including hot water production) and cooling needs are fixed values (depending on the pre-designated building insulation, hot water consumption and day of the year) the final PV-electricity surplus / building-needs-coverage depends on the size of the PV array. Thus different array sizes give eventually a different NPV value and the optimal one is chosen. The decision algorithm is illustrated graphically below in Figure 3:

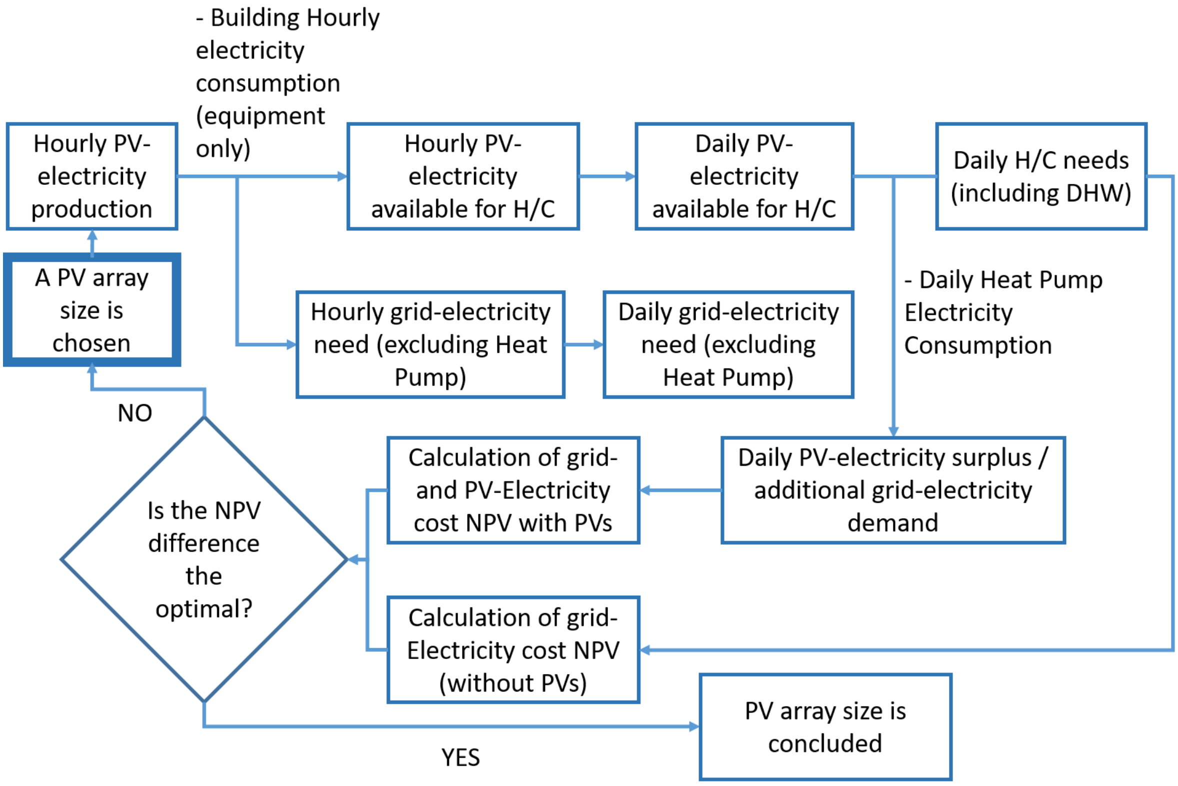


Figure 3: PV size decision algorithm

After the sizing of the PV panels, the sizing of the heat pump is performed. While it is already known the daily amount of electricity consumption of the heat pump, the exact power capacity of it is still a variable. The defining parameter here is the availability of PV-electricity since—once more—the main goal of the design is to achieve a coverage of the high thermal needs of buildings from cheap, clean PV electricity. Consequently, the power rating of the heat pump must be such that in the time available from the PV-panel surplus of production the daily H/C needs of the house must be covered (and stored as thermal energy for use throughout the entire day). In the determination of the maximum power output, two key variables are identified to affect it: A) the days where the PV-electricity available for the heat pump is barely enough (the heat pump will have to run hour-to-hour at the maximum of electricity the PVs can provide) and B) the days which have the highest heat pump loads, year round (since a minimum of power will be required in order to cover these high H/C needs).

Upon definition of the heat pump's size the following step is the sizing of the thermal storage tanks. The most convenient mean of storing thermal energy is water given its inert nature and high thermal capacity. The purpose of the storage is to adequately store the thermal energy to be used throughout the day when it is produced at the hours of PV-electricity production. In order to size the storage tanks simply the day with highest heating, cooling and hot water need are identified and the storage of each is sized in order to achieve the goal. Theoretically the thermal energy to be consumed at the hours of operation of the heat-pump will not have to be stored-since it would be "consumed" directly—but as that would make the calculations more complicated while also thermal storage has a relatively low cost per kWh, it was deemed unnecessary to make the detailed calculations and instead oversize slightly the system for storing the entire day's worth of thermal energy. Additionally the tanks will have to come with the appropriate heat exchangers included, usually a significant cost, in order to have the required performance. The consideration of including heat exchangers in the system could be a cost-forbidding fact on its own since usually these pieces of equipment are expensive. For the cost estimation here, prices will be derived mostly from finned coils used for transferring heat from the coolant/heat-medium to the air. Yet for the storage tank the needed sizes will be effectively much smaller since the heat transfer coefficient of water (the heat storage medium) is much higher than that of air, at minimum 25 times higher [72], [73] even 50 times higher according to different calculations [74], [75]. This significantly reduces the cost as it, roughly, means that a finned coil of 100W nominal heat transfer rate with air has a 25-times-higher 2,500W heat transfer rate once immersed in water, and this is a value that will be taken into consideration for the sizing and costing of the equipment systems.

Concluding the sizing of PV panels - Heat pump - Storage tanks, it is considered that the self-generating HVAC system is concluded. Since this synthesis is dependent on the energy needs of the building and the local solar irradiation it means it variates both depending on the building's level of insulation as well the geographical location. Hence, a total of 9 different combinations of PV-HP-S will have to be assessed. These will be matched with the corresponding building designs and the (investment-) lifetime NPV costs of rent + energy will be calculated, indicating thereafter the cost-optimal NZEB composition, along with its energy and GHG emission performance characteristics.

3.4. Preliminary building-structure financial results.

At this point a clarification needs to be made regarding the selection of the building materials / methods and some early results that affect the direction of the simulation. Three different materials have been chosen in an effort to identify the cheapest method of construction, as this affects the final price of the NZEB. The construction of a building typically requires the creation of a steel-bar reinforced concrete structure—that bears the loads (weight) of the building—and upon that the walls are added and the building is finalised. The first construction method chosen involves this "mainstream" construction approach using common hollow clay bricks for the walls and expanded polystyrene for the insulation. The other two building methods (with YTONG blocks and ORTHOBlock) given the thickness and robustness of the building blocks do not require a reinforced concrete frame in order to build as the walls made are strong enough to bear themselves the weight of the superstructure.

Yet, upon contact with regional building contractors, it proves that—in Greece specifically—no building is allowed to be built without a reinforced concrete frame if it is bigger than one storey high, given the seismic activity of the area [76]. Therefore the expected building-cost reduction advantage of omitting the reinforced concrete frame is impossible. Still, as the building materials have different prices and insulating capacities, it is still expected the choice of wall materials (in accordance to insulation needs of the area) to affect the final cost.

Overall the walls comprise only a small portion of a residence's final construction cost. A variety of products and services have to be performed in order to create a building, from the excavations and the building permits, to the concrete frame, the walls and surfaces, plumbing, electric installations, doors and windows and more. As decided above the only differentiating factor between the three building designs will be the type of walls. Therefore, the rest of the total building cost will be the same. According to professionals an average residence's final cost (from earth lot to turn-key delivery) is about 1200 €/m^2 of floor area [77]. Therefore upon calculation of the walls' cost a differentiation can be made. From prices obtained from the market the total wall cost of the three different designs is comprised as following in table 8. To be noted, the areas used for the calculations are (per floor, total of 3 floors): External walls, 223.5 m^2; Internal walls, 352.12 m^2; Floor/roof, 285.26 m^2.

Design D1 for LARNACA		Design D2 for ATHENS		Design D3 for THESSALONIKI	
YTONG		ORTHOBlock		Hollow brick	
YTONG block price (€/m3)	100.81	ORTHO 300mm price (€/unit)	0.94	Hollow 90mm price (€/unit)	0.25
m3/m2 of 350mm wall	0.35	units per m2 of ext wall	18.00	units per m2 of ext (double) wall	56.00
YTONG bl. ext wall price (€/m2)	35.28	ORTHO bl. Ext wall price (€/m2)	16.88	Hollow br. Ext wall price (€/m2)	14.00
m3/m2 of 250mm slab	0.25	ORTHO 100mm price (€/unit)	0.38		
YTONG sl. floor price (€/m2)	25.20	units per m2 of int wall	18.00	units per m2 of int wall	28.00
m3/m2 of 125mm wall	0.13	ORTHO bl. Int wall price (€/m2)	6.89	Hollow br. Int wall price (€/m2)	7.00
YTONG bl. int wall price (€/m2)	12.60				
building labour (€/m2)	5.00	building labour (€/m2)	6.00	building labour (€/m2)	5.00
mortar price (€/m3) (25kg)	10.00	mortar price (€/m2) (1bag)	7.00	mortar price (€/m2)	2.50
Plaster (M&L) (€/m2)	10.00	Plaster (M&L) (€/m2)	10.00	Plaster (M&L) (€/m2)	10.00
Ext walls final (€/m2)	63.78	Ext walls final (€/m2)	49.88	Ext walls final (€/m2)	41.50
Ext walls final (€)	42,766.00	Ext walls final (€)	33,447.22	Ext walls final (€)	27,825.75
Int walls final (€/m2)	51.45	Int walls final (€/m2)	39.89	Int walls final (€/m2)	34.50
Int walls final (€)	54,197.07	Int walls final (€)	42,022.74	Int walls final (€)	36,340.92
Final walls cost (€)	96,963.08	Final walls cost (€)	75,469.97	Final walls cost (€)	64,166.67
including VAT 24%	120,234.21	including VAT 24%	93,582.76	including VAT 24%	79,566.67
plus insulation Rmin=2.22/0.69		plus insulation Rmin=2.85/0.69		plus insulation (thess Rmin=3.70/1.69)	
Roof 70mm Durosol (€/m2) Rf=2.37	8.05	Roof 90mm Durosol (€/m2) R=f2.97	10.35	Roof 120mm Durosol (€/m2) Rf=3.88	13.80
Roof Insulation cost (€)	2,296.34	Roof Insulation cost (€)	2,952.44	Roof Insulation cost (€)	3,936.59
(YTONG wall Rf=2.27)		(ORTHOBlock wall Rf=2.91)		Wall 100mm Durosol (€/m2) Rf=3.68	11.50
				Ext wall Insulation cost (€)	7,710.75
Ground 20mm Durosol (€/m2) Rf=0.79	2.30	Ground 20mm Durosol (€/m2) Rf=0.79	2.30	Ground 50mm Durosol (€/m2) Rf=1.70	5.75
Ground Insulation cost (€)	656.10	Ground Insulation cost (€)	656.10	Ground Insulation cost (€)	1,640.25
Final wall + insulations cost (€)	99,915.52	Final wall + insulations cost (€)	79,078.50	Final wall + insulations cost (€)	77,454.25
Including VAT 24%	123,895.24	Including VAT 24%	98,057.35	Including VAT 24%	96,043.27

Table 9: Walls final costs, [76], [78]

A striking first observation is that the YTONG wall has a significantly higher cost than the other two methods while at the same time it delivers less insulative value. This drives the search for an alternative wall composition that will deliver the required minimum thermal resistance with a lower cost. Results are presented in the following table 9.

Design D1' for LARNACA		Design D1'' for LARNACA		Design D2' for Athens	
ORTHOBlock		Hollow brick		Hollow brick	
ORTHO 250mm price (€/unit)	0.71	Hollow 90mm price (€/unit)	0.25	Hollow 90mm price (€/unit)	0.25
units per m2 of ext wall	18.00	units per m2 of ext (double) wall	56.00	units per m2 of ext (double) wall	56.00
ORTHO bl. Ext wall price (€/m2)	12.76	Hollow br. Ext wall price (€/m2)	14.00	Hollow br. Ext wall price (€/m2)	14.00
ORTHO 100mm price (€/unit)	0.38				
units per m2 of int wall	18.00	units per m2 of int wall	28.00	units per m2 of int wall	28.00
ORTHO bl. Int wall price (€/m2)	6.89	Hollow br. Int wall price (€/m2)	7.00	Hollow br. Int wall price (€/m2)	7.00
building labour (€/m2)	6.00	building labour (€/m2)	5.00	building labour (€/m2)	5.00
mortar price (€/m2) (1bag)	7.00	mortar price (€/m2)	2.50	mortar price (€/m2)	2.50
Plaster (M&L) (€/m2)	10.00	Plaster (M&L) (€/m2)	10.00	Plaster (M&L) (€/m2)	10.00
Ext walls final (€/m2)	45.76	Ext walls final (€/m2)	41.50	Ext walls final (€/m2)	41.50
Ext walls final (€)	30,683.42	Ext walls final (€)	27,825.75	Ext walls final (€)	27,825.75
Int walls final (€/m2)	39.89	Int walls final (€/m2)	34.50	Int walls final (€/m2)	34.50
Int walls final (€)	42,022.74	Int walls final (€)	36,340.92	Int walls final (€)	36,340.92
Final walls cost (€)	72,706.16	Final walls cost (€)	64,166.67	Final walls cost (€)	64,166.67
including VAT 24%	90,155.64	including VAT 24%	79,566.67	including VAT 24%	79,566.67
plus insulation Rmin=2.22/0.69		sub-case larn Rmin=2.22/0.69		sub-case athens Rmin=2.85/0.69	
Roof 70mm Durosol (€/m2) Rf=2.37	8.05	Roof 70mm Durosol (€/m2) Rf=2.37	8.05	Roof 90mm Durosol (€/m2) Rf=2.98	10.35
Roof Insulation cost (€)	2,296.34	Roof Insulation cost (€)	2,296.34	Roof Insulation cost (€)	2,952.44
ORTHOBlock wall Rf=2.40		Wall 50mm Durosol (€/m2) Rf=2.16	5.75	Wall 70mm Durosol (€/m2) Rf=2.77	8.05
		Ext wall Insulation cost (€)	3,855.38	Ext wall Insulation cost (€)	5,397.53
Ground 20mm Durosol (€/m2) Rf=0.79	2.30	Ground 20mm Durosol (€/m2) Rf=0.79	2.30	Ground 20mm Durosol (€/m2) Rf=0.79	2.30
Ground Insulation cost (€)	656.10	Ground Insulation cost (€)	656.10	Ground Insulation cost (€)	656.10
Final wall + insulations cost (€)	75,658.61	Final wall + insulations cost (€)	70,974.49	Final wall + insulations cost (€)	73,172.73
Including VAT 24%	93,816.67	Including VAT 24%	88,008.36	Including VAT 24%	90,734.19

Table 10: Walls final costs for alternative designs

As can be clearly seen, the YTONG design is inferior in a price-for-insulation cost while the design of standard hollow brick wall with added EPS insulation is always the cheapest option. Yet on the comparison of ORTHOBlock with hollow brick + EPS insulation for Larnaca (D1’ vs D1’’) it is evident that the ORTHOBlock is more expensive while it also provides a higher R values. Eventually it is proved that on a ratio of cost-to-R they are at the same level and since the use of ORTHOBlock only is a simpler construction option (rather than building the double hollow brick wall and adding extra insulation), it will eventually be preferred for Larnaca over YTONG.

Eventually, excluding the case of YTONG, it concludes eventually to the value of ~93,000 € cost for the final walls (bricks, mortar, insulation, labour, plaster and additional insulation required for the roof and ground floor) which corresponds roughly to 11.2% of the total construction cost. Concluding, the building’s cost excluding the walls will be considered (1-0.112)*1200 €/m^2 = ~1,065 €/m^2 and the cost of walls will be added to that eventually in order to reflect the final cost of the building, while adding the energy-related NPV—calculated late on—will give the total investment cost and thus the necessary “tenancy + energy” rent price.

3.5. Simulation Energy-Results

After compilation of the results the following key-figures can be derived for each location:

3.5.1. Larnaca

	Thermal needs			Energy values				
month	Main Zone Total Heating needs [kWh th], Monthly	Main Zone Total Cooling needs [kWh th], Monthly	Hot Water needs [kWh th], Monthly	HP H/C+HW load (after MVHR) [kWh e], Monthly	Electronic equipment (non-HP) consumption [kWh e], Monthly	PV Produced Electricity [kWh e], Monthly	Final Electricity Surplus (wasted PV production [kWh e], Monthly	Final Electricity Deficit (to be grid-bought) [kWh e], Monthly
Jan	661.80	0.00	2,080.36	624.64	3,201.85	1,368.66	365.43	-2,823.27
Feb	404.53	33.51	1,889.45	558.34	2,892.29	1,370.76	348.45	-2,428.32
Mar	0.00	522.86	2,034.21	581.20	3,202.07	1,727.59	529.64	-2,585.32
Apr	0.23	3,058.82	1,829.02	522.58	3,097.96	1,925.83	705.18	-2,399.89
May	0.00	6,769.97	1,682.31	480.66	3,200.22	2,219.98	927.07	-2,387.97
Jun	0.00	10,019.24	1,410.32	462.95	3,096.15	2,448.61	1,091.78	-2,202.28
Jul	0.00	12,666.71	1,318.88	579.05	3,198.71	2,512.17	1,014.40	-2,279.99
Aug	0.00	13,071.54	1,295.81	597.56	3,198.59	2,360.24	938.86	-2,374.77
Sep	0.00	9,956.72	1,348.91	456.12	3,095.98	2,195.45	1,019.62	-2,376.27
Oct	0.00	5,331.23	1,578.48	450.99	3,200.17	1,871.67	798.22	-2,577.72
Nov	0.00	1,479.78	1,728.53	493.87	3,097.91	1,509.90	524.26	-2,606.14
Dec	184.94	0.00	1,976.52	573.17	3,201.71	1,385.14	397.51	-2,787.25
Annual sums	1,251.50	62,910.38	20,172.80	6,381.13	37,683.62	22,895.99	8,660.42	-29,829.18

Table 11: Energy results for Larnaca low-insulation case

	Thermal needs			Energy values				
month	Main Zone Total Heating needs [kWh th], Monthly	Main Zone Total Cooling needs [kWh th], Monthly	Hot Water needs [kWh th], Monthly	HP H/C+HW load (after MVHR) [kWh e], Monthly	Electronic equipment (non-HP) consumption [kWh e], Monthly	PV Produced Electricity [kWh e], Monthly	Final Electricity Surplus (wasted PV production [kWh e], Monthly	Final Electricity Deficit (to be grid-bought) [kWh e], Monthly
Jan	531.58	0.00	2,080.36	618.69	3,201.88	1,368.66	369.41	-2,821.31
Feb	322.16	52.75	1,889.45	554.57	2,892.32	1,370.76	351.58	-2,427.71
Mar	0.00	591.81	2,034.21	581.20	3,202.10	1,727.59	529.64	-2,585.34
Apr	0.13	3,105.44	1,829.02	522.58	3,097.96	1,925.83	705.18	-2,399.89
May	0.00	6,721.20	1,682.31	480.66	3,200.22	2,219.98	927.07	-2,387.97
Jun	0.00	9,869.87	1,410.32	457.05	3,096.15	2,448.61	1,097.68	-2,202.28
Jul	0.00	12,445.56	1,318.88	568.94	3,198.71	2,512.17	1,024.51	-2,279.99
Aug	0.00	12,845.47	1,295.81	587.22	3,198.59	2,360.24	949.20	-2,374.76
Sep	0.00	9,813.08	1,348.91	449.94	3,095.98	2,195.45	1,025.80	-2,376.27
Oct	0.00	5,310.39	1,578.48	450.99	3,200.17	1,871.67	798.22	-2,577.72
Nov	0.00	1,546.59	1,728.53	493.87	3,097.91	1,509.90	524.26	-2,606.15
Dec	131.24	0.32	1,976.52	570.72	3,201.75	1,385.14	399.40	-2,786.73
Annual sums	985.11	62,302.47	20,172.80	6,336.43	37,683.75	22,895.99	8,701.93	-29,826.12

Table 12: Energy results for Larnaca mid-insulation case

	Thermal needs			Energy values				
month	Main Zone Total Heating needs [kWh th], Monthly	Main Zone Total Cooling needs [kWh th], Monthly	Hot Water needs [kWh th], Monthly	HP H/C+HW load (after MVHR) [kWh e], Monthly	Electronic equipment (non-HP) consumption [kWh e], Monthly	PV Produced Electricity [kWh e], Monthly	Final Electricity Surplus (wasted PV production [kWh e], Monthly	Final Electricity Deficit (to be grid-bought) [kWh e], Monthly
Jan	276.09	3.01	2,080.36	607.01	3,201.97	1,368.66	377.65	-2,817.98
Feb	146.74	169.95	1,889.45	546.55	2,892.41	1,370.76	358.59	-2,426.79
Mar	0.00	964.34	2,034.21	581.20	3,202.18	1,727.59	529.63	-2,585.43
Apr	0.00	3,635.58	1,829.02	522.58	3,097.98	1,925.83	705.18	-2,399.91
May	0.00	7,155.29	1,682.31	480.66	3,200.22	2,219.98	927.07	-2,387.97
Jun	0.00	10,112.04	1,410.32	465.49	3,096.15	2,448.61	1,089.25	-2,202.27
Jul	0.00	12,601.27	1,318.88	576.06	3,198.71	2,512.17	1,017.39	-2,279.99
Aug	0.00	12,967.29	1,295.81	592.79	3,198.59	2,360.24	943.63	-2,374.76
Sep	0.00	9,960.84	1,348.91	456.24	3,095.98	2,195.45	1,019.50	-2,376.27
Oct	0.00	5,652.74	1,578.48	450.99	3,200.18	1,871.67	798.22	-2,577.72
Nov	0.00	1,933.30	1,728.53	493.87	3,097.94	1,509.90	524.26	-2,606.17
Dec	38.08	57.06	1,976.52	566.46	3,201.88	1,385.14	402.64	-2,785.84
Annual sums	460.91	65,212.71	20,172.80	6,339.90	37,684.19	22,895.99	8,693.01	-29,821.10

Table 13: Energy results for Larnaca high-insulation case

From a first glance a few interesting observations can be derived. Initially, as insulation increases heating needs decrease but not cooling needs. For the high level of insulation the annual cooling needs rise by about 2.9 MWh_{th}. This, even though controversial on a first sight, is natural as the activity inside the building generates heat that needs to be dissipated in order to cool down. With a thicker insulation, dissipation is prevented on the spring and autumn months so stronger cooling is needed. This behavior is similar to a human body wearing heavy clothes in a not-so-cold weather: it would overheat, unless extra cooling is applied, as the building requires.

Yet coming to the cost-aspect of it, the final decisive parameter is how much electricity is saved from the annual energy bill. And the results there are striking: from low- to mid- to high-insulation the difference is 3 and 5 kWh e per year. This minimum energy difference is supported by the variations in the heat pump consumption: 45 and 3 kWh e. As the heat pump system is designed to draw its electricity need exclusively from the PV production, it makes sense that such small differences do not affect much the grid-bought electricity. The small differences in heat pump demand are reasonable since the thermal needs are covered to a large extend (84%) from “recycling” energy at the Mechanical Ventilation Heat Recovery equipment. Another factor is that large part of the cooling load comes as “waste cold” from the Hot Water production so variations at the cooling needs just utilize more of the waste cold rather than increase the load of the heat pump.

Overall, it proves that with the chosen equipment configuration variations in the insulation level affect marginally the savings in grid-electricity costs, thus the lowest level of insulation will most likely be preferred, *if not an even lower one…*

3.5.2. Athens

	Thermal needs			Energy values				
month	Main Zone Total Heating needs [kWh th], Monthly	Main Zone Total Cooling needs [kWh th], Monthly	Hot Water needs [kWh th], Monthly	HP H/C+HW load (after MVHR) [kWh e], Monthly	Electronic equipment (non-HP) consumption [kWh e], Monthly	PV Produced Electricity [kWh e], Monthly	Final Electricity Surplus (wasted PV production [kWh e], Monthly	Final Electricity Deficit (to be grid-bought) [kWh e], Monthly
Jan	1,676.82	0.00	2,230.35	713.90	3,201.92	971.50	148.70	-3,093.01
Feb	1,840.55	0.00	2,030.14	664.18	2,892.35	968.06	87.99	-2,676.46
Mar	554.98	201.61	2,155.35	641.18	3,202.12	1,344.66	254.65	-2,753.29
Apr	2.31	1,835.53	1,912.76	546.51	3,098.39	1,501.14	356.27	-2,500.03
May	0.63	5,169.99	1,740.00	497.14	3,200.54	1,794.98	521.95	-2,424.65
Jun	0.00	8,983.81	1,449.40	445.88	3,096.09	2,083.92	734.81	-2,192.87
Jul	0.00	11,590.63	1,353.49	529.86	3,198.59	2,182.47	711.67	-2,257.65
Aug	0.00	11,315.93	1,341.96	517.30	3,198.58	1,986.14	659.17	-2,388.90
Sep	0.00	7,882.83	1,427.07	417.64	3,096.27	1,779.27	684.07	-2,418.70
Oct	0.00	2,944.19	1,693.85	483.96	3,200.67	1,321.10	374.18	-2,737.71
Nov	119.29	105.50	1,873.68	540.79	3,098.10	865.77	164.83	-2,937.96
Dec	1,966.91	0.00	2,126.51	697.49	3,201.83	857.75	117.67	-3,159.24
Annual sums	6,161.48	50,030.02	21,334.56	6,695.83	37,685.45	17,656.78	4,815.96	-31,540.46

Table 14: Energy results for Athens low-insulation case

	Thermal needs			Energy values				
month	Main Zone Total Heating needs [kWh th], Monthly	Main Zone Total Cooling needs [kWh th], Monthly	Hot Water needs [kWh th], Monthly	HP H/C+HW load (after MVHR) [kWh e], Monthly	Electronic equipment (non-HP) consumption [kWh e], Monthly	PV Produced Electricity [kWh e], Monthly	Final Electricity Surplus (wasted PV production [kWh e], Monthly	Final Electricity Deficit (to be grid-bought) [kWh e], Monthly
Jan	1,469.33	0.00	2,230.35	704.41	3,201.93	971.50	151.02	-3,085.86
Feb	1,610.91	0.00	2,030.14	653.68	2,892.36	968.06	91.32	-2,669.31
Mar	453.85	232.16	2,155.35	636.56	3,202.14	1,344.66	255.54	-2,749.58
Apr	2.43	1,909.16	1,912.76	546.51	3,098.40	1,501.14	356.27	-2,500.04
May	0.72	5,161.88	1,740.00	497.14	3,200.54	1,794.98	521.95	-2,424.65
Jun	0.00	8,839.46	1,449.40	441.50	3,096.09	2,083.92	739.19	-2,192.87
Jul	0.00	11,374.71	1,353.49	519.99	3,198.59	2,182.47	721.54	-2,257.65
Aug	0.00	11,097.41	1,341.96	507.31	3,198.58	1,986.14	669.16	-2,388.90
Sep	0.00	7,787.70	1,427.07	415.62	3,096.27	1,779.27	686.09	-2,418.70
Oct	0.00	2,991.55	1,693.85	483.96	3,200.67	1,321.10	374.18	-2,737.71
Nov	80.17	121.68	1,873.68	539.00	3,098.13	865.77	164.89	-2,936.26
Dec	1,710.12	0.00	2,126.51	685.75	3,201.84	857.75	120.37	-3,150.22
Annual sums	5,327.53	49,515.70	21,334.56	6,631.43	37,685.56	17,656.78	4,851.53	-31,511.74

Table 15: Energy results for Athens mid-insulation case

	Thermal needs			Energy values				
month	Main Zone Total Heating needs [kWh th], Monthly	Main Zone Total Cooling needs [kWh th], Monthly	Hot Water needs [kWh th], Monthly	HP H/C+HW load (after MVHR) [kWh e], Monthly	Electronic equipment (non-HP) consumption [kWh e], Monthly	PV Produced Electricity [kWh e], Monthly	Final Electricity Surplus (wasted PV production [kWh e], Monthly	Final Electricity Deficit (to be grid-bought) [kWh e], Monthly
Jan	1,113.49	0.00	2,230.35	688.14	3,201.98	971.50	156.67	-3,075.30
Feb	1,227.52	0.00	2,030.14	636.15	2,892.40	968.06	97.11	-2,657.61
Mar	289.65	408.17	2,155.35	629.06	3,202.23	1,344.66	257.31	-2,743.93
Apr	2.13	2,425.99	1,912.76	546.50	3,098.43	1,501.14	356.28	-2,500.07
May	0.00	5,608.50	1,740.00	497.14	3,200.54	1,794.98	521.95	-2,424.65
Jun	0.00	9,074.70	1,449.40	446.09	3,096.09	2,083.92	734.60	-2,192.86
Jul	0.00	11,523.13	1,353.49	526.77	3,198.59	2,182.47	714.76	-2,257.65
Aug	0.00	11,218.57	1,341.96	512.85	3,198.58	1,986.14	663.62	-2,388.90
Sep	0.00	7,952.48	1,427.07	417.89	3,096.27	1,779.27	683.81	-2,418.70
Oct	0.00	3,312.97	1,693.85	483.96	3,200.68	1,321.10	374.18	-2,737.72
Nov	34.83	220.96	1,873.68	536.93	3,098.23	865.77	164.89	-2,934.28
Dec	1,305.11	0.00	2,126.51	667.24	3,201.89	857.75	125.30	-3,136.67
Annual sums	3,972.72	51,745.47	21,334.56	6,588.72	37,685.91	17,656.78	4,850.48	-31,468.33

Table 16: Energy results for Athens high-insulation case

In the case of Athens similar results are observed: heating loads decrease strongly with higher insulation yet cooling loads increase less from mid- to high- insulation (2,230 in Athens vs 2,910 kWh$_{th}$/a in Larnaca). Overall, with higher levels of insulation are managed to be saved 64 (from low- to mid-) and 43 (from mid- to high-) kWh$_{e}$/a. Eventually this corresponds to yet another minimal reduction in the grid-bought electricity, 29 and 43 kWh$_{e}$ respectively.

3.5.3. Thessaloniki

	Thermal needs			Energy values				
month	Main Zone Total Heating needs [kWh th], Monthly	Main Zone Total Cooling needs [kWh th], Monthly	Hot Water needs [kWh th], Monthly	HP H/C+HW load (after MVHR) [kWh e], Monthly	Electronic equipment (non-HP) consumption [kWh e], Monthly	PV Produced Electricity [kWh e], Monthly	Final Electricity Surplus (wasted PV production [kWh e], Monthly	Final Electricity Deficit (to be grid-bought) [kWh e], Monthly
Jan	5,694.44	0.00	2,455.33	961.84	3,203.07	854.78	15.10	-3,325.23
Feb	3,351.56	0.00	2,176.03	774.94	2,893.13	1,154.10	116.41	-2,630.39
Mar	1,571.40	4.34	2,288.03	725.56	3,202.50	1,370.74	197.89	-2,755.20
Apr	60.14	717.43	2,002.08	574.75	3,098.68	1,447.80	347.84	-2,573.47
May	0.00	4,382.57	1,814.99	518.57	3,200.88	1,763.74	471.93	-2,427.63
Jun	0.00	7,700.36	1,516.39	433.88	3,096.42	1,989.94	681.35	-2,221.71
Jul	0.00	10,096.12	1,428.49	467.32	3,199.05	2,069.98	688.63	-2,285.01
Aug	0.00	9,671.58	1,411.18	450.44	3,199.11	1,909.34	681.90	-2,422.11
Sep	0.00	5,703.00	1,510.81	431.66	3,096.93	1,567.46	534.11	-2,495.24
Oct	18.31	1,663.16	1,809.23	517.76	3,201.28	1,215.30	326.24	-2,829.97
Nov	1,501.31	0.07	2,030.00	648.63	3,098.67	874.19	108.69	-2,981.80
Dec	4,974.63	0.00	2,334.18	894.32	3,202.68	717.76	23.40	-3,402.63
Annual sums	17,171.80	39,938.64	22,776.74	7,399.66	37,692.39	16,935.14	4,193.49	-32,350.40

Table 17: Energy results for Thessaloniki low-insulation case

	Thermal needs			Energy values				
month	Main Zone Total Heating needs [kWh th], Monthly	Main Zone Total Cooling needs [kWh th], Monthly	Hot Water needs [kWh th], Monthly	HP H/C+HW load (after MVHR) [kWh e], Monthly	Electronic equipment (non-HP) consumption [kWh e], Monthly	PV Produced Electricity [kWh e], Monthly	Final Electricity Surplus (wasted PV production [kWh e], Monthly	Final Electricity Deficit (to be grid-bought) [kWh e], Monthly
Jan	5,291.30	0.00	2,455.33	943.41	3,203.07	854.78	19.52	-3,311.22
Feb	3,060.56	0.00	2,176.03	761.63	2,893.14	1,154.10	122.73	-2,623.41
Mar	1,376.22	9.68	2,288.03	716.64	3,202.52	1,370.74	201.63	-2,750.04
Apr	36.46	772.57	2,002.08	573.66	3,098.70	1,447.80	348.47	-2,573.03
May	0.00	4,390.39	1,814.99	518.57	3,200.88	1,763.74	471.93	-2,427.63
Jun	0.00	7,595.46	1,516.39	433.61	3,096.42	1,989.94	681.62	-2,221.71
Jul	0.00	9,924.49	1,428.49	460.22	3,199.04	2,069.98	695.73	-2,285.01
Aug	0.00	9,507.26	1,411.18	444.38	3,199.11	1,909.34	687.96	-2,422.11
Sep	0.00	5,677.85	1,510.81	431.66	3,096.93	1,567.46	534.11	-2,495.24
Oct	2.14	1,715.13	1,809.23	517.02	3,201.29	1,215.30	326.24	-2,829.25
Nov	1,298.14	0.61	2,030.00	639.34	3,098.69	874.19	114.15	-2,977.99
Dec	4,606.47	0.00	2,334.18	877.49	3,202.68	717.76	26.05	-3,388.46
Annual sums	15,671.29	39,593.44	22,776.74	7,317.63	37,692.49	16,935.14	4,230.14	-32,305.12

Table 18: Energy results for Thessaloniki mid-insulation case

	Thermal needs			Energy values				
month	Main Zone Total Heating needs [kWh th], Monthly	Main Zone Total Cooling needs [kWh th], Monthly	Hot Water needs [kWh th], Monthly	HP H/C+HW load (after MVHR) [kWh e], Monthly	Electronic equipment (non-HP) consumption [kWh e], Monthly	PV Produced Electricity [kWh e], Monthly	Final Electricity Surplus (wasted PV production [kWh e], Monthly	Final Electricity Deficit (to be grid-bought) [kWh e], Monthly
Jan	4,763.35	0.00	2,455.33	919.28	3,203.08	854.78	26.76	-3,294.33
Feb	2,586.90	0.00	2,176.03	739.98	2,893.17	1,154.10	133.16	-2,612.21
Mar	1,066.53	72.21	2,288.03	702.41	3,202.58	1,370.74	208.34	-2,742.59
Apr	6.55	1,112.90	2,002.08	572.28	3,098.77	1,447.80	349.63	-2,572.88
May	0.00	4,800.38	1,814.99	518.57	3,200.89	1,763.74	471.93	-2,427.64
Jun	0.00	7,838.05	1,516.39	433.92	3,096.42	1,989.94	681.31	-2,221.71
Jul	0.00	10,093.96	1,428.49	467.18	3,199.04	2,069.98	688.77	-2,285.01
Aug	0.00	9,658.07	1,411.18	449.83	3,199.11	1,909.34	682.51	-2,422.11
Sep	0.00	5,871.20	1,510.81	431.66	3,096.93	1,567.46	534.11	-2,495.24
Oct	0.00	1,959.59	1,809.23	516.92	3,201.33	1,215.30	326.24	-2,829.18
Nov	1,035.01	17.74	2,030.00	627.31	3,098.75	874.19	121.28	-2,973.16
Dec	4,127.48	0.00	2,334.18	855.59	3,202.69	717.76	30.00	-3,370.52
Annual sums	13,585.81	41,424.09	22,776.74	7,234.94	37,692.76	16,935.14	4,254.03	-32,246.59

Table 19: Energy results for Thessaloniki high-insulation case

The pattern of results repeats once more for the case of Thessaloniki. From low- to mid- the annual heating needs reduce by ~ 1.5 MWh$_{th}$ and from mid- to high- by another ~2.1 MWh$_{th}$. Accordingly the cooling needs reduce slightly in the first case (~0.4 MWh$_{th}$) while increase, as previously, in the second (~1.9 MWh$_{th}$). Eventually the overall heat pump loads variate annually by 82 and 83 kWh$_{e}$ with the corresponding grid-bought electricity being 45 and 59 kWh$_{e}$ less in each case.

3.5.4. So-far results review and further steps

Summarizing, the results presented from all 3 case locations reveal a surprising truth: for the given configuration of HVAC-HW equipment, increasing levels of insulation provide marginal benefits (of maximum 59 kWh$_{e}$/a) of negligible cost reduction, most certainly not justifying the investment cost of insulation.

Arguably the use of an air recuperator greatly diminishes the H/C needs while heat pumps greatly reduce the electric consumption for the production of heating/cooling. Additionally, the coupling of hot water production with H/C essentially provides for “free” (as waste cold) the cooling needs to a great extent. The benefits of the configuration are obvious but now considering practically how “far” the concept of MVHR & H/C-HW co-production can go, a new case is established: the minimum possible insulation for the locations, based on the existing Greek building regulations.

Current standards for the building insulation requirements can be found at the Regulation for Energy Efficiency in Buildings (KENAK) [79]. According to it minimum U-values are set for the various building elements, with respect to their region as following in Table 20:

	U-value [W/m^{2}·K] (R-value [m^{2}·K/W])

Building Element	Climatic zone		
	A	B	C
Outdoor-exposed horizontal surfaces (i.e. roofs)	0.50 (2.00)	0.40 (2.50)	0.38 (2.63)
Outdoor-exposed vertical surfaces (i.e. facade walls)	0.60 (1.67)	0.50 (2.00)	0.44 (2.27)
Floors in contact with ground or non-heated/cooled spaces	1.50 (0.67)	1.00 (1.00)	0.38 (2.63)
Partition walls in contact with non-heated/cooled spaces	1.50 (0.67)	1.00 (1.00)	0.70 (1.43)

Table 20: U- and R-values current-standards in Greece

The values provided from the Greek regulation are far lower than the Eurima proposed ones, therefore an interesting comparison of end-results is expected. For these bare-minimum designs the building composition of reinforced concrete frame with double hollow brick walls and the appropriate thickness of insulation will be used, as described in Table 21:

Note: The only possibility for a composition other than double-leaf hollow brick with EPS insulation added is in the Thessaloniki option where the ORTHOBlock 250 mm type of external wall would yield a lower yet still sufficient insulation level (R_{final}=2.40 $m^2 \cdot K/W$). Though, the cost estimations prove that it is slightly more expensive and thus the original option will be maintained.

Building Element	U-value [$W/m^2 \cdot K$], (R-value [$m^2 \cdot K/W$]), {Insul. thickness}		
	Climatic zone		
	A	B	C
Outdoor-exposed horizontal surfaces (i.e. roofs)	0.48 (2.07) {60mm}	0.37 (2.67) {80mm}	0.37 (2.67) {80mm}
Outdoor-exposed vertical surfaces (i.e. facade walls)	0.54 (1.86) {40mm}	0.46 (2.17) {50mm}	0.41 (2.47) {60mm}
Floors in contact with ground or non-heated/cooled spaces	1.27 (0.79) {20mm}	0.92 (1.09) {30mm}	0.34 (2.91) {90mm}
Partition walls in contact with non-heated/cooled spaces	1.08 (0.93) {20mm}	0.81 (1.23) {30mm}	0.65 (1.53) {40mm}

Table 21: Final Insulation levels for bare-minimum deigns

The simulation is run again (with the rest of parameters the same) and the results are presented in the following Tables 22-24:

	Thermal needs			Energy values				
month	Main Zone Total Heating needs [kWh th], Monthly	Main Zone Total Cooling needs [kWh th], Monthly	Hot Water needs [kWh th], Monthly	HP H/C+HW load (after MVHR) [kWh e], Monthly	Electronic equipment (non-HP) consumption [kWh e], Monthly	PV Produced Electricity [kWh e], Monthly	Final Electricity Surplus (wasted PV production [kWh e], Monthly	Final Electricity Deficit (to be grid-bought) [kWh e], Monthly
Jan	792.07	0.00	2,080.36	630.60	3,201.83	1,368.66	361.97	-2,825.74
Feb	489.99	19.08	1,889.45	562.24	2,892.26	1,370.76	345.32	-2,429.07
Mar	0.22	461.00	2,034.21	581.21	3,202.04	1,727.59	529.63	-2,585.29
Apr	0.15	3,035.78	1,829.02	522.58	3,097.96	1,925.83	705.18	-2,399.89
May	0.00	6,911.94	1,682.31	480.66	3,200.22	2,219.98	927.07	-2,387.97
Jun	0.00	10,306.41	1,410.32	474.49	3,096.15	2,448.61	1,080.24	-2,202.27
Jul	0.00	13,066.49	1,318.88	597.33	3,198.71	2,512.17	996.12	-2,279.99
Aug	0.00	13,485.13	1,295.81	616.46	3,198.59	2,360.24	919.95	-2,374.76
Sep	0.00	10,225.36	1,348.91	467.76	3,095.98	2,195.45	1,007.98	-2,376.27
Oct	0.00	5,435.37	1,578.48	450.99	3,200.17	1,871.67	798.22	-2,577.72
Nov	0.00	1,446.93	1,728.53	493.87	3,097.90	1,509.90	524.26	-2,606.13
Dec	233.91	0.00	1,976.52	575.41	3,201.68	1,385.14	395.71	-2,787.66
Annual sums	1,516.34	64,393.49	20,172.80	6,453.61	37,683.48	22,895.99	8,591.66	-29,832.76

Table 22: Energy results for Larnaca bare-minimum insulation case

	Thermal needs			Energy values				
month	Main Zone Total Heating needs [kWh th], Monthly	Main Zone Total Cooling needs [kWh th], Monthly	Hot Water needs [kWh th], Monthly	HP H/C+HW load (after MVHR) [kWh e], Monthly	Electronic equipment (non-HP) consumption [kWh e], Monthly	PV Produced Electricity [kWh e], Monthly	Final Electricity Surplus (wasted PV production [kWh e], Monthly	Final Electricity Deficit (to be grid-bought) [kWh e], Monthly
Jan	1,599.19	0.00	2,230.35	710.35	3,201.92	971.50	149.93	-3,090.70
Feb	1,763.44	0.00	2,030.14	660.65	2,892.36	968.06	89.18	-2,674.13
Mar	507.60	250.27	2,155.35	639.02	3,202.14	1,344.66	255.16	-2,751.66
Apr	2.45	2,036.02	1,912.76	546.51	3,098.41	1,501.14	356.27	-2,500.05
May	0.00	5,439.27	1,740.00	497.14	3,200.54	1,794.98	521.95	-2,424.65
Jun	0.00	9,258.02	1,449.40	453.42	3,096.09	2,083.92	727.27	-2,192.86
Jul	0.00	11,899.37	1,353.49	543.97	3,198.59	2,182.47	697.56	-2,257.65
Aug	0.00	11,611.09	1,341.96	530.79	3,198.58	1,986.14	645.67	-2,388.90
Sep	0.00	8,102.08	1,427.07	421.45	3,096.27	1,779.27	680.25	-2,418.70
Oct	0.00	3,127.04	1,693.85	483.96	3,200.68	1,321.10	374.18	-2,737.71
Nov	98.70	140.07	1,873.68	539.85	3,098.13	865.77	164.89	-2,937.11
Dec	1,881.99	0.00	2,126.51	693.61	3,201.84	857.75	118.62	-3,156.32
Annual sums	5,853.37	51,863.24	21,334.56	6,720.73	37,685.54	17,656.78	4,780.94	-31,530.42

Table 23: Energy results for Athens bare-minimum insulation case

	Thermal needs			Energy values				
month	Main Zone Total Heating needs [kWh th], Monthly	Main Zone Total Cooling needs [kWh th], Monthly	Hot Water needs [kWh th], Monthly	HP H/C+HW load (after MVHR) [kWh e], Monthly	Electronic equipment (non-HP) consumption [kWh e], Monthly	PV Produced Electricity [kWh e], Monthly	Final Electricity Surplus (wasted PV production [kWh e], Monthly	Final Electricity Deficit (to be grid-bought) [kWh e], Monthly
Jan	5,430.30	0.00	2,455.33	949.76	3,203.07	854.78	17.98	-3,316.04
Feb	3,048.77	0.00	2,176.03	761.10	2,893.15	1,154.10	122.82	-2,622.96
Mar	1,336.31	49.19	2,288.03	714.75	3,202.54	1,370.74	202.59	-2,749.14
Apr	19.06	1,059.44	2,002.08	572.85	3,098.75	1,447.80	349.05	-2,572.86
May	0.00	4,901.45	1,814.99	518.57	3,200.89	1,763.74	471.93	-2,427.64
Jun	0.00	8,084.23	1,516.39	434.93	3,096.42	1,989.94	680.30	-2,221.71
Jul	0.00	10,461.54	1,428.49	482.22	3,199.04	2,069.98	673.73	-2,285.01
Aug	0.00	10,002.68	1,411.18	462.70	3,199.11	1,909.34	669.64	-2,422.11
Sep	0.00	5,983.56	1,510.81	431.66	3,096.93	1,567.46	534.11	-2,495.24
Oct	4.84	1,925.34	1,809.23	517.14	3,201.30	1,215.30	326.24	-2,829.38
Nov	1,323.67	6.14	2,030.00	640.51	3,098.71	874.19	112.69	-2,977.72
Dec	4,741.98	0.00	2,334.18	883.69	3,202.68	717.76	25.35	-3,393.95
Annual sums	15,904.93	42,473.58	22,776.74	7,369.88	37,692.59	16,935.14	4,186.43	-32,313.77

Table 24: Energy results for Thessaloniki bare-minimum insulation case

When the “low” insulation values of each location are compared to the “bare-minimum” cases energy-results the observations are quite shocking indeed. In Table 25 below the differences are illustrated (positive values indicate increase in the “bare-minimum” case vs the low. Reminder: Electricity Deficit values are by nature negative, thus a negative difference means further expenditure in the “bare-minimum” case, not less.)

	Main Zone Total Heating needs [kWh th], Annually	Main Zone Total Cooling needs [kWh th], Annually	HP H/C+HW load (after MVHR) [kWh e], Annually	Final Electricity Surplus (wasted PV production) [kWh e], Annually	Final Electricity Deficit (to be grid-bought) [kWh e], Annually
Larnaca	264.84	1,483.11	72.47	-68.75	-3.57
Athens	-308.11	1,833.22	24.90	-35.03	10.04
Thessaloniki	-1,266.87	2,534.94	-29.78	-7.06	36.63

Table 25: Differentiation of Energy and annual Utility cost from low to bare-minimum cases for each location

As can be seen, thermal values and heat pump loads differentiate to various levels but still, the eventual change in the annual cost of grid-bought electricity is not even close to justifying the insulation investment. This remark makes it a compelling argument to drive the design to the ultimate limit (even in violation of the regulations): complete lack of insulation.

This decision is made since all regulations and suggestions developed regarding insulation levels are derived from an “organic” cost-optimality of a capital investment versus ongoing energy costs. Yet so far the findings indicate differently and by testing the cost-optimality of a no-insulation case will be the most extreme test, proving if there is an optimal point of insulation at any range of the no-to high-insulation “spectrum”.

For that reason a no-insulation building composition is established. The exact design comprises simply of a reinforced concrete frame and double-leaf hollow brick external walls (and single-leaf hollow brick partition walls). The results obtained for each location are provided in the Tables 26-28 below:

	Thermal needs			Energy values				
month	Main Zone Total Heating needs [kWh th], Monthly	Main Zone Total Cooling needs [kWh th], Monthly	Hot Water needs [kWh th], Monthly	HP H/C+HW load (after MVHR) [kWh e], Monthly	Electronic equipment (non-HP) consumption [kWh e], Monthly	PV Produced Electricity [kWh e], Monthly	Final Electricity Surplus (wasted PV production [kWh e], Monthly	Final Electricity Deficit (to be grid-bought) [kWh e], Monthly
Jan	4,128.77	0.00	2,080.36	783.13	3,201.66	1,368.66	277.88	-2,894.01
Feb	2,950.91	0.00	1,889.45	674.74	2,891.98	1,370.76	271.59	-2,467.55
Mar	1,049.84	2.14	2,034.21	629.19	3,201.58	1,727.59	497.43	-2,600.61
Apr	18.19	1,474.36	1,829.02	523.41	3,097.80	1,925.83	704.39	-2,399.75
May	0.00	6,117.19	1,682.31	480.66	3,200.20	2,219.98	927.07	-2,387.95
Jun	0.00	11,241.62	1,410.32	515.99	3,096.14	2,448.61	1,038.75	-2,202.27
Jul	0.00	15,012.29	1,318.88	686.28	3,198.71	2,512.17	907.18	-2,279.99
Aug	0.00	15,523.35	1,295.81	709.64	3,198.59	2,360.24	826.78	-2,374.76
Sep	0.00	11,112.12	1,348.91	507.98	3,095.98	2,195.45	967.76	-2,376.27
Oct	0.00	4,382.91	1,578.48	450.99	3,200.14	1,871.67	798.22	-2,577.69
Nov	100.27	550.88	1,728.53	498.45	3,097.56	1,509.90	521.93	-2,608.05
Dec	2,602.33	0.00	1,976.52	683.68	3,201.33	1,385.14	325.52	-2,825.39
Annual sums	10,850.29	65,416.85	20,172.80	7,144.15	37,681.66	22,895.99	8,064.50	-29,994.32

Table 26: Energy results for Larnaca no-insulation case

	Thermal needs			Energy values				
month	Main Zone Total Heating needs [kWh th], Monthly	Main Zone Total Cooling needs [kWh th], Monthly	Hot Water needs [kWh th], Monthly	HP H/C+HW load (after MVHR) [kWh e], Monthly	Electronic equipment (non-HP) consumption [kWh e], Monthly	PV Produced Electricity [kWh e], Monthly	Final Electricity Surplus (wasted PV production [kWh e], Monthly	Final Electricity Deficit (to be grid-bought) [kWh e], Monthly
Jan	6,106.77	0.00	2,230.35	916.41	3,201.79	971.50	86.39	-3,233.09
Feb	6,242.40	0.00	2,030.14	865.41	2,892.24	968.06	51.97	-2,841.55
Mar	3,212.37	0.17	2,155.35	762.67	3,201.79	1,344.66	210.66	-2,830.46
Apr	302.10	651.77	1,912.76	560.31	3,098.06	1,501.14	343.04	-2,500.27
May	0.02	4,148.90	1,740.00	497.14	3,200.49	1,794.98	521.95	-2,424.60
Jun	0.00	10,195.34	1,449.40	499.04	3,096.08	2,083.92	681.65	-2,192.86
Jul	0.00	13,912.43	1,353.49	636.00	3,198.58	2,182.47	605.53	-2,257.64
Aug	0.00	13,645.32	1,341.96	623.79	3,198.57	1,986.14	552.68	-2,388.90
Sep	0.00	8,434.70	1,427.07	438.75	3,096.26	1,779.27	662.95	-2,418.69
Oct	0.00	1,618.31	1,693.85	483.96	3,200.57	1,321.10	374.19	-2,737.61
Nov	2,061.12	0.00	1,873.68	629.56	3,097.76	865.77	142.45	-3,004.00
Dec	6,712.17	0.00	2,126.51	914.42	3,201.73	857.75	58.15	-3,316.55
Annual sums	24,636.96	52,606.95	21,334.56	7,827.45	37,683.93	17,656.78	4,291.63	-32,146.23

Table 27: Energy results for Athens no-insulation case

	Thermal needs			Energy values				
month	Main Zone Total Heating needs [kWh th], Monthly	Main Zone Total Cooling needs [kWh th], Monthly	Hot Water needs [kWh th], Monthly	HP H/C+HW load (after MVHR) [kWh e], Monthly	Electronic equipment (non-HP) consumption [kWh e], Monthly	PV Produced Electricity [kWh e], Monthly	Final Electricity Surplus (wasted PV production [kWh e], Monthly	Final Electricity Deficit (to be grid-bought) [kWh e], Monthly
Jan	12,226.48	0.00	2,455.33	1,260.45	3,203.03	854.78	0.00	-3,608.70
Feb	8,720.90	0.00	2,176.03	1,020.39	2,893.05	1,154.10	19.77	-2,779.11
Mar	5,578.02	0.00	2,288.03	908.72	3,202.28	1,370.74	124.57	-2,864.83
Apr	1,174.46	209.30	2,002.08	625.71	3,098.29	1,447.80	324.17	-2,600.38
May	4.40	3,342.83	1,814.99	518.77	3,200.79	1,763.74	471.73	-2,427.54
Jun	0.00	8,337.64	1,516.39	447.01	3,096.41	1,989.94	668.23	-2,221.70
Jul	0.00	11,734.89	1,428.49	539.04	3,199.04	2,069.98	616.91	-2,285.01
Aug	0.00	11,224.80	1,411.18	517.00	3,199.11	1,909.34	615.34	-2,422.11
Sep	0.00	5,364.04	1,510.81	431.66	3,096.92	1,567.46	534.11	-2,495.23
Oct	893.01	705.90	1,809.23	557.75	3,201.08	1,215.30	326.24	-2,869.77
Nov	5,394.87	0.00	2,030.00	826.62	3,098.50	874.19	27.45	-3,078.37
Dec	11,010.81	0.00	2,334.18	1,170.26	3,202.63	717.76	0.00	-3,655.13
Annual sums	45,002.96	40,919.41	22,776.74	8,823.38	37,691.14	16,935.14	3,728.51	-33,307.89

Table 28: Energy results for Thessaloniki no-insulation case

Results for the no-insulation cases are reasonable with substantial increases in the thermal needs, especially for the space heating and proportionally to the coldness of the locations zone. Yet still the final electricity differences do not seem to be substantial. This image is clarified in the following Table 29 where the change of energy and final cost values from the "low-" case scenario to the "no-insulation" one is illustrated:

	Main Zone Total Heating needs [kWh th], Monthly	Main Zone Total Cooling needs [kWh th], Monthly	HP H/C+HW load (after MVHR) [kWh e], Monthly	Final Electricity Surplus (wasted PV production) [kWh e], Monthly	Final Electricity Deficit (to be grid-bought) [kWh e], Monthly
Larnaca	9,598.79	2,506.48	763.01	-595.91	-165.14
Athens	18,475.48	2,576.93	1,131.62	-524.34	-605.77
Thessaloniki	27,831.17	980.76	1,423.72	-464.97	-957.49

Table 29: Differentiation of Energy and annual Utility cost from low- to no-insulation cases for each location

As seen, in the worst case of Thessaloniki the final grid-bought electricity increase is by 957.49 kWh per year, which translates (€0.06/kWh) to a €1,723.48 extra cost for the 30-year designated pay-back period of the investment. This cost is by far lower than the investment cost of insulating the floor, roof and external walls of the building. A counter argument is that in the case of no-insulation a more powerful (i.e. costlier) heat-pump will be needed and larger thermal storage tanks. The validity of such an estimation (that the cost of stronger equipment will exceed the savings from the omission of insulation) could be verified through techno-economical calculations, yet it is pointless as the building will have to abide by minimum regulations even if it is not cost-reasonable eventually.

The bottom-line of this assessment is different: given that with no insulation at all the "final" energy needs of the residence (i.e. grid-bought electricity) is not substantially different from even the lowest assumed insulation level, this possibly confirms the initial hypothesis that the configuration of integrated H/C-HW through a heat-pump & thermal storage set operating mostly under PV-produced electricity is such a highly-efficient equipment arrangement of covering the residence's thermal needs that the insulation level becomes eventually of secondary significance. This hypothesis is supported readily from the fact that according to literature about 80% of a household's energy consumption is for the covering of thermal needs. Yet here, the thermal-needs-related energy consumption (i.e. the heat pump load) is approximately only 15% of the total electricity consumption of the facility. Assuming that the electronic equipment consumption is realistic and not exaggerated (according to personal estimation it could be considered even under-estimated) then the final energy used for heating through this equipment configuration is indeed 65% more efficient than the average used in literature. To roughly double-check that a new assumption is made: that the heating and cooling needs are covered without energy recovery and from a piece of equipment with electricity-to-heating/cooling efficiency of 1. In that case the thermal loads transform into an average of 68% for low insulation and 73% for no insulation of the total energy consumption of the residence. These final values are much closed to the 80% of the literature sources and perhaps with a stricter assumption of poorer air-tightness (thus stronger air infiltration) the simulation results would yield even closer to the 80% value. Even so, the results converge on the fact that the low energy consumption of the residence is due to the design of thermal-loads provision-equipment and not the passive thermal performance of the building.

Hence, by this point a double decision is made: A) the bare-minimum limits of insulation according to the current Greek regulation will be used, with building element compositions to be decided accordingly and B) benchmark cases will be simulated with an alternative energy-provision equipment-combination used, closer to the norm of the Greek building sector.

For the benchmark cases, once more from KENAK some key efficiency values are derived regarding the thermal equipment installed. The minimum standards require a heating boiler of at least one star "*" of efficiency, which corresponds to roughly 88% thermal efficiency [80], and Domestic Hot Water production must be covered by solar thermal systems by an annual minimum share of 80, 75 and 70% for Greek climatic zones A, B and C correspondingly [79].

Therefore, coming to the benchmark design, a realistic assumption would be that the average solicitor of such a residence project would intend to minimize the investment as to maximize payback rate. For that reason not only the minimum insulation but also the lowest-cost-possible equipment set will be selected. Moving with this rationale ahead—and based also on personal experience—the following thermal equipment configuration will be considered for the benchmark designs: for coverage of the heating needs the residence will have a diesel fuel boiler of 88% efficiency, while only natural ventilation will be available for cooling. In addition, no mechanical ventilation system will be installed as it is not necessary (based on KENAK). Then, regarding DHW, the most common technology is solar-thermal collectors with buffer tanks equipped with electric resistance for complementary heating, therefore PV panels will be removed (all electricity will be grid-bought) and replaced by the solar thermal system which's size will determined by the minimum annual production they must have based on the designated for the climate zone share. Lastly, no thermal storage tanks will be used.

In absence of a ventilation and cooling system there will be of course no energy (and thus cost) expenses regarding air circulation in the building and no mean of extracting heat as to not exceed the maximum comfortable indoor temperature limit. In order to fulfil the fresh air and cooling needs of the Main Zone (as much as possible) natural ventilation will be assumed (by means of opening windows, balcony doors etc.) decided upon the time of the day and the heat retention/rejection needs of the occupants. The previous designs had a maximum ventilation rate of 0.135 m^3/s equivalent to ~0.27 ACH. The new maximum possible natural ventilation rate will be assumed at 2.7 m^3/s, 20 times higher than the previous one, with the overall air-change rate (5.44 ACH) being considered an achievable volume for natural ventilation. The new seasonal schedule of ventilation is based on 4 "tiers" (the original max rate and 3 new ones, 5, 10 and finally 20 times higher) which are distributed throughout the year according to minimization of indoor maximum temperatures, without though increasing any heating loads as well.

3.5.5. Larnaca benchmark-design comparison

Beginning with Larnaca the minimum-Insulation benchmark-design case yields the following results, seen in Table 30 below:

	Thermal needs			Energy values				
month	Main Zone Total Heating needs [kWh th], Monthly	Main Zone Total Cooling needs [kWh th], Monthly	Hot Water needs [kWh th], Monthly	Boiler fuel consumption [kWh th], Monthly	Electronic equipment consumption [kWh e], Monthly	Hot Water Produced [kWh th], Monthly	Supplemental Electricity for Hot Water [kWh e], Monthly	Final Electricity Consumption (grid-bought) [kWh e], Monthly
Jan	486.15	0.00	2,080.36	552.45	3,074.49	1,157.18	923.18	-3,997.66
Feb	251.73	0.00	1,889.45	286.06	2,776.96	1,228.56	660.89	-3,437.85
Mar	1.02	0.00	2,034.21	1.16	3,074.49	1,556.96	485.56	-3,560.04
Apr	0.00	0.00	1,829.02	0.00	2,975.31	1,735.89	216.06	-3,191.37
May	0.00	0.00	1,682.31	0.00	3,074.49	1,885.73	84.15	-3,158.64
Jun	0.00	0.00	1,410.32	0.00	2,975.31	1,984.97	0.00	-2,975.31
Jul	0.00	0.00	1,318.88	0.00	3,074.49	2,071.46	0.00	-3,074.49
Aug	0.00	0.00	1,295.81	0.00	3,074.49	2,103.87	0.00	-3,074.49
Sep	0.00	0.00	1,348.91	0.00	2,975.31	1,978.18	0.00	-2,975.31
Oct	0.00	0.00	1,578.48	0.00	3,074.49	1,686.69	117.32	-3,191.81
Nov	0.00	0.00	1,728.53	0.00	2,975.31	1,303.75	427.50	-3,402.81
Dec	98.32	0.00	1,976.52	111.73	3,074.49	1,152.74	823.78	-3,898.27
Annual sums	837.22	0.00	20,172.80	951.38	36,199.61	19,845.99	3,738.43	-39,938.04
Annual costs				-95.14				-2,396.28

Table 30: Energy results for Larnaca benchmark-design case

As observed the table-format differs from the previous ones. The heat-pump's electricity consumption is replaced by the furnace-boiler's fuel consumption. Since PV panels are replaced by solar-thermal panels, the corresponding column now hosts the on-site DHW production. Lastly the next column (previous "PV production surplus") now denotes the amount of electricity required for supplemental heating of water.

To begin interpreting the table, the annual energy costs have been calculated based on the latest average price of heating-Diesel fuel in Greece: 0.95 €/L [81] and the average retail price of electricity, 0.06 €/kWh, as established earlier in the research. It has to be noted that the solar-thermal panels have been sized in order to provide 81.47% of the annual DHW needs, as to be up to regulations' minimum standards.

Now for to the comparison of the integrated PV-HVAC-DHW-TS design with the benchmark case, beginning from the heating and cooling needs it is observed that heating needs are about half in the benchmark than the original case. This is due to the reduced ventilation of the building, especially at nights that people are considered to normally close their windows for safety/psychological issues. As "forced" cooling does not exist, so do not exist the cooling loads too. Now one would expect a large reduction in electricity consumption due to the lack of intense cooling loads (more than 64 MWh_{th}/a of cooling for the HVAC scenario) but strikingly the opposite happens: the total grid electricity load here is about 10 MWh_e/a more than the HVAC case, bringing an additional utility bill cost of ~600 €/a. This great increase in grid electricity consumption even at absence of an excessive heat pump cooling load (~6.4 MWh_e/a) proves the significance of the integrated PV system in the original design. That is since a large part of the PVs' production goes to the consumption of the rest of electronics devices (overall PVs cover ~14.3 MWh_e/a of final electricity consumption in the residence).

Still, the two building equipment compositions are quite different and the comparison cannot be concluded before the core goal of the issue at hand is addressed: the indoor thermal comfort and air quality the occupants enjoy. For that reason the most crucial aspects of TC and IAQ are gathered for both cases in Charts 1 and 2 below:

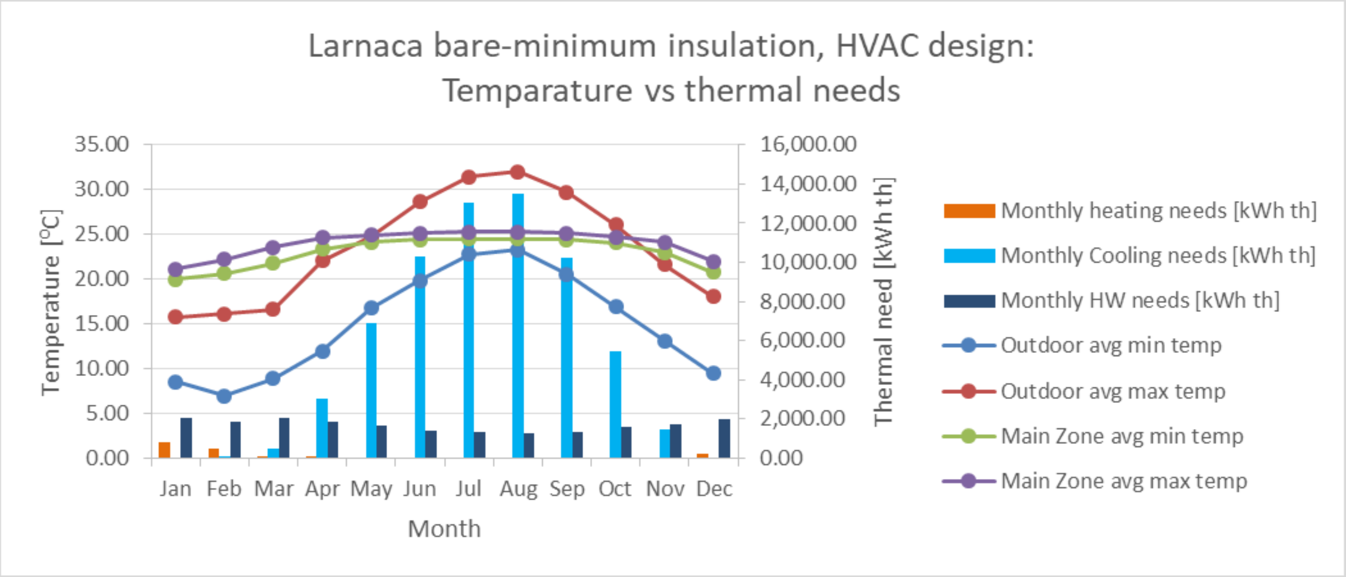


Chart 7: Larnaca bare-minimum insulation, HVAC design: Temperature vs thermal needs

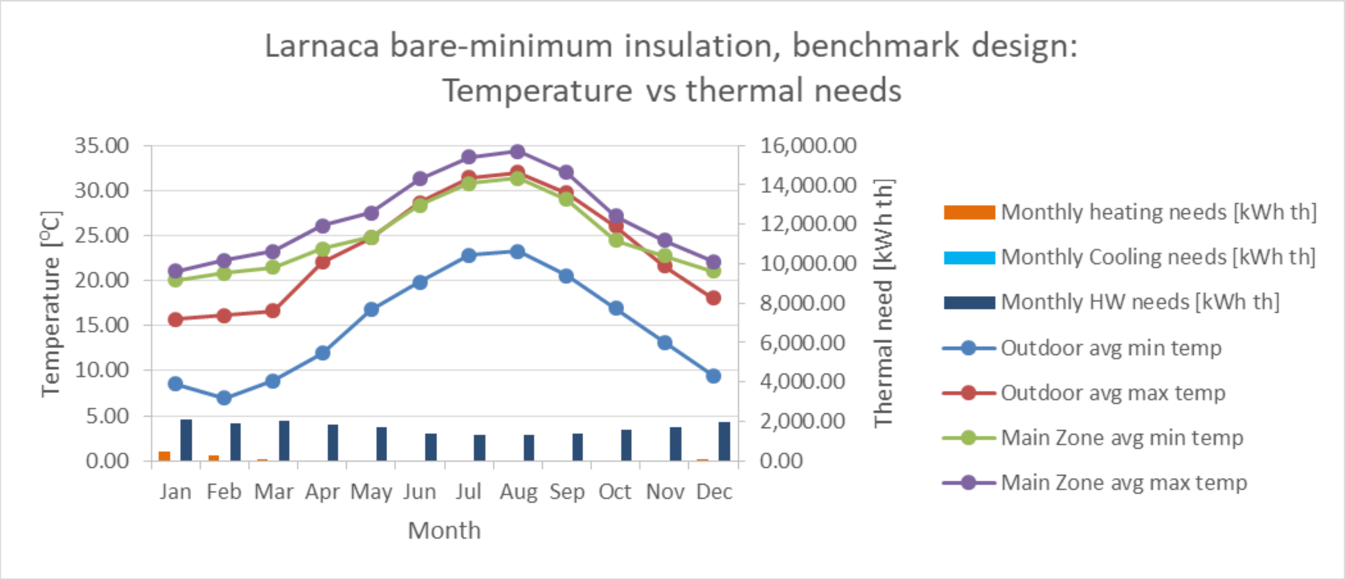


Chart 8: Larnaca bare-minimum insulation, benchmark design: Temperature vs thermal needs

As observed clearly in these charts the indoor temperature range is well maintained between 20 – 24 ^{0}C in the HVAC case, but in the benchmark even increased natural ventilation is not able to maintain constantly temperatures below 24 ^{0}C for the period of April to end of October. In this period max temperatures peak at about 34 ^{0}C indoor, a rather suffocating condition. Realistically one can expect that even higher natural ventilation rate can be achieved but still, since from May to October the outdoor temperatures exceed 24 ^{0}C it is practically (and thermodynamically too) impossible to achieve a more comfortable temperature indoors with just ventilation in this period. Floor or ceiling fans may improve the situation but such a comfort parameter cannot be evaluated here, even though a high indoor temperature is meant to be a discomfort with only ailment the extraction of heat from the space. *Unfortunately this is the reality for a majority of Greek households…*

In regard to the indoor air quality the following Charts 3 and 4 provide rather insightful information:

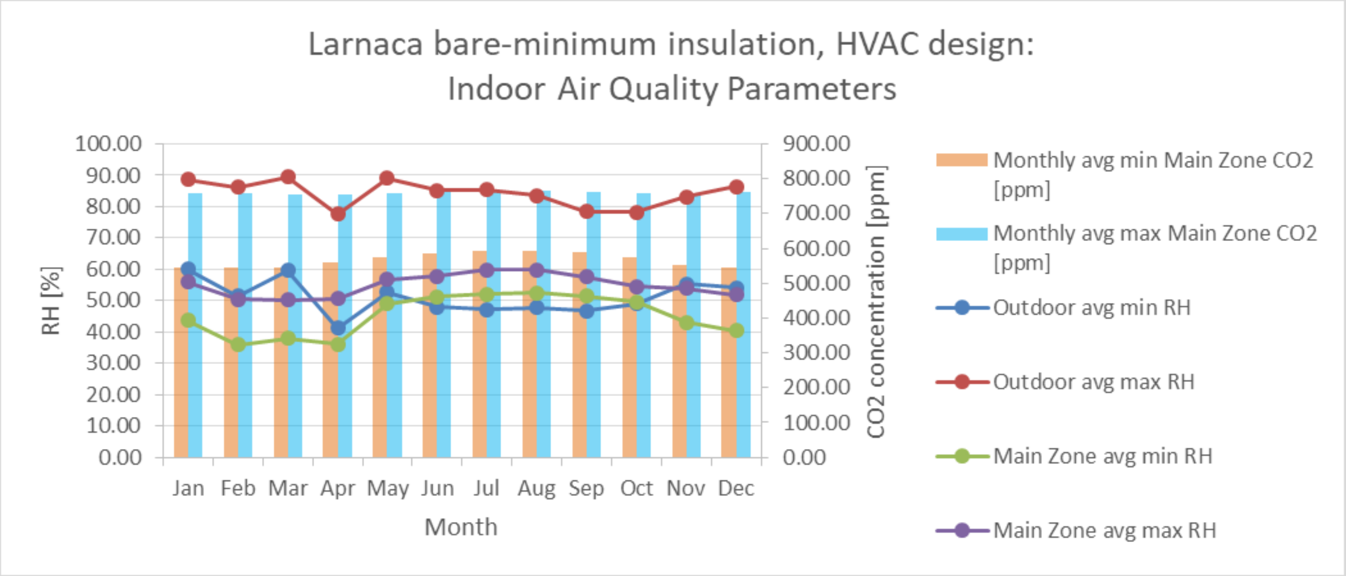


Chart 9: Larnaca bare-minimum insulation, HVAC design: Indoor Air Quality Parameters

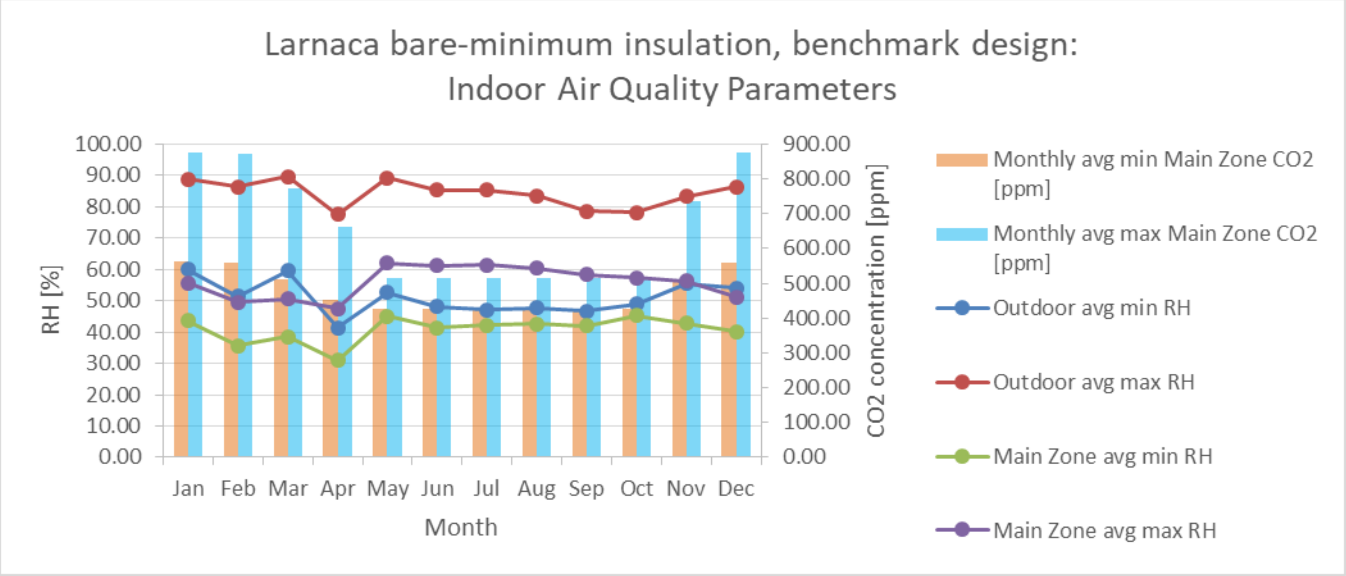


Chart 10: Larnaca bare-minimum insulation, benchmark design: Indoor Air Quality Parameters

The effect of ventilation is much more profound here. For the HVAC case, the levels of CO2 are maintained rather stable due to the stable ventilation rate. For the benchmark case though they fluctuate greatly with indoor air being much more fresh (lower CO2) in the summer when ventilation is exercised in an effort to cool the building and much more stale in the winter when ventilation is minimised in an effort to maintain heat. Therefore in the benchmark case indoor-CO2 might be maintained below the ASHRAE suggestion of less-thn-700-ppm-above-outdoor [82] but exceeds the standard of 800 and 700 ppm according to some other building organisations [83] in the winter months of December, January and February.

Furthermore, humidity is an issue as well. With the HVAC system the relative humidity is maintained rather steady year-round mostly within the range of 40-60 %. In the benchmark case though the variation of humidity levels is much greater reaching almost 30% in April and May to August slightly exceeding the 60%, the official ASHRAE limits.

Overall in an effort to summarise the cost vs benefit of the two designs, HVAC and benchmark, the proposed HVAC one has a far more complex design and a great upfront cost, to be precisely assessed later on while the benchmark is the cheapest, most familiar option. Yet eventually, the benchmark equipment synthesis comes at a high extra annual expense of electricity (about 700 €/a, i.e. an NPV of -7.187.61 € for the 30-year lifetime of the investment) and most importantly at a far lower indoor thermal comfort and air quality. To quantify that, EnergyPlus can check at each time-step of the simulation if the achieved conditions are in accordance with the ASHRAE Standard 55 (Thermal Environmental Conditions for Human Occupancy). The results indicate that for the HVAC model a total of 721.75 hours of the year (8.24% of the time) the zone is not comfortable. For the benchmark design the uncomfortable hours are 4,226.50 (48.25%). To conclude, the upfront cost of the HVAC system will be much greater, in absolute terms, than the benchmark's NPV of higher energy costs (i.e. financially not making sense) but the thermal comfort of the occupants is considered the main goal and has to be fulfilled regardless. The exact impact of the final cost in the decision will be established in later on at the cost analysis section. For now, more results and conclusions are to be extracted for the rest of locations, Athens and Thessaloniki.

3.5.6. Athens benchmark-design comparison

For the Athens bare-minimum insulation, benchmark case the results are illustrated below in Table:

	Thermal needs			Energy values				
month	Main Zone Total Heating needs [kWh th], Monthly	Main Zone Total Cooling needs [kWh th], Monthly	Hot Water needs [kWh th], Monthly	Boiler fuel consumption [kWh th], Monthly	Electronic equipment consumption [kWh e], Monthly	Hot Water Produced [kWh th], Monthly	Supplemental Electricity for Hot Water [kWh e], Monthly	Final Electricity Consumption (grid-bought) [kWh e], Monthly
Jan	1,233.01	0.00	2,230.35	1,401.15	3,074.49	1,115.95	1,114.39	-4,188.88
Feb	1,393.02	0.00	2,030.14	1,582.98	2,776.96	1,193.72	838.23	-3,615.19
Mar	345.96	0.00	2,155.35	393.14	3,074.49	1,661.76	611.95	-3,686.44
Apr	0.23	0.00	1,912.76	0.26	2,975.31	1,855.30	316.77	-3,292.08
May	69.58	0.00	1,740.00	79.07	3,074.49	2,114.37	136.23	-3,210.72
Jun	0.00	0.00	1,449.40	0.00	2,975.31	2,367.83	13.71	-2,989.02
Jul	0.00	0.00	1,353.49	0.00	3,074.49	2,520.41	0.00	-3,074.49
Aug	0.00	0.00	1,341.96	0.00	3,074.49	2,437.55	0.00	-3,074.49
Sep	0.00	0.00	1,427.07	0.00	2,975.31	2,198.93	0.00	-2,975.31
Oct	31.65	0.00	1,693.85	35.97	3,074.49	1,632.69	222.91	-3,297.40
Nov	30.41	0.00	1,873.68	34.55	2,975.31	1,029.47	844.64	-3,819.95
Dec	1,502.95	0.00	2,126.51	1,707.90	3,074.49	980.62	1,145.89	-4,220.38
Annual sums	4,606.82	0.00	21,334.56	5,235.02	36,199.61	21,108.59	5,244.72	-41,444.33
Annual costs				-523.50				-2,486.66

Table 31: Energy results for Athens benchmark-design case

As seen here the heating needs reach about 4.6 MWh_{th}/a (1.2 MWh_{th} less than the HVAC design) due to decreased natural ventilation in the colder months. The previously existing cooling load of ~51.8 MWh_{th}/a ceases to exist thus an electric load of ~6.7 MWh_{e} of the heat pump are cancelled. Yet due to the lack of PV panels and the extra water heating load (24.58% of total DHW needs) the final grid-electricity demand is at ~41.4MWh_{e}/a (increased, in absolute terms, by 9.9 MWh_{e}/a in comparison to the PV-HVAC case). The extra electricity cost with the added boiler fuel cost reaches an extra of ~1,100 €/a.

Now coming to the indoor thermal comfort and air quality the results are presented in the Charts 5-8 below:

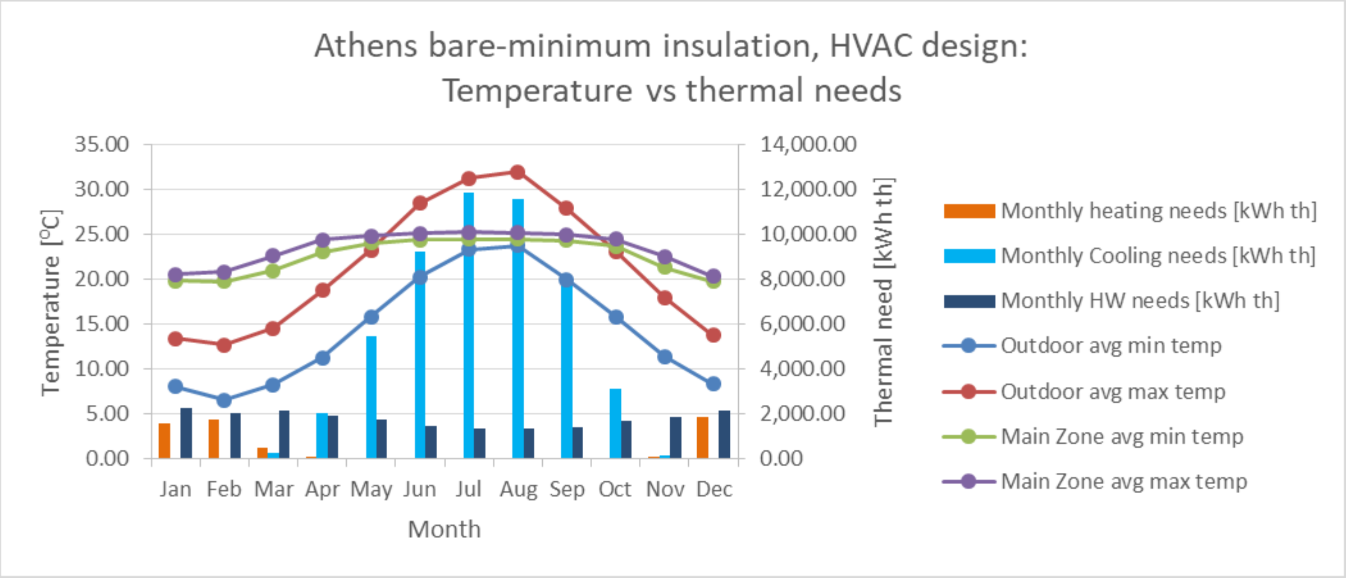


Chart 11: Athens bare-minimum insulation, HVAC design: Temperature vs thermal needs

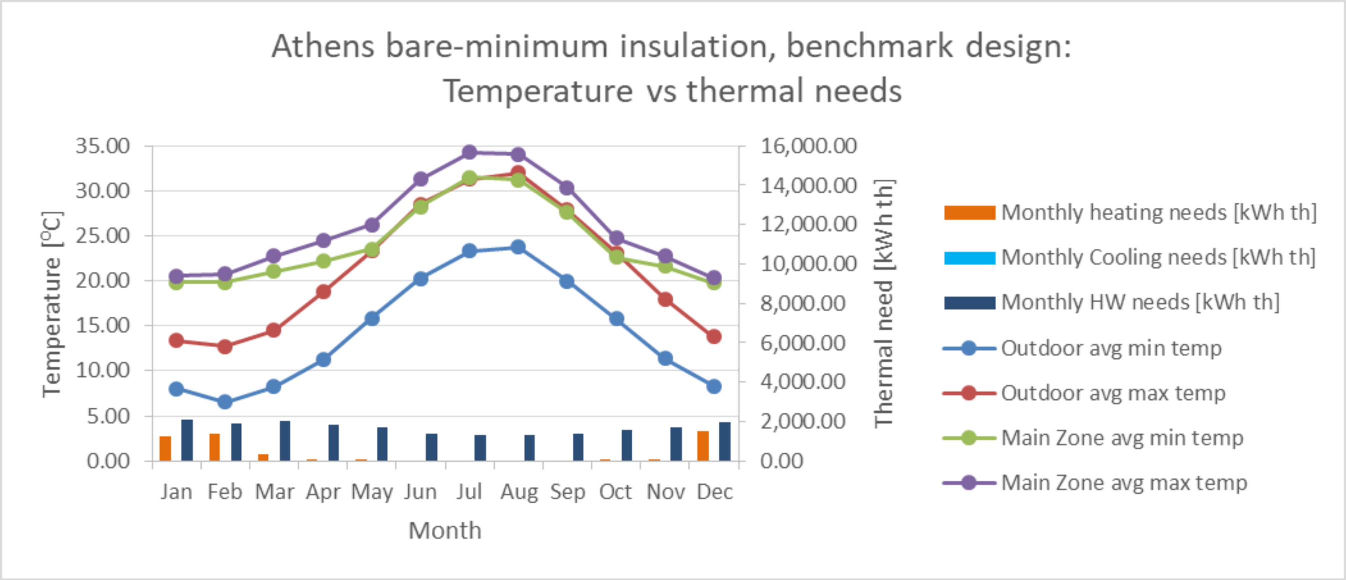


Chart 12: Athens bare-minimum insulation, benchmark design: Temperature vs thermal needs

Here also the lack of effective cooling systems is evident: from mid-April to end of September the indoor temperatures rise above 24 °C, up to 34 °C again, while outdoor temperatures make a cooling system necessary for the period mid-May to mid-September where outdoor temperatures rise above 24 °C as well.

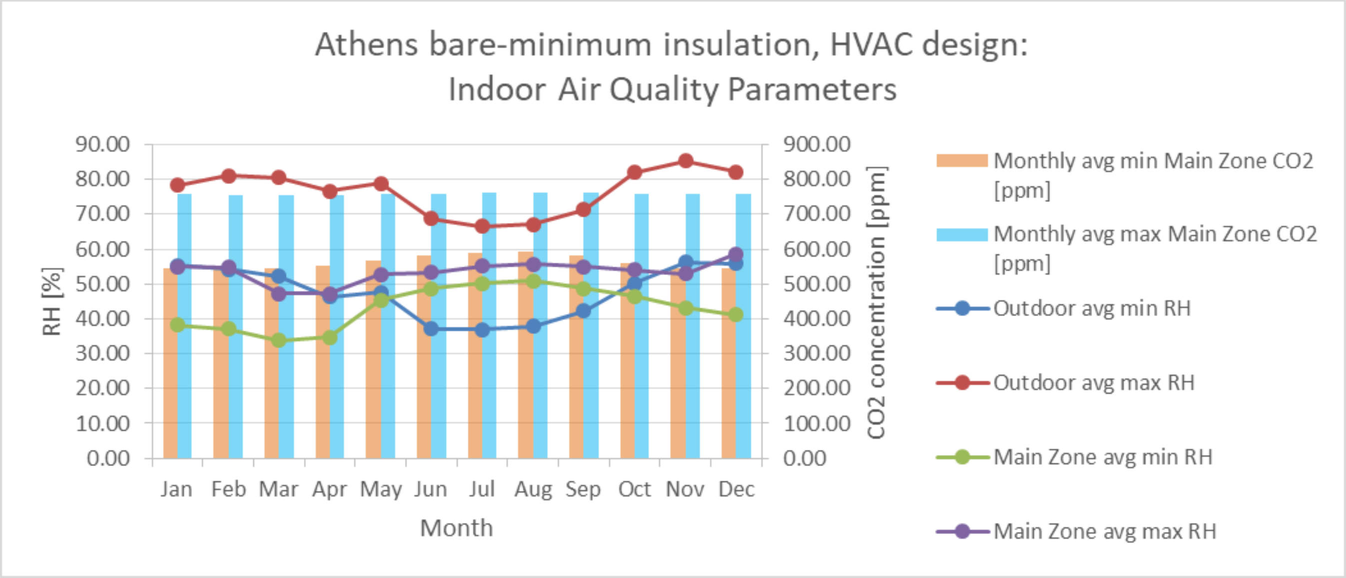


Chart 13: Athens bare-minimum insulation, HVAC design: Indoor Air Quality Parameters

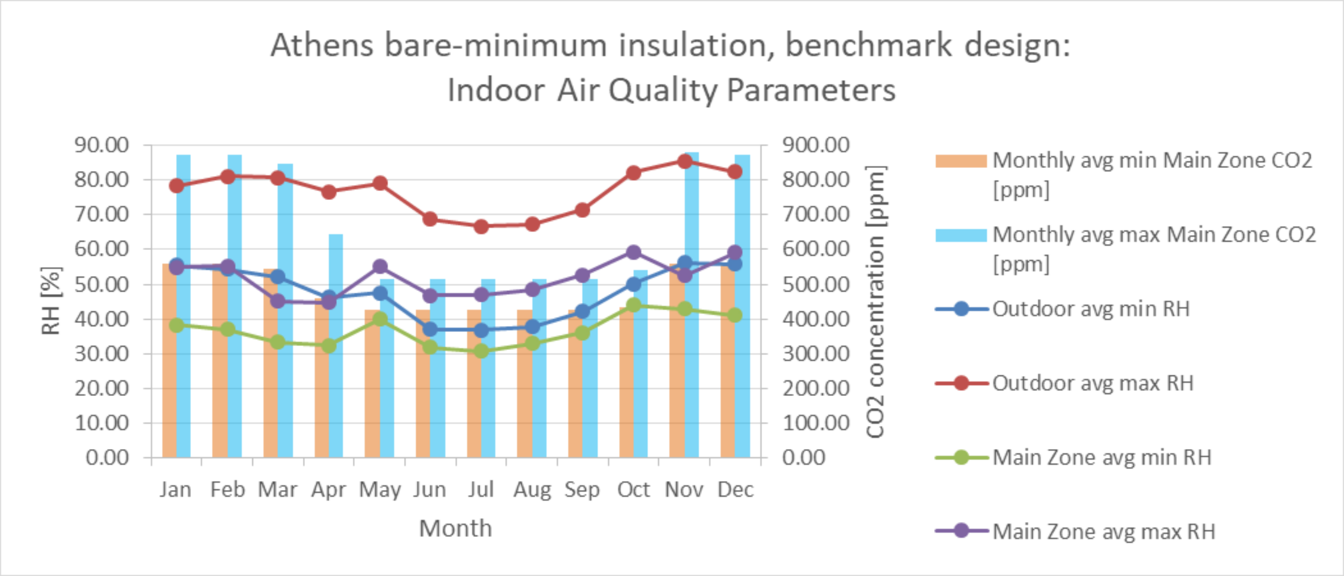


Chart 14: Athens bare-minimum insulation, benchmark design: Indoor Air Quality Parameters

The relative humidity annual fluctuation has a better behaviour here since Athens has naturally a lower humidity than Larnaca (and even Chania) which is a directly coastal city. The variation and levels of indoor CO2 concentration follow the same pattern as in Larnaca since the outdoor CO2 levels and its indoor production from the occupants is irrelevant to the location.

Summing up, in the case of Athens the extra energy costs of benchmark design versus the HVAC design rise up to more than 1,100 €/a giving a final extra NPV value of -11,459 €. This NPV value is higher, in absolute terms, compared to the one in Larnaca which makes an initial investment more attractive. Especially in combination to the fact that lower peak loads in Athens mean a less expensive HVAC system, it seems that the integrated-HVAC system is an even more sustainable choice for a colder climate. Therefore it remains to see the results from Thessaloniki in order to assess this assumption. Finally, once more it’s the cost analysis that will illustrate the exact financial picture but regarding the comfort of the occupants the EnergyPlus results of the ASHRAE 55 standard compliance indicate 4,809.75 hours of the year (54.91% of the time) not met in the benchmark case while for the HVAC one it is 1,984.75 hours (22.66% of the time). This significantly higher percentage relates mostly to the winter months. Since in the HVAC cases the temperature is very well regulated within the comfort limits of 20 – 24 ^{o}C while the lowest humidity levels are higher in the case of Larnaca than in Athens (and Larnaca has far less hours of not meeting the ASHRAE 55 Standard) more it is concluded that the humidity is the factor relating mostly in lack of comfort. With an HVAC system the addition of humidity in the conditioned air is rather simple and inexpensive, through the addition of a humidifier in the system. On the contrary for the benchmark cases there is no convenient way of adding humidity to the air. Thus, eventually, reducing the uncomfortable hours is rather easy in the HVAC case but too difficult in the benchmark case.

3.5.7. Thessaloniki benchmark-design comparison

Similarly for the city of Thessaloniki the following results are obtained for the case of benchmark design, as seen in Table 32 below:

	Thermal needs			Energy values				
month	Main Zone Total Heating needs [kWh th], Monthly	Main Zone Total Cooling needs [kWh th], Monthly	Hot Water needs [kWh th], Monthly	Boiler fuel consumption [kWh th], Monthly	Electronic equipment consumption [kWh e], Monthly	Hot Water Produced [kWh th], Monthly	Supplemental Electricity for Hot Water [kWh e], Monthly	Final Electricity Consumption (grid-bought) [kWh e], Monthly
Jan	4,773.94	0.00	2,455.33	5,424.93	3,074.49	970.14	1,485.19	-4,559.68
Feb	2,443.60	0.00	2,176.03	2,776.82	2,776.96	1,386.16	789.87	-3,566.82
Mar	903.92	0.00	2,288.03	1,027.19	3,074.49	1,693.75	604.35	-3,678.84
Apr	0.00	0.00	2,002.08	0.00	2,975.31	1,789.23	399.21	-3,374.52
May	27.19	0.00	1,814.99	30.90	3,074.49	2,106.22	153.86	-3,228.34
Jun	0.00	0.00	1,516.39	0.00	2,975.31	2,307.67	5.40	-2,980.71
Jul	0.00	0.00	1,428.49	0.00	3,074.49	2,427.91	6.96	-3,081.45
Aug	0.00	0.00	1,411.18	0.00	3,074.49	2,347.59	19.43	-3,093.91
Sep	0.00	0.00	1,510.81	0.00	2,975.31	1,937.30	89.48	-3,064.79
Oct	612.44	0.00	1,809.23	695.96	3,074.49	1,502.78	421.51	-3,496.00
Nov	1,006.90	0.00	2,030.00	1,144.20	2,975.31	1,011.99	1,018.01	-3,993.32
Dec	4,174.18	0.00	2,334.18	4,743.39	3,074.49	814.04	1,520.14	-4,594.63
Annual sums	13,942.18	0.00	22,776.74	15,843.39	36,199.61	20,294.78	6,513.40	-42,713.00
Annual costs				-1,584.34				-2,562.78

Table 32: Energy results for Thessaloniki benchmark-design case

For Thessaloniki the benchmark case's annual heating needs are at ~ 13.9 $\mathrm{MWh_{th}}$, about 2 $\mathrm{MWh_{th}}$ less than in the HVAC case. As observed—and normally expected—the colder the climate is, the more energy is managed to be saved by a reduced ventilation rate. The annual cooling load avoided here is just ~22.8 $\mathrm{MWh_{th}}$ so the ~7.4 $\mathrm{MWh_{e}}$ saved from not having a heat-pump relate mostly to the winter months' heating and hot water production. This is replaced instead by ~15.8 $\mathrm{MWh_{H}}$ of fuel and ~6.5 $\mathrm{MWh_{e}}$ for supplemental water heating. A striking realization at this point is that the electricity consumed merely for covering the almost 28.60% of annual DHW needs (less than 30%, as mandated by the Greek regulations for this climatic zone) is just 0.9 $\mathrm{MWh_{e}}$ less than the electricity needed to cover the entire air-conditioning and hot water needs in the HVAC case. Eventually the grid-electricity consumed here is ~10.4 $\mathrm{MWh_{e}}$ more than in the HVAC case and with the fuel cost the overall annual energy expenditure is higher by 2.208 €.

The comparison of the 2 cases is completed with the thermal comfort and indoor air quality results as presented in Charts 9-12 below:

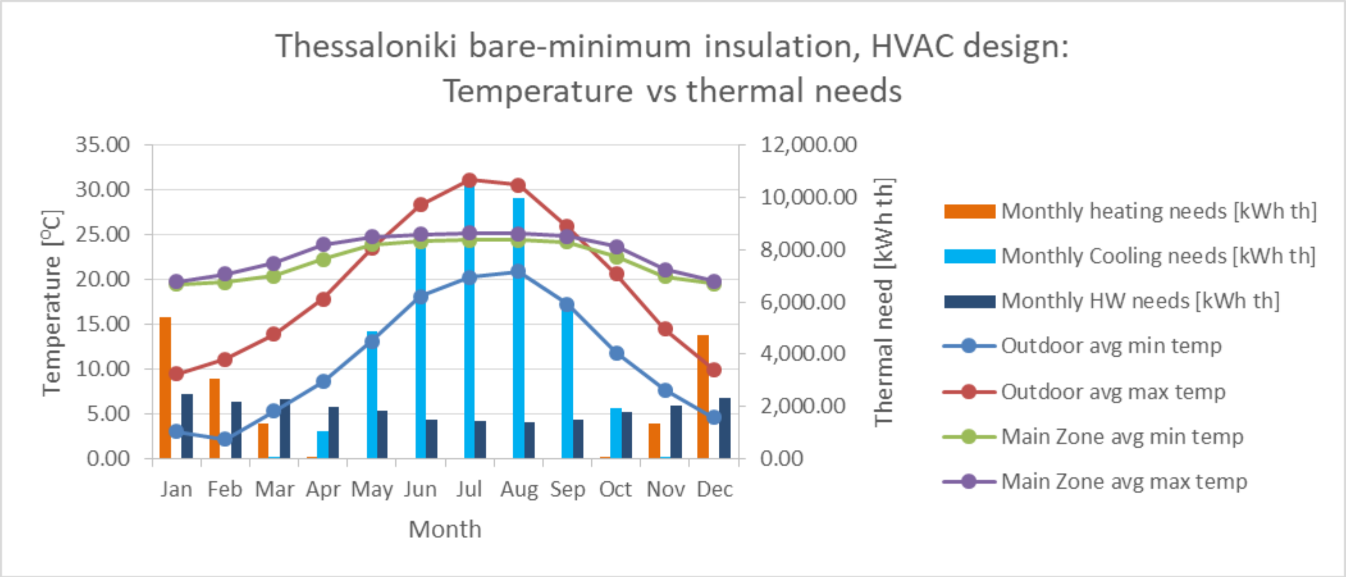


Chart 15: Thessaloniki bare-minimum insulation, HVAC design: Temperature vs thermal needs

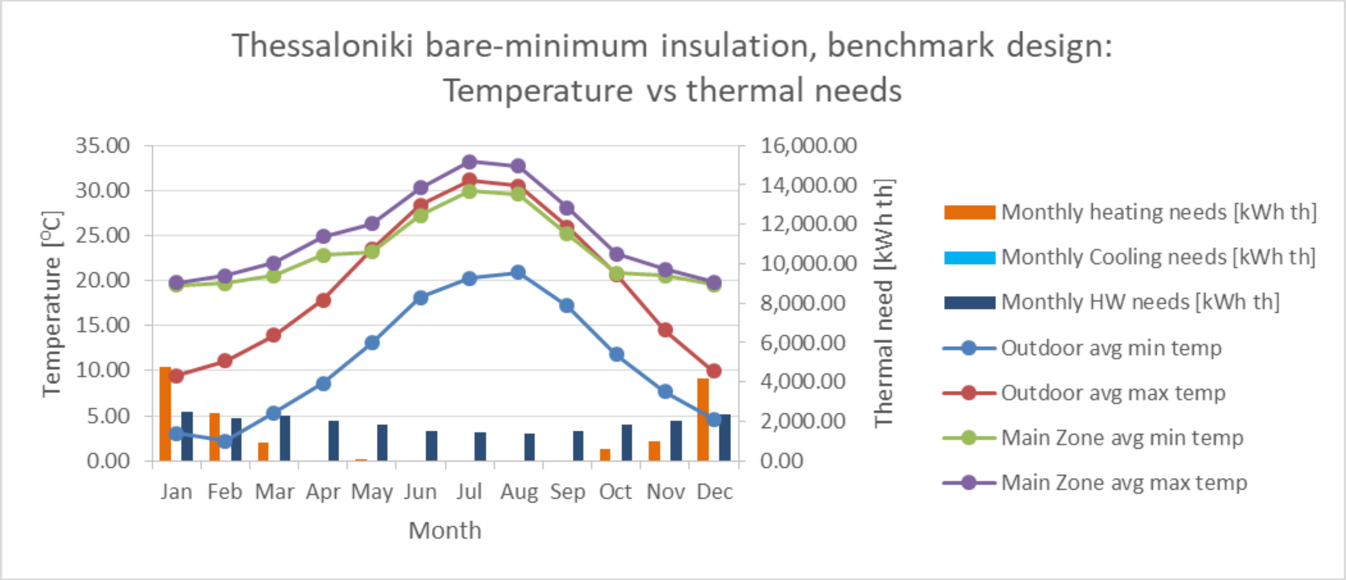


Chart 16: Thessaloniki bare-minimum insulation, benchmark design: Temperature vs thermal needs

Thessaloniki as in a normally colder region than the previous two cities has a smaller issue of overheating in the summer months. Here the indoor-uncomfortable season (above 24 ^{o}C) is only from mid-May to end of August and indoor peak temperatures in July average at around 33 ^{o}C.

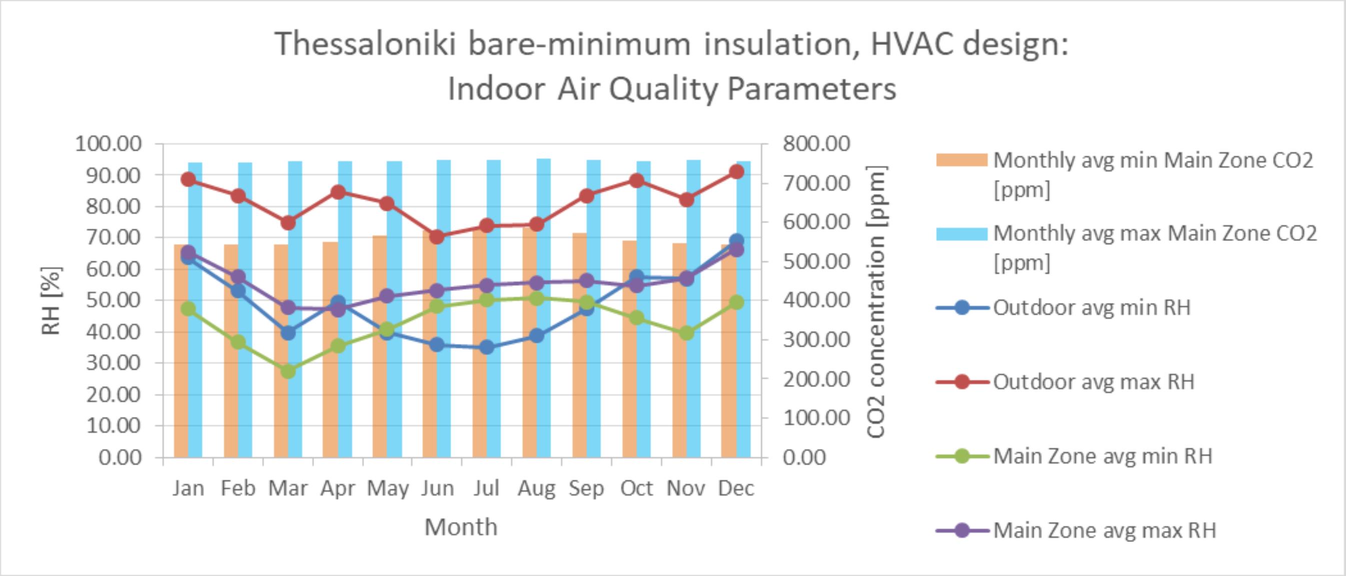


Chart 17: Thessaloniki bare-minimum insulation, HVAC design: Indoor Air Quality Parameters

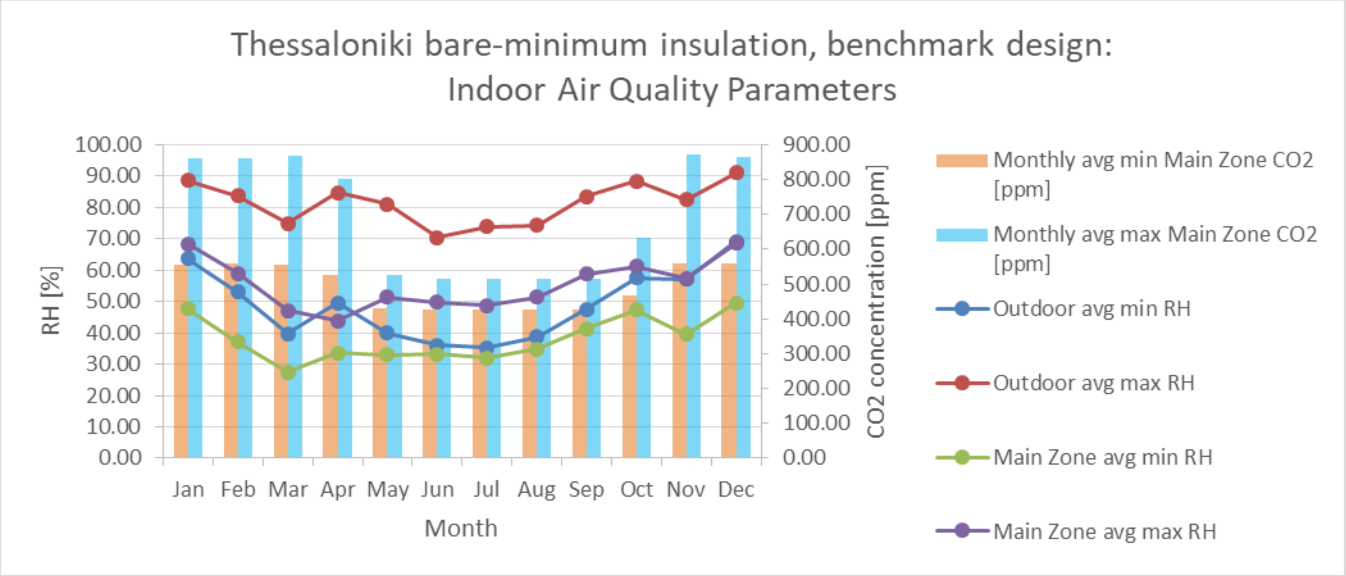


Chart 18: Thessaloniki bare-minimum insulation, benchmark design: Indoor Air Quality Parameters

While indoor-CO2 levels tend to follow the same pattern as in previous cases (with a slight increase in the duration of higher-CO2-concentrations season, given the colder climate and the prolonged “clamp-down” on natural ventilation) humidity here is more out-of-limits mostly because of the natural humidity levels/fluctuations of the area. Still, of course a better control is observed in the case of the HVAC system, both in terms of overall mitigated extreme values and a narrower range in the summer months, which means a more stable and thus comfortable indoor air quality. Nonetheless, it is always a more convenient option to add a humidity-regulating module to the HVAC system than establish “from ground” a similar system in the benchmark case.

Summarising the comparison, the benchmark case comes at a higher annual energy expenditure of 2,208 €, an extra energy-cost NPV of -22,627 €. As assumed previously from the results of Larnaca and Athens an efficient integrated-HVAC system is an even more competitive option here. Perhaps not even in this case it will make a financially-sensible option but the environmental benefits would be significantly higher and most notably the thermal comfort would be guaranteed. In the benchmark case the unmet comfort hours in the year, as by ASHRAE 55 Standard, are 5,500.50 (62.79% of the time) while for the HVAC case they are 2,894.00 (33.04% of the time). Once more the still high amount of unmet hours is expected to be due to the humidity which can be far more easily and cheaply regulated in the HVAC than the benchmark case.

3.6. Covering the energy needs of the building

By this point a rather explicit description is needed on the exact equipment arrangement that will be utilised in each case in order to deliver the heating, cooling and hot water needs. As discovered and concluded from the simulation results, previously on Chapter 3, two different arrangements will be assessed eventually: the original "integrated-HVAC" design and additionally the "benchmark" design that will allow for proving (or rejecting) the fact that a more efficient H/C system might be more a more expensive investment and more complex to utilise, but in the long-run far more sustainable (financially, environmentally and eventually socially).

3.6.1. The "integrated-HVAC" design

This specific equipment arrangement is the corner-stone of the case-study NZEB's high energy efficiency profile, and as the simulation results have showed it might be even more important than initially assessed. As explained briefly in the Abstract of this document it is a design that allows for an integrated coordination of PV electricity generation, provision of heating and cooling and hot water production. The exact arrangement has two key advantages: A) the use of PV electricity for the H/C-Hot Water needs and B) the simultaneous production of hot water and cooling loads in the summer.

To delve deeper in this concept the initial argument is that thermal storage is much cheaper than electricity storage. The possibility of producing and storing thermal energy manages to "un-peg" the operation of a heat pump from the time the H/C-HW needs occur. Additionally a heat-pump is the most efficient way of producing thermal loads from an energy source of great low-carbon potential: electricity. For that reason an on-site PV array will provide some, essentially, zero-carbon electricity. The sole weakness of a PV system is the lack of control over the generation times but due to the use of thermal storage this is not an issue here as the heat pump can operate when the PV array generates and the H/C-HW will be utilised later when necessary. Therefore, eventually the PV array will be able to provide the most (always within a cost-optimal frame) of heat-pump's energy consumption, and also from a zero-carbon source. Additionally, the PV array will be able to provide part of the house's electronic equipment daily consumption (while the sun shines and the PVs generate, electricity will be extracted from there for the electronic equipment and the rest of PV production will be used for the heat-pump).

An energy-use "efficiency-bonus" occurs in the summer when cooling needs exist, for conditioning the indoor air, but also heating, for the domestic hot water use. As heat-pump is a piece of equipment for the "forced" transfer of heat, this means that the heat extracted from the indoor space can be added to the domestic hot water reservoir. In the current building energy-equipment designs, these are usually two distinct operations, each one consuming its own share of energy to run. By merging them together is achieved, theoretically, the elimination of one of these two loads as the energy needed for the one of them is now the waste-energy derived from the other.

Overall, to have a visual representation, the equipment arrangement will look as in the figure below:

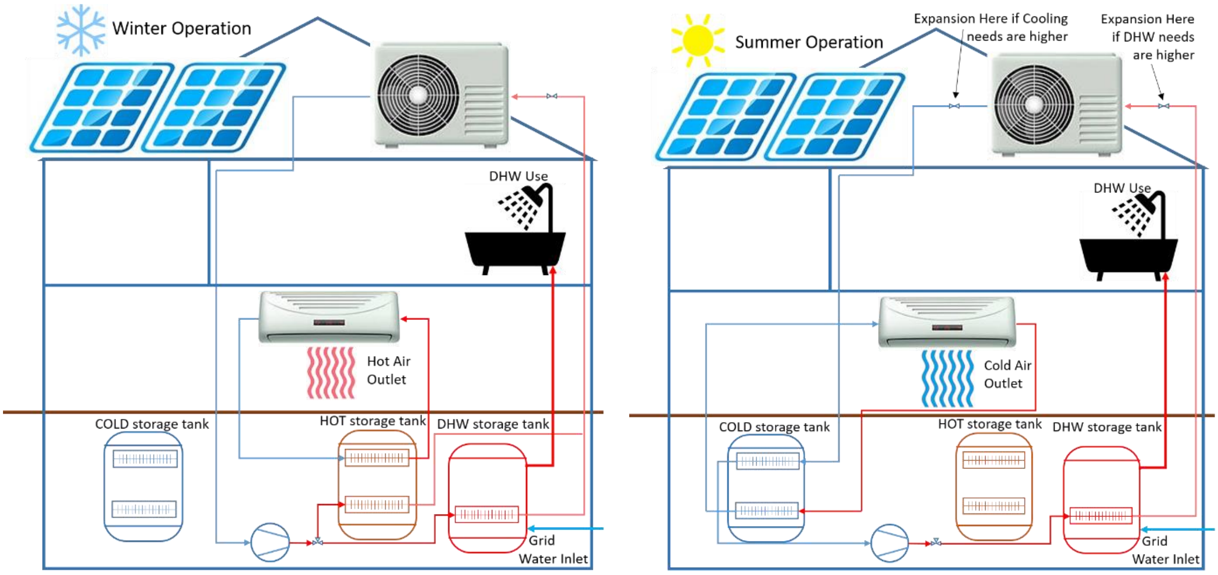


Figure 4: The Integrated-HVAC system design, operating in Winter and Summer

3.6.2. The "Benchmark" design

The composition of energy-equipment of the benchmark design is the one that someone would expect to find normally at the average Greek household. To begin from the heating system, most Greek residential buildings have a fuel-oil (diesel) boiler at some part of the basement and a natural-flow water pipe-system that connects the boilers to radiators in the living spaces. For the Hot Water production as the Greek regulation mandates, some form of solar-thermal system is necessary with a complementary source of water heating. For that reason most residences use a "double-energy" thermosiphon, meaning a DHW storage tank with a natural-flow water circulation with the solar collector and an electric resistance inside the storage tank that aids to reaching the desired temperature. For cooling in the summer many houses have off-the-shelf A/C units installed but given the relatively high purchase cost and the high electricity consumption, many people prefer to just "mitigate" the hot feeling with floor fans. Although the increased air circulation from the fans reliefs slightly the hot sensation it eventually provides a less-uncomfortable rather than an actually comfortable indoor environment.

4. Cost-benefit analysis of the NZEB case-study

As described from an early point in this work, the main goal is to eventually make the NZEB concept an attractive one versus the business-as-usual / cheapest-option-at-present-cost. The work so far aimed to test some parameters and eventually conclude to an extensive NPV comparison between numerous multi-parameter scenarios. Yet, even the preliminary energy results have indicated that parameters initially considered extremely critical—such as the thickness of insulation—eventually do not affect the ongoing energy savings to an extent that would justify the insulation's extra investment cost, something eventually credited to the efficacy of the H/C-HW provision equipment-set synthesis. Ergo, in the end, the minimum levels of insulation have been applied for each location and the cost-comparison will be set among the integrated-HVAC vs Benchmark equipment systems and among the three locations / climatic regions. A total of 6 scenarios to be compared in sets of 2 and 3.

4.1. Investment cost

4.1.1. Building cost

As explained previously in Chapter 3.4 the total cost of the building is broken into the walls & insulation cost and the rest of the building. The price for the rest building structure has been calculated (based on average wall costs) to 1,065 €/m^2 of floor area. Therefore the total wall costs will be derived here and thus eventually the building cost for each location's bare-minimum insulation composition

The wall total costs are evaluated as below in Table 33:

Design M1 for Larnaca		Design M2 for Athens		Design M3 for Thess	
Hollow brick		Hollow brick		Hollow brick	
Hollow 90mm price (€/unit)	0.25	Hollow 90mm price (€/unit)	0.25	Hollow 90mm price (€/unit)	0.25
units per m2 of ext (double) wall	56.00	units per m2 of ext (double) wall	56.00	units per m2 of ext (double) wall	56.00
Hollow br. Ext wall price (€/m2)	14.00	Hollow br. Ext wall price (€/m2)	14.00	Hollow br. Ext wall price (€/m2)	14.00
units per m2 of int wall	28.00	units per m2 of int wall	28.00	units per m2 of int wall	28.00
Hollow br. Int wall price (€/m2)	7.00	Hollow br. Int wall price (€/m2)	7.00	Hollow br. Int wall price (€/m2)	7.00
building labour (€/m2)	5.00	building labour (€/m2)	5.00	building labour (€/m2)	5.00
mortar price (€/m2)	2.50	mortar price (€/m2)	2.50	mortar price (€/m2)	2.50
Plaster (M&L) (€/m2)	10.00	Plaster (M&L) (€/m2)	10.00	Plaster (M&L) (€/m2)	10.00
Ext walls final (€/m2)	41.50	Ext walls final (€/m2)	41.50	Ext walls final (€/m2)	41.50
Ext walls final (€)	24,426.90	Ext walls final (€)	24,426.90	Ext walls final (€)	24,426.90
Int walls final (€/m2)	34.50	Int walls final (€/m2)	34.50	Int walls final (€/m2)	34.50
Int walls final (€)	41,354.46	Int walls final (€)	41,354.46	Int walls final (€)	41,354.46
Final walls cost (€)	65,781.36	Final walls cost (€)	65,781.36	Final walls cost (€)	65,781.36
including VAT 24%	81,568.89	including VAT 24%	81,568.89	including VAT 24%	81,568.89
plus insulation		plus insulation		plus insulation	
Roof 60mm Durosol (€/m2) Rf=2.07	6.90	Roof 80mm Durosol (€/m2) Rf=2.67	9.20	Roof 80mm Durosol (€/m2) Rf=2.67	9.20
Roof Insulation cost (€)	1,968.29	Roof Insulation cost (€)	2,624.39	Roof Insulation cost (€)	2,624.39
Ext Wall 40mm Durosol (€/m2) Rf=1.86	4.60	Wall 50mm Durosol (€/m2) Rf=2.17	5.75	Wall 60mm Durosol (€/m2) Rf=2.47	6.90
Ext wall Insulation cost (€)	2,707.56	Ext wall Insulation cost (€)	3,384.45	Ext wall Insulation cost (€)	4,061.34
Part Wall 20mm Durosol (€/m2) Rf=0.93	2.30	Part Wall 30mm Durosol (€/m2) Rf=1.23	3.45	Part Wall 40mm Durosol (€/m2) Rf=1.53	4.60
Partition Wall Insulation cost (€)	175.81	Partition Wall Insulation cost (€)	263.72	Partition Wall Insulation cost (€)	351.62
Ground 20mm Durosol (€/m2) Rf=0.79	2.30	Ground 30mm Durosol (€/m2) Rf=1.09	3.45	Ground 90mm Durosol (€/m2) Rf=2.91	10.35
Ground Insulation cost (€)	656.10	Ground Insulation cost (€)	984.15	Ground Insulation cost (€)	2,952.44
Final Insulation cost (€)	5,507.76	Final Insulation cost (€)	7,256.71	Final Insulation cost (€)	9,989.80
including VAT 24%	6,829.63	including VAT 24%	8,998.32	including VAT 24%	12,387.35
Final wall + insulations cost (€)	71,874.98	Final wall + insulations cost (€)	73,536.02	Final wall + insulations cost (€)	76,181.20
Including VAT 24%	89,124.98	Including VAT 24%	91,184.66	Including VAT 24%	94,464.69

Table 33: Wall costs for the bare-minimum insulation cases

Note: for the calculation of the costs above the following building-element areas were taken into consideration, as extracted from the building's blueprint: Exterior walls, 588.60 m^2; Interior walls (no insulation), 1,122.24 m^2; Partition walls (with insulation), 76.44 m^2; Floor/roof slab, 285.26 m^2.

Therefore this allows the final building costs for each location to be calculated as following in Table 34:

	Larnaca	Athens	Thessaloniki
Rest-of-building (€)	740,888.55	740,888.55	740,888.55
Wall costs (€)	89,124.98	91,184.66	94,464.69
Total cost (€)	830,013.53	832,073.21	835,353.24

Table 34: Final bare-minimum insulation buildings costs

CAPEX for the NZEB and comparison with a standard one

4.1.2. Equipment cost

Although the equipment arrangement is the same, the different H/C-HW needs of the buildings call and for a different size of equipment which affects the final cost proportionately. The equipment-list is as described in Table 36 below:

System element	**Details**
Heat Pump (including ext. unit)	According to the necessary peak HP output
COLD storage tank	For the storage of produced cooling loads
COLD High-Power finned coil	For charging the storage, according to peak HP cold-output
Low-Power finned coil	For transferring “cold” to the HVAC system
HOT storage tank	For the storage of produced heating loads
HOT High-Power finned coil	For charging the storage, according to peak HP hot-output
HOT Low-Power finned coil	For transferring “heat” to the HVAC system
DHW storage tank (with coil)	For the storage of produced domestic hot water
HVAC intake blower	For introducing the fresh air to the building
HVAC exhaust blower	For extracting the indoor air
HVAC finned coil	For adding heat/cold to the intake air
HVAC recuperator	For recovering heat from extracted to intake air
Ducts	For the distribution of conditioned air throughout the building

Table 35: Equipment list for the HVAC scenarios

Average costs have been identified for each major piece of equipment that will be participating in the final system, based on an online market survey. The prices are concluded as following in Table 36:

Equipment	Price	Notes-Sources
Photovoltaic Panels	113.71 €/m^2	Nominal output 165.96 W/m^2, [63]
Inverter	150 €/kW	Average 2016 inverter price (NREL), [84]
Heat Pump	500 € / TR	1 TR (ton of refrigeration) = 12,000 BTU = consumption of 1 kWh$_e$ (on a COP=3.5) **Invalid source specified.**, **Invalid source specified.**, **Invalid source specified.**, **Invalid source specified.**
Heat-exchanging finned coil	240 € / TR	**Invalid source specified.**, **Invalid source specified.**,
Water tank (thermal storage)	85.12·V + 58.40 €/m^3	V in m^3 (for the range 0.5 – 5 m^3), [85], **Invalid source specified.**
Thermal storage insulation	90 €/m^2 (tank surface)	Sprayed PU coating around the tank for a final R=7 m^2·K/W, **Invalid source specified.**

Pressurised water tank with Heat-exchange coil (DHW storage)	601.15·V + 149.6 €/m^3	V in m^3 (for the range 0.3 – 3 m^3), [86]
Air Blower	327 €	[87]
HVAC Recuperator	2,486.65 €	[88]
Ventilation Ducts	95 €/m	Minimum price (Mat.&Lab.), [89]

Table 36: Prices for HVAC system elements

Finally, for each location/case the system is sized according to the needs (as explained earlier in Chapter 3.3. Methodology) and the final size/cost of the system is derived, as presented below in Table 37:

	Larnaca		Athens		Thessaloniki	
Equipment	Size	Cost (€)	Size	Cost (€)	Size	Cost (€)
PV panels (m2)	78.09	8,879.61	78.09	8,879.61	78.09	8,879.61
PV inverter (kW)	11.09	1,663.80	9.75	1,462.55	9.42	1,413.27
Heat Pump (including ext. unit) (kW)	4.50	2,250.00	7.00	3,500.00	7.50	3,750.00
COLD storage tank (m3)	6.65	2,396.67	6.31	2,313.34	5.64	2,144.39
COLD High-Power finned coil (kWeq)	0.41	27.88	0.62	42.03	0.62	42.02
COLD Low-Power finned coil (kWeq)	0.18	12.32	0.19	12.96	0.19	12.98
HOT storage tank (m3)	0.60	491.92	1.47	840.08	1.82	958.56
HOT High-Power finned coil (kWeq)	0.11	7.35	0.33	22.25	0.37	24.92
HOT Low-Power finned coil (kWeq)	0.08	5.55	0.10	6.64	0.13	8.84
DHW storage tank (with coil) (m3)	1.60	1,111.44	1.60	1,111.44	1.60	1,111.44
HVAC in+out blowers	-	654.00	-	654.00	-	654.00
HVAC finned coil (kW)	4.51	307.90	4.75	324.04	4.76	324.55
HVAC recuperator	-	2,486.65	-	2,486.65	-	2,486.65
Ducts (m)	200.00	19,000.00	200.00	19,000.00	200.00	19,000.00
Total system sum		39,295.10		40,655.60		40,811.24

Table 37: Equipment CAPEX for each HVAC location-case

For the benchmark case now, the equipment requirements are entirely different, as see in Table 38 below:

Diesel furnace-boiler	Compact units for the production of heating water
Diesel storage tank	For storing the furnace's fuel
DHW storage tank	For the production of hot water to be consumed (e.g. showers)
Radiators	For the delivery of heat in the indoor spaces
Distribution pipes	For the connection of boiler with the radiators
Solar thermal collectors	For the production of majority of DHW

Table 38: Equipment list for the benchmark scenarios

According to the market survey the costs are occurring as below in Table 39:

Equipment	Price	Notes-Sources
Diesel furnace-boiler	5.69·Q + 604.1 €	Q in Mcal/h (for the range 20-50), [90]
Diesel storage tank	85.12·V + 58.40 €/m^3	V in m^3 (for the range 0.5 – 5 m^3), [85]
Pressurised water tank with Heat-exchange coil (DHW storage)	601.15·V + 149.6 €/m^3	V in m^3 (for the range 0.3 – 3 m^3), [86]

Radiators	55.8 €/kW	From modules of 175W each, [91]
Distribution pipes	25 €/m^2 of floor area	Based on a 200 m^2 household (mat.&lab.), [92]
Solar thermal collectors	64.22 €/m^2	Based on 2x1m module [93]

Table 39: Prices for benchmark system elements

The final equipment-costs per benchmark case are presented briefly in the following Table 40:

	Larnaca		Athens		Thessaloniki	
Equipment	Size	Cost (€)	Size	Cost (€)	Size	Cost (€)
Diesel Furnace-boiler (Mcal/h)	10.00	661.00	30.00	774.80	60.00	945.50
Diesel Storage tank	0.09	66.40	0.52	102.40	1.56	191.56
DHW storage tank (m3)	0.53	470.21	0.53	470.21	0.53	470.21
Radiators (total kW)	8.54	476.58	17.77	991.36	44.39	2,477.15
Heat distribution pipes (floor m2)	695.67	17,391.75	695.67	17,391.75	695.67	17,391.75
Solar thermal collectors (m2)	10.00	642.20	12.00	770.64	12.00	770.64
Total system sum (€)		19,708.14		20,501.16		22,246.81

Table 40: Equipment CAPEX for each benchmark location-case

At this point the final cost values for each case of construction and equipment systems are derived and thus the final building costs can be calculated

4.1.3. Total Investment cost per case

Upon the cost values derived previously the final building costs are concluded as following in Table 41:

	Larnaca	Athens	Thessaloniki
Building cost	830,013.53	832,073.21	835,353.24
Equipment cost	39,295.10	40,655.60	40,811.24
HVAC-case total	**869,308.63**	**872,728.81**	**876,164.48**
Building cost	830,013.53	832,073.21	835,353.24
Equipment cost	19,708.14	20,501.16	22,246.81
Benchmark-case total	**849,721.67**	**852,574.37**	**857,600.05**

Table 41: Final sum-investment cost for each insulation-level, equipment-type case

As observed the difference among the HVAC cases is ~3,500 € for both low-to-mid and mid-to-high while among the benchmark cases is ~2,900 € and ~5,000 € correspondingly. The larger differences for the equipment among benchmark cases is because hourly thermal loads increase severely and total radiator area needs to increase accordingly, eventually driving the costs up. For the HVAC cases though there exists a larger amount of parameters that some increase while others decrease with the increased insulation levels / heating needs and thus a more stable overall cost is formed, versus the benchmark case that all parameters increase with heating needs.

Comparing now between HVAC and benchmark for each location case the difference in cost is much more significant, at ~19,000 € overall. This value makes it clear why people prefer to install conventional systems, keeping in mind that they are usually not aware of the long-term savings: the investment cost is much smaller. To be more accurate here the integrated-HVAC system includes a rather expensive PV installation. This addition to the system has been designed to be as cost-neutral (on and NPV base) as possible. What this practically means is that a shift has been achieved from the ongoing energy costs to the initial investment costs. Therefore one could expect an integrated-HVAC system to cost less by ~10,000 € (PVs and inverter cost) with a similar investment pay-back period (on the same final rent + energy price). Yet still, this option was made here as the profitability of the investment (NPV) doesn't essentially change but a large reduction of CO_2 emissions is avoided and that is considered a crucial benefit.

Summing up the investment difference among all 6 scenarios varies to its greatest extent by ~26,400 €. This cost when split up among the number of residents and expected payback period is reduced to a not-so-much significant added cost (~30 extra per month per tenant). Therefore the co-assessment of ongoing energy costs is still expected to have a significant impact on the final outcome.

4.2. Fixed costs

Based on the prices for grid-electricity and diesel-oil previously described (0.06 €/kWh and 0.95 €/L correspondingly) and the energy needs of each location-equipment case, the following annual energy costs are derived, as illustrated in Table 42 below:

	Larnaca		Athens		Thessaloniki	
	HVAC	Benchmark	HVAC	Benchmark	HVAC	Benchmark
Grid-Elec (kWh/a)	29,832.76	39,938.04	31,530.42	41,444.33	32,313.77	42,713.00
Fuel (L/a)	-	94.01	-	517.29	-	1,565.55
Total Cost (€/a)	**1,789.97**	**2,491.42**	**1,891.83**	**3,010.16**	**1,938.83**	**4,147.12**

Table 42: Annual energy costs for the 6 cases

Here the impact of different climate regions and equipment-systems becomes more profound. Comparing initially the HVAC cases among them the difference is ~100 and ~50 €/a more from Larnaca to Athens and Athens to Thessaloniki. Once more this brings to spotlight the high efficiency of the HVAC system which consumes rather low regardless of the climatic needs. The same though cannot be said for the benchmark system which's consumption increases sharply by ~500 and ~1,100 €/a correspondingly! When this is put into perspective (over the 30-year "lifetime" of the investment) it yields a whooping ~34,000 €, illustrating how prone is the consumption of such systems to the weather conditions and thus the importance of investing in energy-saving interventions.

Eventually, the most interesting part of the comparison is the one among HVAC and benchmark cases for each location. And the results here are the ones expected. The HVAC systems hold always a cost advantage over the benchmark ones, an advantage that increases as the climate get "colder". In specific the HVAC systems manage to save per year: 701.46 € in Larnaca, 1,118.34 € in Athens and 2,208.29 € in Thessaloniki. The "lifetime" savings for each case are accordingly 21,043.67 €; 33,550.08 € and finally a striking 66,248.79 €! To put that directly in perspective the extra cost of an HVAC over a benchmark system is compared to the "lifetime" extra energy costs in the following Table 43:

	Larnaca	Athens	Thessaloniki
HVAC cost (€)	39,295.10	40,655.60	40,811.24
Benchmark cost (€)	19,708.14	20,501.16	22,246.81
CAPEX Difference (€)	**19,586.95**	**20,154.44**	**18,564.43**
HVAC cost (€/a)	1,789.97	1,891.83	1,938.83
Benchmark cost (€/a)	2,491.42	3,010.16	4,147.12
OPEX 30-year diff. (€)	**-21,043.67**	**-33,550.08**	**-66,248.79**
Lifetime cost diff. (€)	**-1,456.71**	**-13,395.64**	**-47,684.37**

Table 43: Lifetime cost-benefits of HVAC over Benchmark cases

The results are definitive: when comparing the "lifetime" costs of HVAC over benchmark systems, the HVACs have a lower cost (hence the "minus" sign) that increases—potentially—exponentially as the climate gets colder. Therefore if the HVAC system "out-performs" the benchmark one in the warmest zone of Larnaca city and its competitiveness only improves as the location is shifted further north, this essentially means that—at least in the European area—the HVAC system solution is always, regardless of location, the cost-optimal. At this point it should be reminded the additional actual value of the HVAC system as it is able to provide indoor comfort not only in the winter but also in the summer, that the benchmark system did not have the capability to do so. Eventually the HVAC system proved to be better the conventional ones in terms of lower costs and higher indoor comfort while lastly it remains to assess and compare the environmental impact of the two systems for each location.

4.3. Environmental benefits

The assessment of a source's emissions is a very important and, admittedly, very complicated work. Generation of electricity and fuel burning are both intensely emitting procedures, it terms of quantity and variety of pollutants as well. Due to lack of further resources in the current work, unfortunately, focus will be spent solely in the CO_2 emissions related to the energy consumption of the designated building. Furthermore the assessment of emission footprint can cover a very narrow or wide time span, from a mere mass-equilibrium for the fuel to a complete cradle-to-grave analysis of all material, machinery and auxiliary processes related to it. Once more due to lack of resources the focus will be only upon the use-phase of the building relating to the consumption of fuels for the coverage of energy needs.

The two fuels used in the scenarios established previously are electricity and diesel. For the production of electricity in Greece the average emission intensity is, as mentioned earlier, 497 $grCO_2eq/kWh_e$ [9]. For that it should be taken additionally into consideration that the Greek grid has about 2.9% losses of transmission and distribution (2016 values) [94] which will have to be taken into consideration for the final calculations. For the diesel fuel, assuming a complete combustion, the emissions intensity is 2.64 kg CO_2/L [95]. It must be noted that these are actual CO_2 values and not CO_2-equivalent which include other pollutants as well, thus the final sum will be eventually a conservative value. These values allow for the calculation of total CO_2 emissions from the residence for each case. In an effort to bring attention to the value of the on-site PV system on reducing emissions, a dummy-case will be co-assessed here: the coverage of HVAC scenarios' electricity needs strictly from grid-bought electricity.

Upon all previous information the annual CO_2-equivalent emissions of the cases are presented in the Table 44 below:

		Larnaca	Athens	Thessaloniki
HVAC	PV-elec (kWhe/a)	14,301.69	12,865.43	12,747.71
	Grid-elec (kWhe/a)	29,832.76	31,530.42	32,313.77
	Fuel (L/a)	-	-	-
	Emissions (t CO2eq/a)	**15.27**	**16.14**	**16.54**
HVAC (no PV)	PV-elec (kWhe/a)	-	-	-
	Grid-elec (kWhe/a)	44,134.45	44,395.86	45,061.47
	Fuel (L/a)	-	-	-
	Emissions (t CO2eq/a)	**22.59**	**22.72**	**23.06**
Benchmark	PV-elec (kWhe/a)	-	-	-
	Grid-elec (kWhe/a)	39,938.04	41,444.33	42,713.00
	Fuel (L/a)	94.01	517.29	1,565.55
	Emissions (t CO2eq/a)	**20.69**	**22.58**	**26.00**
HVAC: (PV) - (no PV)				
	Emissions (t CO2eq/a)	-7.32	-6.59	-6.52
(HVAC) - (Benchmark)				
	Emissions (t CO2eq/a)	-5.42	-6.44	-9.46

Table 44: CO2eq emissions comparison among all the scenarios

Once more the results are in, approximate, accordance with expectations. First of all, from the comparison of HVAC system with on-site PV generation versus completely grid-bought electricity, becomes evident the achieved reduction in CO_2: on average 7 tons per year, a reduction around 30%. The comparison between an HVAC no-PV and Benchmark case, proves that the HVAC no-PV case emissions can be higher (for cases such as Larnaca and Athens). This is not so relevant to the emission per kWh of each fuel (higher for electricity) and efficiency of the conversion equipment (lower for the diesel furnace) but to the fact that Larnaca and Athens have greater cooling needs than Thessaloniki that are satisfied in the HVAC scenarios and thus consume more energy that increases the total emissions. Yet for the actual case of HVAC with PVs versus benchmark designs as can be seen from the table, even more significant CO_2 reduction results are achieved reaching up to 9.46 tCO_2eq/a less, while also providing more comfort, and also at a lower cost. To illustrate clearly the so-far proven superiority of the HVAC designs, the following chapter consists of an all-inclusive cost-benefit summary of the financial, emissions and comfort values obtained yet.

4.4. Costs and benefits comparison

After extensive research on various aspects of the insulation level, equipment arrangement and location of the residence building, all necessary values are obtained for the final comparison of the scenarios among them and to conclude on the final most investment-attractive one. Considering upon financial, environmental and comfort parameters the scenarios compare as below in Table 45:

		Larnaca	Athens	Thessaloniki
HVAC	CAPEX (€)	869,308.63	872,728.81	876,164.48
	OPEX (€/a)	1,789.97	1,891.83	1,938.83
	NPV (€)	-887,649.89	-892,113.80	-896,031.08
	Emissions (tCO2eq/a)	15.27	16.14	16.54
	ASHRAE-55 not met (h)	721.75	1,984.75	2,894.00
Benchmark	CAPEX (€)	849,721.67	852,574.37	857,600.05
	OPEX (€/a)	2,491.42	3,010.16	4,147.12
	NPV (€)	-875,250.55	-883,418.63	-900,094.40
	Emissions (tCO2eq/a)	20.69	22.58	26.00
	ASHRAE-55 not met (h)	4,226.50	4,809.75	5,500.50

Table 45: Final financial, environmental and comfort results for the 6 scenarios

For the final comparison and definition of the most investment-attractive the CAPEX-OPEX-NPV, total emissions and un-met hours of indoor comfort (according to ASHRAE standard 55) are taken into consideration. For the easier processing of the figures above, two more Tables have been prepared, one for comparison among the locations (for each equipment arrangement) and one for comparison among the equipment systems (for each of the cities) as seen in Tables 46 and 47 below:

		(Athens) - (Larnaca)	(Thessaloniki) - (Athens)
HVAC	CAPEX (€)	3,420.18	3,435.67
	OPEX (€/a)	101.86	47.00
	NPV (€)	-4,463.91	-3,917.28
	Emissions (tCO2eq/a)	0.87	0.40
	ASHRAE-55 not met (h)	1,263.00	909.25
Benchmark	CAPEX (€)	2,852.69	5,025.69
	OPEX (€/a)	518.74	1,136.96
	NPV (€)	-8,168.08	-16,675.77
	Emissions (tCO2eq/a)	1.89	3.42
	ASHRAE-55 not met (h)	583.25	690.75

Table 46: Comparison among locations for each technology used

As can be clearly observed above, progressing from Larnaca to Athens to Thessaloniki (i.e. towards colder climates) CAPEX, OPEX, emissions and un-met hours of comfort (i.e. difficulty to satisfy the thermal needs) increase, while—normally—the NPV value decreases. This is a reasonable expectation since the colder the climate, the more demanding the energy needs of the building, eventually requiring stronger equipment and more energy input to satisfy them. All this make the investment and ongoing costs rise, which is unattractive for a venture. Therefore, when not taking into consideration the local real estate market, the location of Larnaca would seem more attractive for the investment, but only marginally since e.g. compared to Athens it yields an NPV higher by ~4,500 € when the total cost of the investment is ~870,000 € (i.e. 0.5% profit over the total cost). This essentially means that as an investment in Athens it will only take a couple years more to pay back than in Larnaca.

(HVAC) - (Benchmark)	Larnaca	Athens	Thessaloniki
CAPEX (€)	19,586.95	20,154.44	18,564.43
OPEX (€/a)	-701.46	-1,118.34	-2,208.29
NPV (€)	-12,399.34	-8,695.17	4,063.32
Emissions (tCO2eq/a)	-5.42	-6.44	-9.46
ASHRAE-55 not met (h)	-3,504.75	-2,825.00	-2,606.50

Table 47: Comparison among technologies for each location chosen

Now when comparing among HVAC and benchmark technologies the image is slightly different. Although the investment costs are higher and the ongoing costs are less for all HVAC cases when considered together in the NPV it proves that only Thessaloniki is clearly a more attractive choice the HVAC system, since only in this case all values are better than the benchmark case. But still this is over a minimal margin compared to the size of the investment. Eventually, when taking into consideration the environmental and comfort benefit over the relatively-to-CAPEX negligible NPV reduction the HVAC systems provide by far the best value-for-money option, while the colder the climate the higher the benefits they yield over the benchmark alternative.

4.5. Market competitiveness

4.5.1. Rent and energy monthly cost of the residence

As concluded (surprisingly) previously, the Net Present Value of the 6 cases do not differ significantly and thus it cannot be clearly said that eventually one seems more attractive than the other. Indeed, in the end, it is only the rent + energy costs of the residence compared to the rest of proximate alternative housing options that will indicate the true market competitiveness of the investment. According to reaching a net-zero 30-year NPV the rent + energy monthly cost is derived as according to Table 48 below:

Monthly Rent+Energy	Larnaca	Athens	Thessaloniki
HVAC	248.93	250.18	251.28
Benchmark	245.45	247.74	252.42

Table 48: Required monthly (per tenant) income cashflow

The final results are just disarming. On the 6 cases the monthly fee for the tenants is on average 249.33 € with a standard deviation among them of 2.52 €. What this practically means is that more or less the initial capital spent dominates the required monthly cash-flow for payback of the investment while the ongoing costs do not influence the outcome as much. With the main construction of the building being the largest part of the initial capital expenditure (1,065 €/m^2 * 695.69 m^2 = 740,888.55 € before walls and equipment, 84-87% of total) the required rents are more or less the same, as it proves, for the payback to occur. An additional reason the rents rise so high while also the future ongoing costs do not affect the required monthly cashflows is the assumed very high interest rate. In a few words, higher interest rates mean that cashflows in the future have lower impact on the present time (for they are discounted to the present proportionately to the interest rate). Overall, higher interest rates make everything else in the economy more expensive. To assess thus the non time-influenced value of the residence's payback, the monthly cashflow per tenant has been recalculated upon a 0% interest rate and results are presented in Table 49 below:

Monthly Rent+Energy	Larnaca	Athens	Thessaloniki
HVAC	88.41	89.03	89.50
Benchmark	88.55	90.31	94.06

Table 49: Required monthly (per tenant) income cashflow for 0% interest rate

Results are shockingly different. Monthly fees are still very similar to each other but represent better the impact of ongoing energy costs, as all HVAC cases are cheaper than the benchmark ones. The average rent price is 89.98 € with a standard deviation of 2.12 €. The average monthly fee now is a striking 160 € less than the previous one which makes the room a far more competitive real-estate opportunity versus the previous one.

This comparison illustrates the importance of interest rate in such a long-term investment as the residence assessed here. The 10% interest rate is an average historic value that illustrates the competitiveness of an investment versus the "average" investment one could make. Hence, the financial verdict is rather straightforward: among all investments possible on the world at the moment ("average investment") constructing such a residence building in Greece now is far from the preferable option, since—for the current domestic real estate market—an energy-inclusive rent price of ~250 €/month for a 15 m^2 room with a 10-people shared kitchen is not an attractive proposal.

Thus, from a decision-making perspective, one would not invest in such a venture if he/she would be interested only in profit. Having said that, the scope of the investment must change in order to keep assessing the possibility of investing. That would essentially mean that someone wishes for other than strictly financial reasons to create such a building (e.g. social conscience). Now, from the point of view of someone who wishes to specifically create a residence-building for students, other ("average") investments are not any more eligible options and this affects the interest rate of the NPV accordingly.

Since the investment is narrowed down to be the residence-building and only that, a different method of calculating the minimum monthly tenant fee will be utilized and upon that the competitiveness of the result will be compared to the local real estate markets. Now, monthly installments will be calculated for a 30-year investment loan, equivalent to the residence's initial capital investment, with a fixed interest rate at 5.01% [22]. Then on this monthly basis of necessary cashflow will be added the normalized monthly energy costs and the sum divided to the population of tenants to yield the monthly tenant fee. For the values declared above and the individual CAPEXs the monthly values for each scenario are derived as below in Table 50:

	Larnaca		Athens		Thessaloniki	
	HVAC	Benchmark	HVAC	Benchmark	HVAC	Benchmark
Install. (€/m)	4,671.95	4,566.68	4,690.33	4,582.02	4,708.80	4,609.03
OPEX (€/m)	149.16	207.62	157.65	250.85	161.57	345.59
Tenant fee (€/m)	**166.25**	**164.63**	**167.17**	**166.65**	**167.94**	**170.85**

Table 50: Required monthly (per tenant) income cashflow for a standard investment loan

The results now provide a more realistic and also more appealing image. The average rent + energy cost comes at 167.25 ± 2.08 €. From personal real estate market experience this price for the value offered seems to be a much more competitive proposal than the previous ones.

4.5.2. Rent and Energy monthly cost of current real estate market

At this point the rent and energy costs of other competitive housing options have to be assessed and taken into consideration for the conclusion of the proposed residence's market attractiveness and thus financial viability as an investment.

Beginning with the energy prices, initially the current energy consumption of similar dwellings has to be researched and costs be derived from there. From a 2014 Greek statistical report of the Ministry of Environment, Energy and Climate Change it is derived that each Greek household on average consumes 13,994 kWh/a for its energy needs, of which 73.2% is thermal energy and 26.8% is electrical [96]. Furthermore, the actual energy consumption per climate zone, per type of building is mentioned. For a more accurate comparison the values of apartment buildings will be considered only as these have the most relevance to the type of building designed here, as presented in Table 51 below:

		Zone A		Zone B		Zone C	
		Thermal	Elec	Thermal	Elec	Thermal	Elec
Actual	Energy total (kWh/m2/a)	195.99		218.95		286.53	
	Energy (kWh/m2/a)	143.46	52.53	160.27	58.68	209.74	76.79
	Cost total (€/m2/a)	**17.50**		**19.55**		**25.58**	
KENAK reference	Energy total (kWh/m2/a)	89.40		96.12		127.17	
	Energy (kWh/m2/a)	65.44	23.96	70.36	25.76	93.09	34.08
	Cost total (€/m2/a)	**7.98**		**8.58**		**11.35**	
HVAC	Energy total (kWh/m2/a)	42.88		45.32		46.45	
	Energy (kWh/m2/a)	-	42.88	-	45.32	-	46.45
	Cost total (€/m2/a)	**2.57**		**2.72**		**2.79**	
Benchmark	Energy total (kWh/m2/a)	58.78		67.10		84.17	
	Energy (kWh/m2/a)	1.37	57.41	7.53	59.57	22.77	61.40
	Cost total (€/m2/a)	**3.58**		**4.33**		**5.96**	

Table 51: Thermal- Electricity consumption and annual cost of buildings based on current stock, National guideline and the proposed HVAC-benchmark scenarios

Using the proposed share of thermal-to-electricity consumption and the energy prices used previously the final annual per m^2 costs are derived. As it becomes evident the 6 scenarios proposed here have indeed an annual advantage over the actual energy-expenditures of current apartment tenants. To derive a more tangible value, for a reference apartment size of ~24 m^2 (the total size of the residence divided by the number of tenants) the costs above are formed as below in Table 52:

	Zone A	Zone B	Zone C
Actual (€/m)	35.00	39.10	51.16
KENAK ref. (€/m)	15.96	17.16	22.71
HVAC (€/m)	5.15	5.44	5.57
Benchmark (€/m)	7.16	8.65	11.92
(HVAC) - (Actual)	-29.85	-33.66	-45.59

Table 52: Monthly energy costs per equivalent apartments of ~24m^2

The results are finally encouraging! As it is proved, the energy-cost benefit of the proposed residence building-energy_equipment versus a current, equivalent-size apartment begins at ~30 €/month less and reaches up to ~45 €/month. This gives a significant cost-advantage to the residence that can influence greatly the final price difference (including the rent) and make the residence’s room a very market-competitive option.

For the estimation of rents now, once more actual market prices will be used for each location. To remind briefly, the original city for climatic zone A was Chania in Crete, but due to lack of weather data for the simulation, Larnaca was chosen instead. Now, the rent prices will be derived indeed from Chania, Athens and Thessaloniki. The online add/real-estate platform of “spitogatos.gr” will be used since it contains a large volume of places available for rent. In specific, neighbours close to the city centre and major universities will be considered. From these areas the cheapest adds available will be selected (assuming this would be the rationale of a student) and the rent prices will be derived in form of €/m^2. Then, the rent will be derived again for a reference 24m^2 apartment and finally the actual monthly rents will be compared to the ones of the residence. The results derived, as described above, are presented in the following Table 53:

	Chania	Athens	Thessaloniki
Average rent (€/m2/m)	7.30	5.67	6.56
24 m2 apt.-eq (€/m)	175.20	136.00	157.50

Table 53: Rent values for the locations of interest

Results are eventually very encouraging as the residence_room-equivalent current-market apartment (mostly "studio" type) rent prices are considerably high when compared to the ones derived for the integrated-HVAC residences of each corresponding location. The final verdict though will be made when rent and energy costs are summed for both cases, for each location

4.5.3. Rent and Energy monthly cost comparison among residence and market

Putting together all the financial values derived so far, the final comparison is performed in the following Table 54:

		Zone A	Zone B	Zone C
Market	Energy costs (€/m)	35.00	39.10	51.16
	Rent (€/m)	175.20	136.00	157.50
	Monthly R+E fee (€/m)	**210.20**	**175.10**	**208.66**
HVAC	Energy costs (€/m)	5.15	5.44	5.57
	Rent (€/m)	161.10	161.73	162.37
	Monthly R+E fee (€/m)	**166.25**	**167.17**	**167.94**
(HVAC) - (Market)				
	Monthly R+E fee (€/m)	**-43.95**	**-7.92**	**-40.72**

Table 54: Final comparison of rent + energy monthly costs among the Residence and average Market options

The final results are definitive. As observed the local market rent prices affect greatly the competitiveness of a new building. For Athens (Zone B) the rent—solely itself—is clearly not competitive and for Thessaloniki (Zone C) still, but marginally. Eventually it is, as originally assumed, the lower energy costs that can make it competitive, as observed after the "rent + energy" costs comparison. For Chania (Zone A) in specific, it is the already existing higher rent that drives the final price difference to 43.95 €/m less for the HVAC-Residence while in Thessaloniki, the great ongoing energy costs are the ones that eventually turn around the final result to a lower cost for the HVAC-residence by 40.72 €/m. In Athens, the very lower market rent is offset by the large energy savings, but eventually leaving only a small competitive margin for the HVAC-residence.

Nonetheless, even if from a student it is expected that the low price will be the core decision criterion, it should not be left un-considered that everyone is willing to pay a premium for better living conditions (it just varies on the amount of that premium according to the overall financial "capacity" of each tenant). For the currently proposed residence, initially, it proves that eventually in all cases it is financially more attractive than the market options. Then, considering the literature findings about tenants with unsatisfied heating and cooling needs (and as well from own experience), the proposed residence is superior to the market choices in terms of achieved indoor thermal comfort and air quality. Lastly, given the rising concern of citizens in regards to CO_2 emissions and Climate Change, the Residence has a provenly reduced carbon footprint which makes it appealing even from the environmental perspective. Overall, the proposed NZEB here manages to achieve a 3-out-of-3 better performance than the competition, in cost, comfort and eco-friendliness. This eventually makes it a rather compelling investment proposal, encouraging the implementation and proliferation of the concept and consequently achieving the energy consumption (and thus emissions) reduction that are necessary in order to tackle climate change (along with energy poverty, resources abuse and more).

As concluded, the NZEB residence is a market-competitive option in multiple aspects and thus it proves that reducing the emissions from buildings (and improving indoor comfort) is in alignment with lower costs. Zooming down—finally—on the emissions issue, what is left now is to see to which extent the proposed NZEB concept has to be implemented in order to achieve the desired emission-reduction results in the national building sector. Yet, as extensively mentioned in various Official sources, adopting the NZEB concept for new buildings only is not enough. Renovation of existing building stock is a key action in the effort to catch the building emissions goals. For that reason a rough assessment will be performed, priorly, on the cost-benefit of NZEB-Renovating of existing buildings.

4.6. Cost-benefit analysis for renovations

For the creation of the NZEB student-residence the core technical part was implementing an insulation up to the minimum standards and then a very efficient PV-HP-DHW-TS system. Essentially, the insulation of the envelope is a layer applied on top of the exterior walls and the equipment-arrangement is installed regardless of the construction phase. What this practically means is that the exact composition of elements used for the New NZEB can also be applied on already existing buildings as renovation, without significant alterations.

Once more, even for renovations, the cost-optimality is the key-goal according to the EU guidelines. Therefore, primarily, the investment of adding insulation and replacing the energy-provision system will be compared to the achieved long-term energy savings in order to identify the competitiveness of such an intervention. Given that the exact cost of adding insulation and sizing the equipment depends largely on the architectural design and element composition of the building a more “approximate” approach has to be taken here: based on floor area. Narrowing down the buildings-to-intervene to apartment complexes it can be assumed that a similar ratio of exterior walls (affecting the insulation area) and thermal performance (affecting equipment size and energy consumption) versus the total floor area exists between apartment-blocks and the Residence designed here. Therefore with values presented on a per-floor-area manner there can be expected convenient yet rather accurate results.

Using the current Residence design as reference, insulation has to be added in accordance with KENAK to a minimum extent. Same min. U-values apply for the renovated buildings as for the new ones. Therefore, assuming that already existing buildings are constructed with simple red-clay hollow-brick double-leaf exterior walls, then the insulation thickness for each climate zone is the same as for the residence building. The difference in cost thus lies on the fact that no wall needs to be built but extra labor is required for the application of the insulation. These costs along with the final sum (per zone) are presented and summarized in Table 55 below:

Renovation R1 for Larnaca		Renovation R2 for Athens		Renovation R3 for Thess	
Insulation application (M&L) (€/m2)	12.00	Insulation application (M&L) (€/m2)	12.00	Insulation application (M&L) (€/m2)	12.00
Facade plaster (M&L) (€/m2)	10.00	Plaster (M&L) (€/m2)	10.00	Plaster (M&L) (€/m2)	10.00
Ins. app. and plaster cost (€)	27,182.32	Ins. app. and plaster cost (€)	27,182.32	Ins. app. and plaster cost (€)	27,182.32
Roof 60mm Durosol (€/m2) Rf=2.07	6.90	Roof 80mm Durosol (€/m2) Rf=2.67	9.20	Roof 80mm Durosol (€/m2) Rf=2.67	9.20
Roof Insulation cost (€)	1,968.29	Roof Insulation cost (€)	2,624.39	Roof Insulation cost (€)	2,624.39
Ext Wall 40mm Durosol (€/m2) Rf=1.86	4.60	Wall 50mm Durosol (€/m2) Rf=2.17	5.75	Wall 60mm Durosol (€/m2) Rf=2.47	6.90
Ext wall Insulation cost (€)	2,707.56	Ext wall Insulation cost (€)	3,384.45	Ext wall Insulation cost (€)	4,061.34
Part Wall 20mm Durosol (€/m2) Rf=0.93	2.30	Part Wall 30mm Durosol (€/m2) Rf=1.23	3.45	Part Wall 40mm Durosol (€/m2) Rf=1.53	4.60
Partition Wall Insulation cost (€)	175.81	Partition Wall Insulation cost (€)	263.72	Partition Wall Insulation cost (€)	351.62
Ground 20mm Durosol (€/m2) Rf=0.79	2.30	Ground 30mm Durosol (€/m2) Rf=1.09	3.45	Ground 90mm Durosol (€/m2) Rf=2.91	10.35
Ground Insulation cost (€)	656.10	Ground Insulation cost (€)	984.15	Ground Insulation cost (€)	2,952.44
Final Insulation cost (€)	5,507.76	Final Insulation cost (€)	7,256.71	Final Insulation cost (€)	9,989.80
including VAT 24%	6,829.63	including VAT 24%	8,998.32	including VAT 24%	12,387.35
Envelope renovation final cost (€)	34,011.95	Envelope renovation final cost (€)	36,180.64	Envelope renovation final cost (€)	39,569.67

Table 55: Envelope renovation costs per location

The costs of renovation are, naturally, much lower than raising new walls, yet not proportionally lower as renovating has a significant "retrofitting" cost, in this case the work required for adding the insulation, at about 12 €/m^2 [76]. Then considering also the equipment costs previously calculated for each location-case (as these will be identical) the final Renovation cost can be concluded as below in Table 56:

	Larnaca	Athens	Thessaloniki
Envelope renovation cost (€)	34,011.95	36,180.64	39,569.67
Integrated-HVAC system cost (€)	39,295.10	40,655.60	40,811.24
Total Energy-Renovation cost (€)	73,307.05	76,836.23	80,380.91
E-Renovation cost (€/m2 of floor area)	**105.38**	**110.45**	**115.54**

Table 56: Energy-Renovation cost per floor area estimation of apartment-buildings for each climate zone (representative city)

Since the insulation levels before and after the renovation are the same as the ones assessed previously then the pre- and post-renovation energy-consumption values will be the same too. According to these the investment performs as in the Table 57 below:

	Larnaca	Athens	Thessaloniki
E-Renovation cost (€/m2 of floor area)	105.38	110.45	115.54
Reduction of energy costs (€/m2/a)	14.92	16.83	22.79
Payback time (a)	**7.06**	**6.56**	**5.07**
5.01% fixed-rate loan payoff (<a)	**9.00**	**9.00**	**6.00**

Table 57: financial performance of Energy-Renovation investment per location

Results are encouraging and in accordance with other results in literature as well. In general the payback period of an "energy efficiency upgrade" on a building ranges from 5 to 10 years, as calculations indicate here too. Assessing the more realistic scenario where a loan is taken in order to undertake the renovation the payoff time increases slightly due to the interest rate applied but eventually still within the 5-10 year range.

To conclude on a clear note, the call for renovations as well is the "cost-optimality" i.e. the intervention that achieves the highest impact for the least cost. Here the financial performance of only one intervention has been assessed (adding insulation and installing an integrated-HVAC system) but this is done so in the confidence that this is the cost-optimal choice indeed, based on the results that have occurred so far in the current research.

5. Scalability and impact projection

Through all the work so far it has been proven that using an HVAC system to cover the thermal comfort needs of a residence in combination with its Hot Water needs while being powered by a PV array and using thermal storage as a flexibility mechanism (here previously called "PV-HP-DHW-TS" system) allows for reduced—in the long-run—expenses, better comfort and less CO_2 emissions. While cost and comfort are important parameters, the lower CO_2 emissions are a significant goal for the building sector. The European Union has stated clearly on its aim for a 20% reduction (versus 1990 levels) of GHG emissions by year 2020 but this goal has not been found to be clearly separated in sub-goals per sector. Therefore there exists not clear reference point for comparison of the NZEB implementation efficacy of the current design. To set a benchmark the 2020 goal of reduced emissions will be proportionally set upon the current emission portions. For Greece thus, in 1990 total emissions were 105.6 $MtCO_2eq$ which makes the 2020 goal at 84.48 $MtCO_2eq$. At 2015 total emissions were 98.6 $MtCO_2eq$ which leaves a need of further 14.12 $MtCO_2eq$ less by 2020, a reduction of 14.32%. For the Greek household sector the 2015 emissions were at 14.65 $MtCO_2eq$. For an equal 14.32% reduction this means that a net reduction of ~2.1 $MtCO_2eq$ is necessary from renovations. Considering that new buildings will emerge (emitting naturally additional CO_2 regardless of how low) the renovations will have to increase in order to counter-act these new sources. Overall, based on the reference CO_2eq reduction values established here, the effect of new and renovated NZEBs (according to the student-residence findings) proliferation will be analysed in this chapter.

5.1. Scale-up impact for new NZEBs

While new buildings will no-way achieve a reduction in GHG emissions, the economy and society keep on growing (thankfully) and so reducing the environmental impact of that growth is essential in any case. Thus, the key assessment here will be a "new residential buildings NZEB" versus "new residential buildings business-as-usual" projection until 2020.

From the Hellenic Statistic Authority values can be obtained regarding the building permits issued in Greece. According to the latest data available the average new-built area per year is established as in Table below:

	Aug to Jul (1000m2)				Annual average
Eastern Macedonia & Thrace	186.3	126.9	88.0	118.2	129.9
Central Macedonia	457.8	485.6	405.9	391.8	435.3
Western Macedonia	103.8	330.6	72.2	75.4	145.5
Thessalia	174.7	169.6	169.9	190.4	176.2
Epirus	86.6	76.2	88.1	110.8	90.4
Ionian Islands	84.0	115.9	103.7	184.6	122.1
Western Greece	211.0	190.1	174.1	162.9	184.5
Central Greece	203.7	210.2	150.6	172.1	184.2
Pelloponese	231.9	238.6	216.8	233.6	230.2
Attica	476.0	404.4	386.2	533.4	450.0
North Aegean	50.8	77.2	61.2	45.9	58.8
South Aegean	245.4	197.2	169.2	185.8	199.4
Crete	258.1	232.1	229.7	290.7	252.7
Sum	2,770.1	2,854.6	2,315.6	2,695.6	2,659.0
Zone A	777.4	725.9	667.6	802.4	**743.3**
Zone B	1,070.1	1,016.1	912.1	1,117.4	**1,028.9**
Zone C	922.6	1,112.7	736.0	775.8	**886.8**

Table 58: average annual new-built area for each climate zone [97]

Note: within the regions of Macedonia and Thrace exists also "Climate Zone D" with even harsher cold climate, i.e. stronger heating needs. Yet as it didn't coincide with a European-wide Hardiness Zone it has been merged here with the Climate zone C. Therefore the results obtained for these regions will be considered rather conservative estimations as with the normal values of Zone D also they would have been higher.

There exists a fluctuation among new-built area on a year-to-year basis but for the needs of the current work there will be considered a standard area (the 4 year average) for the following years. The values here represent the total new area built i.e. public and private, domestic and commercial. As stated earlier the projections will focus on apartment buildings only so the fraction of these has to be extracted from the total. According to other literature 72% of the total current Greek building stock area are residences, of which 45% is apartment blocks or semi-detached houses [96].

For calculating the total emissions of the new apartment-buildings, first the emission intensity has to be identified. Based on the energy consumption, type of fuel (and the previously identified carbon-intensities of fuels, $kgCO_2/kWh$) the according values are derived and presented in the following in Table 59:

		Climate Zone A		Climate Zone B		Climate Zone C	
		Fuel	Electricity	Fuel	Electricity	Fuel	Electricity
Energy use	NZEB [HVAC] (kWh/m2/a)	-	42.88	-	45.32	-	46.45
	Market (kWh/m2/a)	143.46	52.53	160.27	58.68	209.74	76.79
Emissions caused	NZEB [HVAC] (kgCO2/m2/a)	-	**21.95**	-	**23.20**	-	**23.78**
	Market (kgCO2/m2/a)	37.43	26.88	41.81	30.03	54.71	39.30
	Market sum (kgCO2/m2/a)	**64.31**		**71.84**		**94.02**	

Table 59: Emission intensity of building type per Climate Zone

For the emission intensities of each type of building per location, the total emissions caused from new apartment-buildings are assessed for various levels of NZEB-design penetration. The results are presented in Table 60 below:

		Zone A		Zone B		Zone C		
	New Apt. Blocks (m2/a)	240,829.20		333,363.60		287,315.10		
		NZEB	B.-as-Usual	NZEB	B.-as-Usual	NZEB	B.-as-Usual	Emissions
	emissions (kgCO2/m2/a)	21.95	64.31	23.20	71.48	23.78	94.02	total sum
Total new apt.-buildings emissions (ktCO2/a)	0% NZEB	15.49		23.83		27.01		66.33
	20% NZEB	13.45		20.61		22.98		57.03
	40% NZEB	11.41		17.39		18.94		47.74
	60% NZEB	9.37		14.17		14.90		38.44
	80% NZEB	7.33		10.95		10.87		29.15
	100% NZEB	5.29		7.73		6.83		19.85

Table 60: Annual additional emissions per year for different levels of NZEB penetration

As observed the final annual emissions difference for the full-NZEB versus none-NZEB scenarios is an additional 46.48 $ktCO_2/a$ avoided. Maintaining the new-emissions level at a 19.85 $ktCO_2/a$ allows for a much more manageable curve of GHG emissions for the building sector, making the reduction to 80%-of-1990 levels easier to achieve through the renovations. The extent, though, of renovations that is necessary in order to achieve this will be assessed in the next sub-chapter.

5.2. Scale-up impact for renovated NZEBs

As mentioned previously, if the general goal of reaching by 2020 an 80% of the 1990 levels of GHG emissions is broken down proportionally per region, sector etc. then the building sector of Greece much achieve a net reduction of ~2.1 $MtCO_2eq$. Breaking this down further by 72% to households and 45% further to apartment-buildings, this specific type of buildings must achieve a 680.4 $ktCO_2eq$

reduction by 2020. The argument thus rises upon what is the current renovation rate in Greece, what it should be in order to achieve that reduction and how much would that cost (?).

It occurs that currently residences in Greece undergo renovations at a rate of 25,000 residences per year. For an average residence size of ~75m^2 this means a rate of 1,870,000 m^2/a floor area renovated [96]. Assuming a distribution of renovations in the same proportion of new buildings among climate zones, this equals roughly to 53.95 kgCO$_2$/a less per m^2 of floor area renovated. Thus, for the current renovation rate this means 101.16 ktCO$_2$/a less per year. That is a very encouraging figure as it is in the same order of magnitude as the total reduction goal identified previously. Combining the additional emissions of new buildings (for 100% NZEBs) and the reduced emissions of renovations at the current average rates a net reduction of 81.31 ktCO$_2$/a is expected. This means that the emissions reduction benchmark value will be achieved not within 2 years (by 2020 indeed) but within 9 years (8.37 to be precise) i.e. within 2025.

Admittedly, given the current situation in Greece (level of emissions, market-readiness, resident awareness, finance etc.) it is indeed a highly improbable scenario to achieve any 2020 emissions goals in time. Hence, it is a rather pleasant realisation that if just the current new building and renovation rates are maintained and only the nature of the interventions changes—into utilising the highly efficient integrated-HVAC system assessed here—the goals can be achieved with only 5 years of delay.

Since the timeline of reducing emissions is realistically-speaking acceptable, the last thing to assess is the financial "intensity" of the renovation interventions. As derived earlier the average cost of such an energy-renovation for a building comes at ~105-115 €/m^2 (depending on location). The average 75m^2 household equal to 8,250 € expenditure. Such a cost is a manageable/bankable investment. Yet this value comes from system designed for a 695.67 m^2 building, thus economies of scale apply. What this practically means is that—to have such a low price—not a sole apartment but the entire building has to be renovated at once. And this brings to surface various coordination-among-tenants and split-incentives (between tenants and owners) issues that prevent such extensive renovations.

Discussion and Epilogue

A long journey—in turbulent and dark waters indeed eventually—comes to a conclusion. At the beginning of this thesis a goal was set: to identify which parameters are crucial in order to make an NZEB cost-competitive on the current market. The cornerstone of "80% of a households energy needs are for heating and cooling" backed up by the fact that thermal storage is the cheapest form of energy storage has led to the inception of a highly efficient thermal system (using a heat pump at its core) that can cover the majority of a household's energy needs (heating/cooling and hot water, the "80%") from a clean energy source (of on-site PVs) that thanks to the thermal storage the maximum of energy for heating/cooling would be derived from the PVs when solar energy is abundant.

Taking into consideration the importance of climatic regions and insulation levels at the energy consumption of a household, these were the parameters that was decided to be put to the test eventually. Different levels of insulation were used in each climate region in order to see the cost-benefit relationship between "climatic harshness", insulation and energy savings. The first remarkable results emerged here as it proved that insulation did not have so much impact on the final energy savings. Comparing this to the literature—praising the significance of insulation for energy savings—the attention has been shifted to the equipment arrangement. In an effort to identify if the extremely efficient HVAC-HW system devised made such difference, the nature of the work has changed: for the regulations-imposed minimum of insulation for each location, what is the energy-, emissions- and cost-savings (as well final comfort achieved) of the "integrated-HVAC" system versus a conventional one. The results proved that a conventional system—even if a cheaper investment—comes with a 40 – 114% higher annual energy costs than the integrated-HVAC one. Such a finding is critical for it proves that the efficiency of the thermal system is more impactful than the efficiency of the building's envelope in reducing energy consumption.

As the superiority of the proposed HVAC system is concluded then the cost-competitiveness is assessed for new and renovated buildings. For a new building (in the form of a student-residence), its market competitiveness depends both on the local rents as well the energy demands of the local climate. Rent-wise a new building would not be competitive in 2 out of 3 locations. But when the energy costs are co-calculated then in all cases the new building with an integrated-HVAC system achieves a lower monthly price. This fact shows that lower energy costs can actually make the market-difference and support the proliferation of new NZEBs. For the renovations, the interventions require a significant, yet manageable, investment in the beginning but all achieve a payback time within 9 years (even earlier in colder climates). Even if financially this is sensible, for the average home-owner this payback period is considered a high risk with a lot of uncertainty and so such renovations rarely occur. Thus what is proved is the need for formulation of appropriate bodies and legal entities that understand those risks and have the financial means of covering the initial expenses. This way, e.g. ESCOs can undertake such profitable activities safely while at the same time providing a significant benefit to home-residents and the environment.

Overall the end results are encouraging: colder climates being naturally more profitable for renovations and the insulation level is eventually less crucial than the efficiency of the building's thermal equipment. Yet it has to be recognised that these results were extracted under a large amount of approximations and assumptions, in the end even the proposed equipment arrangement is not a commercially tested end-product. Thus the most valuable findings of this work are the remarks during the process of it, rather than the end findings. The most crucial of them being:

- For the work here an average COP of 3.5 is assumed for the heat pump. Yet practically a heat pump's efficiency depends highly on the temperature gradient it is called to cover. Thus the first step in refining the findings is to improve the simulation model with a more realistic heat pump COP based on the weather conditions as well.
- From the calculations it proves that a lot of energy is required for the production of Domestic Hot Water. With hot water being a large part of the total water consumption and mains-water coming at a temperature higher than the outdoor in the winter months the conclusion is derived that a significant amount of heat (and also at a favourable temperature exists) on the waste-water stream. Thus waste-water could be used as a heat source in the winter in order to improve efficiency and reduce overall consumption of the heat pump.
- The initial rationale behind the PV & heat pump proposal (instead of a mere solar thermal system) was that a heat pump has a COP that when combined with the efficiency of a PV it achieves a thermal output comparable to a solar-thermal collector system, but the PV-HP arrangement can also provide cooling. Yet as it occurred a very small area (and thus investment cost) of solar-thermal collectors can yield easily the 80% of annual Hot Water needs. Thus it seems to be more sensible financially to install along solar-thermal collectors and downsize the PV-HP equipment. The directly produced thermal energy can cover part of the DHW needs and also work as a heat source for the heat pump, improving its COP. Overall the idea of Photovoltaic-Thermal Hybrid panels rises as an attractive alternative worthy of further assessment.
- Regarding the ventilation rates, for a significant part of the year outdoor temperatures are favourable for the natural cooling of the building to comfortable levels. Therefore a model

that can adapt to reduce ventilation to the minimum acceptable level when heat is needed to be retained in the winter, increase it when it provides energy-free cooling and reduce it again outdoor is hotter than the maximum comfortable temperature (as to reduce cooling loads) would allow for estimating the best possible energy savings. Yet such thing is more complicated to simulate and, unfortunately, impossible to do with the currently limited resources.

In the bottom-line of the extensive work performed here the prominent conclusion is one: there already exist energy-efficient solutions that—apart for environmentally beneficial—are technically reliable and financially sensible investments, yet they are not meeting the market up-take one would rationally expect. Combining findings from literature, personal perception of the market and general intuition regarding human-nature, the lack of adopting such solutions comes down to three main reasons A) the lack of understanding, on the home-occupants side, of the overall and personal benefits of such an intervention; B) the lack of saved personal funds (or maturity of financial/bank products) for undertaking such a renovation and C) the lack of willingness (human reluctance in general) to try out and familiarise with novice technologies.

What, thus, the entire situation boils down to is a market ready (from every rational sense) to implement new products but held back by mostly emotional/psychological reasons. This feels to resemble a physics-system with a natural tendency but high activation-energy. What is necessary thus to unlock this chain reaction of multiple benefits is some “catalyst” points. Someone with understanding of the issue’s technical nuances, able to minimise the risks, yield field-results and “standardise” the “product” (e.g. bodies / companies / pioneer-groups) has to undertake the first market trials and start proving the multiple benefits of the solution. These controlled, positive outcomes will thus work as “nucleation sites” for the larger proliferation of such solutions. Once these begin to compound, then the actual mitigation of Climate Change can be considered begun.

As brilliantly stated elsewhere *today’s problems persist not due to lack of skill, but lack of will.* The time for action is now. Thank you and good luck.

References

[1] “European Comission,” 2017. [Online]. Available: http://ec.europa.eu/energy/en/topics/energy-efficiency/buildings.

[2] “European Environment Agency,” 2017. [Online]. Available: https://www.eea.europa.eu/data-and-maps/indicators/final-energy-consumption-by-sector-9/assessment-1.

[3] “European Comission,” 2017. [Online]. Available: https://ec.europa.eu/energy/en/topics/energy-efficiency/heating-and-cooling.

[4] “Eurostat,” 2017. [Online]. Available: http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_production,_consumption_and_market_overview.

[5] “European Environmental Agency,” 2017. [Online]. Available: https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-1/assessment.

[6] “U.S. Energy Information Administration,” 2017. [Online]. Available: https://www.eia.gov/environment/emissions/co2_vol_mass.cfm.

[7] “Eurostat,” 2017. [Online]. Available: http://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emissions_by_industries_and_households.

[8] “Eurostat,” 2017. [Online]. Available: http://ec.europa.eu/eurostat/web/products-datasets/-/tsdpc320.

[9] “Electricity Map,” 2017. [Online]. Available: https://www.electricitymap.org/?wind=false&solar=false&page=map.

[10] BPIE, “Nearly Zero Energy Buildings definitions across Europe,” BPIE, 2015.

[11] “European Comission,” 2017. [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2020_en.

[12] EuropeanCommission, “Clean Energy for All Europeans,” Brussels, 2016.

[13] EuropeanCommission, “An EU Strategy on Heating and Cooling,” Brussels, 2016.

[14] EuropeanCommission, “Commision Staff working document on "An EU strategy for Heating and Cooling" part 1/2,” Brussels, 2016.

[15] EuropeanParliament, “Directive 2012/27/EU on Energy Efficiency,” 2012.

[16] EuropeanParliament, “Directive 2010/31/EU on the Energy Performance of Buildings,” 2010.

[17] “Smart Building S.A.,” 2017. [Online]. Available: https://smartbuilding.gr/%CF%85%CF%80%CE%BF%CE%BB%CE%BF%CE%B3%CE%B9%CF%83%CF%84%CE%AE%CF%82-%CE%BA%CF%8C%CF%83%CF%84%CE%BF%CF%85%CF%82.

[18] "Loupasis Inc.," 2017. [Online]. Available: http://www.loupassis.gr/ti-building-el.jsp.

[19] "Dikaiologitika," 2017. [Online]. Available: http://www.dikaiologitika.gr/eidhseis/oikonomia/91389/oi-pinakes-me-tis-antikeimenikes-aksies-ton-akiniton-ana-perioxi-kai-zoni-se-oli-tin-ellada.

[20] "European Central Bank," 2017. [Online]. Available: https://www.ecb.europa.eu/stats/policy_and_exchange_rates/key_ecb_interest_rates/html/index.en.html.

[21] "Statistical Data Warehouse ECN," 2017. [Online]. Available: http://sdw.ecb.europa.eu/reports.do?node=1000002883.

[22] "Bank Of Greece," 2017. [Online]. Available: http://www.bankofgreece.gr/Pages/el/Bank/News/PressReleases/DispItem.aspx?Item_ID=5634&List_ID=1af869f3-57fb-4de6-b9ae-bdfd83c66c95&Filter_by=DT.

[23] "Eurostat," 2017. [Online]. Available: http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics.

[24] "xe.gr," 2017. [Online]. Available: http://www.xe.gr/energy/allazorevma.html.

[25] "Aerio Attikis," 2017. [Online]. Available: https://www.aerioattikis.gr/el/timi-eksikonomisi-timi-se-sxesi-me-alla-kafsima.

[26] "CNN greece," 2017. [Online]. Available: http://www.cnn.gr/news/ellada/story/18756/poy-kymainontai-oi-times-gia-to-petrelaio-thermansis-ana-geografiki-perioxi.

[27] Waste2Go, "D 2.2 Waste Profiling," (Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V., 2014.

[28] "Eurostat," 2017. [Online]. Available: http://ec.europa.eu/eurostat/statistics-explained/index.php/Municipal_waste_statistics.

[29] EEA, "Managing municipal solid waste — a review of achievements in 32 European countries," European Environment Agency, 2013.

[30] E. Tilley, L. Ulrich, C. Lüthi, P. Reymond and C. Zurbrügg, "Compendium of Sanitation Systems and Technologies (2nd ed.)," Swiss Federal Institute of Aquatic Science and Technology (Eawag), Duebendorf, Switzerland.

[31] United Nations Population Division, "Charting the Progress of Populations," United Nations.

[32] K. S. Blake, R. L. Kellerson and A. Simic, "Measuring Overcrowding in Housing," U.S. Department of Housing and Urban Development, Office of Policy Development and Research , Bethesda, Maryland, 2007.

[33] LEED, "Leadership in Energy and Environmental Design," 2017. [Online]. Available: https://www.usgbc.org/node/2614120?return=/credits/healthcare/v4.

[34] “Windows for high-performance commercial buildings,” 2017. [Online]. Available: http://www.commercialwindows.org/codesstandards_ashrae90_1_more.php.

[35] ASHRAE, “ASHRAE Technical FAQ, ID 92”.

[36] M. Holladay, “Green Building Advisor,” 2013. [Online]. Available: http://www.greenbuildingadvisor.com/blogs/dept/musings/how-much-fresh-air-does-your-home-need.

[37] “HVAC Design Pros,” 2017. [Online]. Available: https://homeenergypartners.com/2012/05/ashrae-62-2-construction-calculate-required-amount-ventilation/.

[38] “Contracting business,” 2006. [Online]. Available: http://www.contractingbusiness.com/archive/how-much-fresh-air-enough.

[39] “Engineering Toolbox,” 2017. [Online]. Available: http://www.engineeringtoolbox.com/air-change-rate-room-d_867.html.

[40] C. Tzanakis, Interviewee, *Professional inshights into design and thermal performance of buildings.* [Interview]. 2016.

[41] “Wikipedia - Hardiness Zone,” 2017. [Online]. Available: https://en.wikipedia.org/wiki/Hardiness_zone.

[42] Eurima, “U-Values for better energy performance of buildings,” 2007.

[43] “EEA,” 2017. [Online]. Available: https://www.eea.europa.eu/data-and-maps/indicators/heating-degree-days.

[44] “Weather Underground,” 2017. [Online]. Available: https://www.wunderground.com/about/faq/degreedays.asp?MR=1.

[45] “DegreeDays,” 2017. [Online]. Available: http://www.degreedays.net/#.

[46] “BRICKWORKS D.I. KOKKINOGENIS S.A.,” 2017. [Online]. Available: http://www.kokkinogenis.gr/en/.

[47] Z. L. &. Z. R. Milica Arsenovic, “CLay Brick Walls Thermal Properties,” International Journal of Modern Manufacturing Technologies, Belgrade, 2010.

[48] “Engineering Toolbox,” 2017. [Online]. Available: http://www.engineeringtoolbox.com/specific-heat-solids-d_154.html.

[49] “KEBE Northern Greece Ceramics,” 2017. [Online]. Available: http://kebe-sa.gr/e/brochures/.

[50] “YTONG Product list”.

[51] “YTONG product brochure”.

[52] “Frangoulakis supply,” 2017. [Online]. Available: https://www.monotikaylika.gr/durosol-external/.

[53] “Engineering Toolbox,” 2017. [Online]. Available: www.engineeringtoolbox.com/specific-heat-capacity-d_391.html.

[54] “Koufomata Expert,” 2017. [Online]. Available: http://koufomata-expert.blogspot.gr/2011/09/thermal-conductivity.html).

[55] “Mr Money Mustache forum,” 2017. [Online]. Available: https://forum.mrmoneymustache.com/ask-a-mustachian/how-many-loads-of-laundry-per-week/.

[56] C. Pakula and R. Stamminger, “Electricity and water consumption for laundry washing by washing machine worldwide,” ResearchGate, Energy Efficiency, 2010.

[57] “Energy Use Calculator,” 2017. [Online]. Available: http://energyusecalculator.com/electricity_clotheswasher.htm.

[58] “Energy Use Calculator,” 2017. [Online]. Available: http://energyusecalculator.com/electricity_stovetop.htm.

[59] “Techlife Samsung,” 2017. [Online]. Available: http://techlife.samsung.com/right-size-refrigerator-family-four-1038.html.

[60] “Better Homes and Gardens,” 2017. [Online]. Available: http://www.bhg.com/kitchen/appliances/selecting-a-refrigerator/.

[61] “Panelektriki,” 2017. [Online]. Available: http://www.panelektriki.gr/pitsos-pknb56vl30.html.

[62] “Wikipedia,” 2017. [Online]. Available: https://en.wikipedia.org/wiki/Room_temperature.

[63] Amerisolar, “AS-6P30 Polycrystalline Module brochure,” 2017.

[64] Technical Chamber of Greece, “Directive "T.O.T.E.E. 20701-1/2010" for the calculation of energy efficiency in buildings,” Athens, 2010.

[65] O. Gerin, B. Bleys and K. D. Cuyper, “Seasonal variation of hot and cold water consumption in apartment buildings,” CIBW062 Symposium 2014, 2014.

[66] N. Beemkumar, “Energy and Water Consumption Analysis of Washing Process in a Fully Automatic Washing Machine,” ResearchGate, 2015.

[67] “Olimpia Splendid,” 2017. [Online]. Available: http://www.olimpiasplendid.com/seer-scop.

[68] “The Renewable Energy Hub,” 2017. [Online]. Available: https://www.renewableenergyhub.co.uk/heat-pumps-information/heat-pump-efficiency-vs-temperature.html.

[69] “REHVA,” 2017. [Online]. Available: http://www.rehva.eu/publications-and-resources/rehva-journal/2014/022014/requirements-for-seasonal-efficiency-for-air-conditioning-units.html.

[70] Natural Resources Canada, “Heating and Cooling with a Heat Pump,” 2004.

[71] “Zehnder America,” 2017. [Online]. Available: http://zehnderamerica.com/wp-content/uploads/2014/11/CA550-2015.03.25.pdf.

[72] “Physics Classroom,” 2017. [Online]. Available: http://www.physicsclassroom.com/class/thermalP/Lesson-1/Rates-of-Heat-Transfer.

[73] “Physics Forums,” 2017. [Online]. Available: https://www.physicsforums.com/threads/properties-of-air-vs-water.293733/.

[74] “Wikipedia,” 2017. [Online]. Available: https://en.wikipedia.org/wiki/Heat_transfer_coefficient.

[75] “Quora,” 2017. [Online]. Available: https://www.quora.com/Which-one-has-the-stronger-convective-heat-transfer-air-or-water-Why.

[76] T. Kritikos, Interviewee, *Construction material merchant.* [Interview]. 2017.

[77] S. Loulourgas, Interviewee, *Civil engineer.* [Interview]. 2017.

[78] “Frangoulakis supply,” 2017. [Online]. Available: https://www.monotikaylika.gr/durosol-external/.

[79] Hellenic Government, “KENAK,” *Government Gazette,* p. 2367, 2017.

[80] European Economic Comunity, “COUNCIL DIRECTIVE 92 / 42 / EEC on efficiency requirements for new hot-water boilers fired with liquid or gaseous fuels,” 1992.

[81] “Capital.gr,” 2017. [Online]. Available: http://www.capital.gr/oikonomia/3246978/se-poia-timi-tha-agorasoume-fetos-petrelaio-thermansis.

[82] ASHRAE, “Standard 62-2001, Section 6.3.1.,” 2017.

[83] Green Building Council of Australia, “Green Building Council of Australia,” 2017. [Online]. Available: https://www.gbca.org.au/uploads/147/35475/IEQ_Quality%20of%20Indoor%20Air_Template_D1.pdf.

[84] “UnderSolar,” 2017. [Online]. Available: https://understandsolar.com/solar-inverter-costs/.

[85] “Climabox.gr,” 2017. [Online]. Available: https://www.climabox.gr/index.php/el-gr/deksamenes-petrelaiou/%CE%B4%CE%B5%CE%BE%CE%B1%CE%BC%CE%B5%CE%BD%CE%B5%CF%83/%CE%B4%CE%B5%CE%BE%CE%B1%CE%BC%CE%B5%CE%BD%CE%B5%CF%83-%CE%BA%CE%B1%CF%84%CE%B1%CE%BA%CE%BF%CF%81%CF%85%CF%86%CE%B5%CF%83-%CE%BA%CF%85%CE%.

[86] “Climabox.gr,” 2017. [Online]. Available: https://www.climabox.gr/index.php/el-gr/doxeia-adraneias/%CE%B4%CE%BF%CF%87%CE%B5%CE%B9%CE%B1-%CE%B1%CE%B4%CF%81%CE%B1%CE%BD%CE%B5%CE%B9%CE%B1%CF%83-

%CE%BC%CE%B5-1-%CF%83%CE%B5%CF%81%CF%80%CE%B1%CE%BD%CF%84%CE%B9%CE%BD%CE%B1.

[87] Systemair, “Systemair Price List,” 2017.

[88] Zehnder, “Comfosystem Prices,” 2013.

[89] “Fixr,” 2017. [Online]. Available: https://www.fixr.com/costs/ductwork.

[90] “Skroutz.gr,” 2017. [Online]. Available: https://www.skroutz.gr/c/1406/levites/m/6534/Thermostahl/f/427602/petrelaiou.html?keyphrase=%CE%BB%CE%B5%CE%B2%CE%B7%CF%84%CE%B1%CF%82+%CF%80%CE%B5%CF%84%CF%81%CE%B5%CE%BB%CE%B1%CE%B9%CE%BF%CF%85+%CE%BC%CE%B5+%CE%BA%CE%B1%CF%85%CF%83%CF%84%CE%B7%CF%81%CE%.

[91] “Balkan Energy,” 2017. [Online]. Available: https://www.balkanenergy.gr/el/aluminium-radiator-kaldo-h600.html.

[92] “MP Energy,” 2017. [Online]. Available: https://www.mp-energy.gr/%CE%B1%CE%BD%CF%84%CE%BB%CE%B9%CE%B5%CF%83-%CE%B8%CE%B5%CF%81%CE%BC%CE%BF%CF%84%CE%B7%CF%84%CE%B1%CF%83/%CE%B5%CE%BE%CE%BF%CE%B9%CE%BA%CE%BF%CE%BD%CE%BF%CE%BC%CE%B7%CF%83%CE%B7-%CE%B5%CE%BD%CE%B5%CF%81%CE%B3%CE%B5%CE%B9%CE%B1%CF%8.

[93] “MasterSol,” 2017. [Online]. Available: https://www.mastersol.gr/hliakoi-thermosifones-solar/meri-hliakon/hliakoi-syllektes/product/73-s20-iliakos-syllektis-2-0tm.

[94] “EnergyPedia,” 2017. [Online]. Available: https://energypedia.info/wiki/Greece_Energy_Situation.

[95] “Ecoscore,” 2017. [Online]. Available: http://ecoscore.be/en/info/ecoscore/co2.

[96] Hellenic Ministry of Environment, Energy and Climate Change, “Report on long-term strategy for mobilising investment in the renovation of the national stock of residential and commercial buildings, both public and private.,” National Press, Athens, 2014.

[97] “Hellenic Statistic Authority,” 2017. [Online]. Available: http://www.statistics.gr/en/statistics/-/publication/SOP03/-.

[98] “DEI,” 2017. [Online]. Available: https://www.dei.gr/el/oikiakoi-pelates/xrisimes-plirofories-gia-to-logariasmo-sas/logariasmos-kai-xrewseis/ti-einai-to-migma-kausimou-pou-emfanizetai-sto-log.

[99] “Gardenia,” 2017. [Online]. Available: https://www.gardenia.net/guide/european-hardiness-zones.

[100] “Energy Learning,” 2017. [Online]. Available: http://www.energy-learning.com/index.php/archive/96-solar-cooling-with-small-size-chiller-state-of-the-art.

[101] “Dimitris Rizos Building Workshop,” 2017. [Online]. Available: https://rizosdimitris.blogspot.gr/2012/01/4.html.

Appendix A

Architectural blueprint of the proposed NZEB student residence

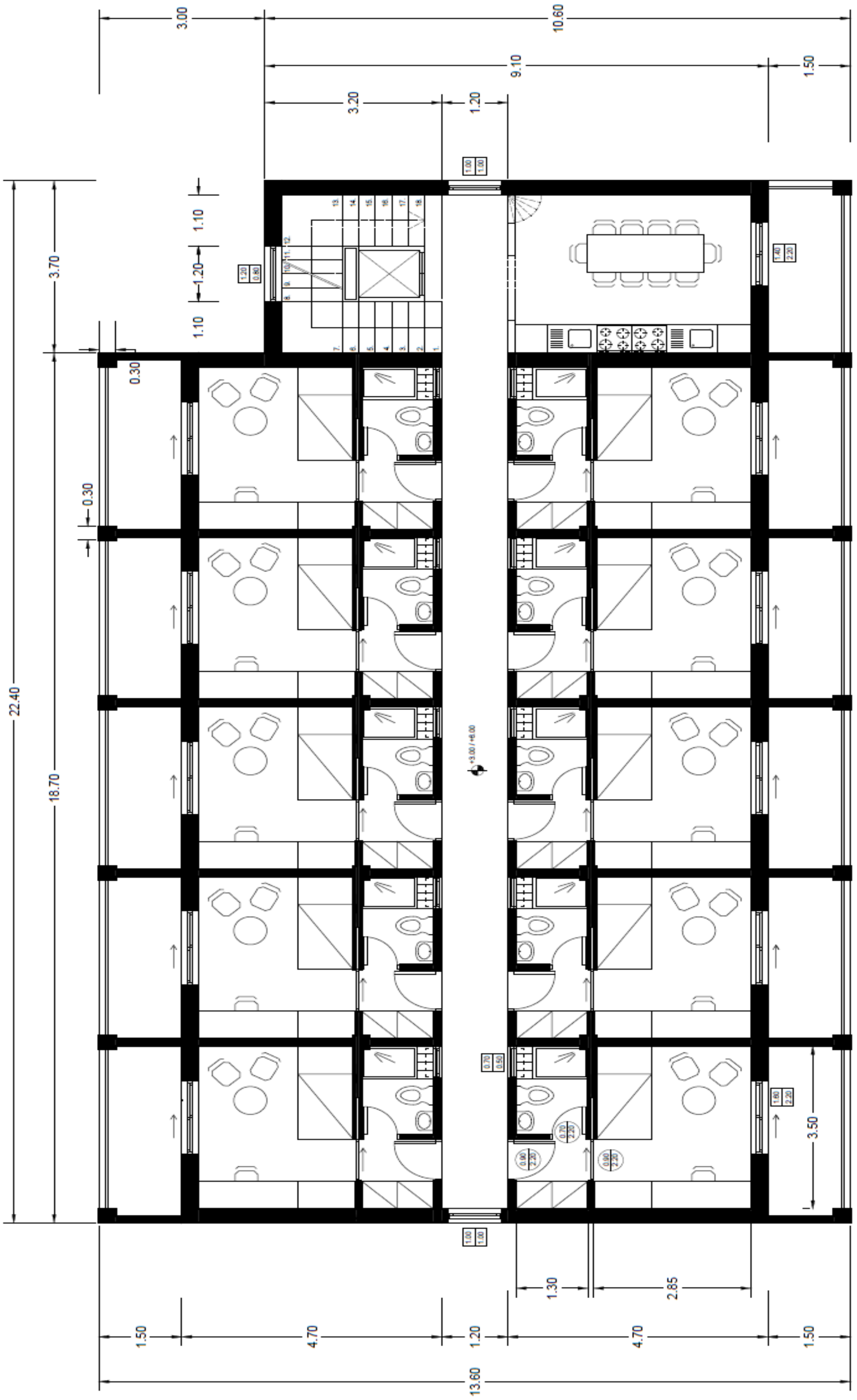


Figure A.1: Blueprint of the building (North facade up), courtesy of Anastasia Dendia, MSc Architect.

Appendix B

Climatic regions of Europe

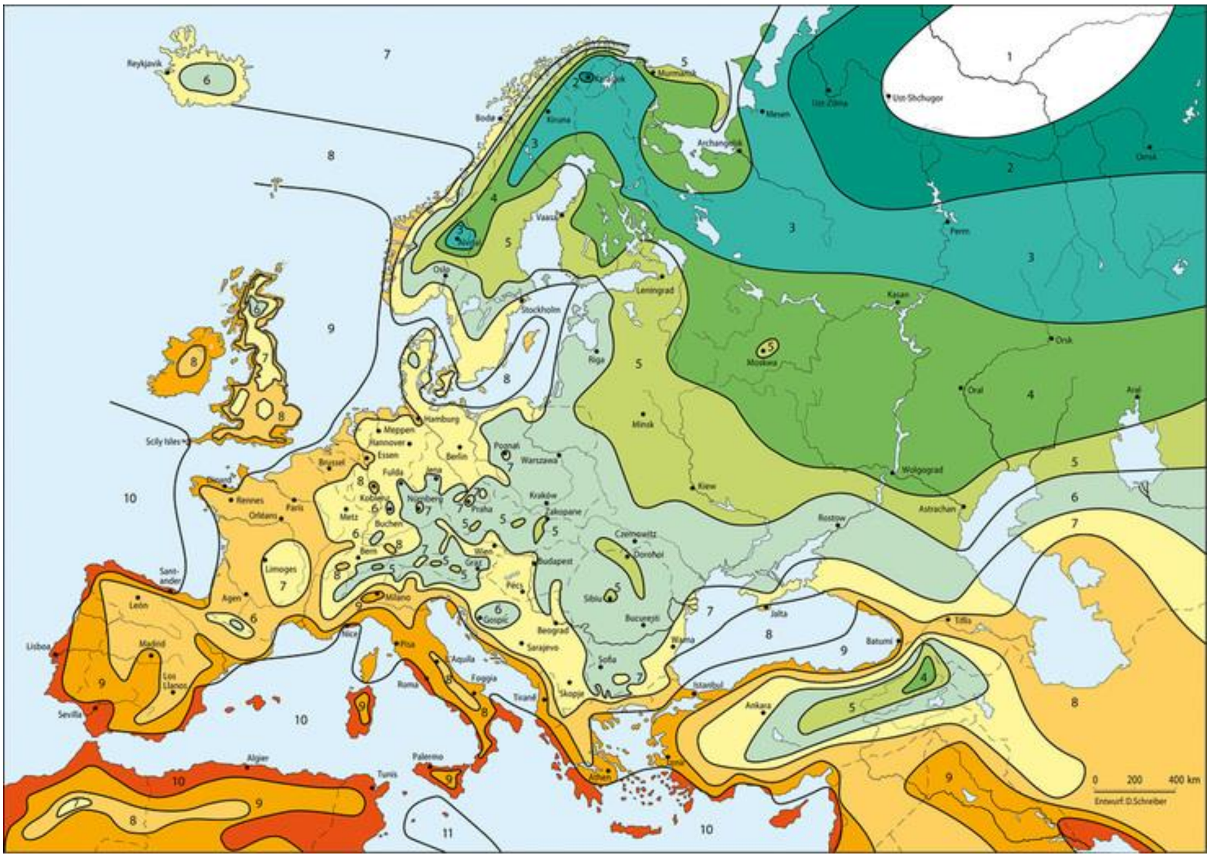


Figure B.1: Hardiness zones of Europe, (Gardenia, 2017)

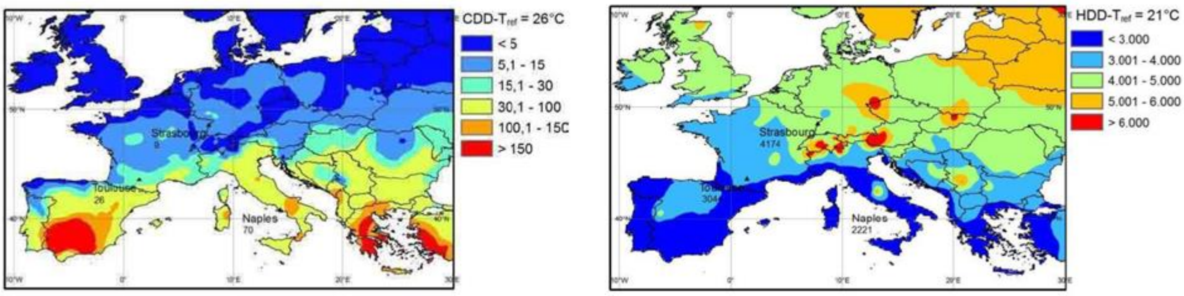


Figure B.2: HDDs and CDDs of Europe