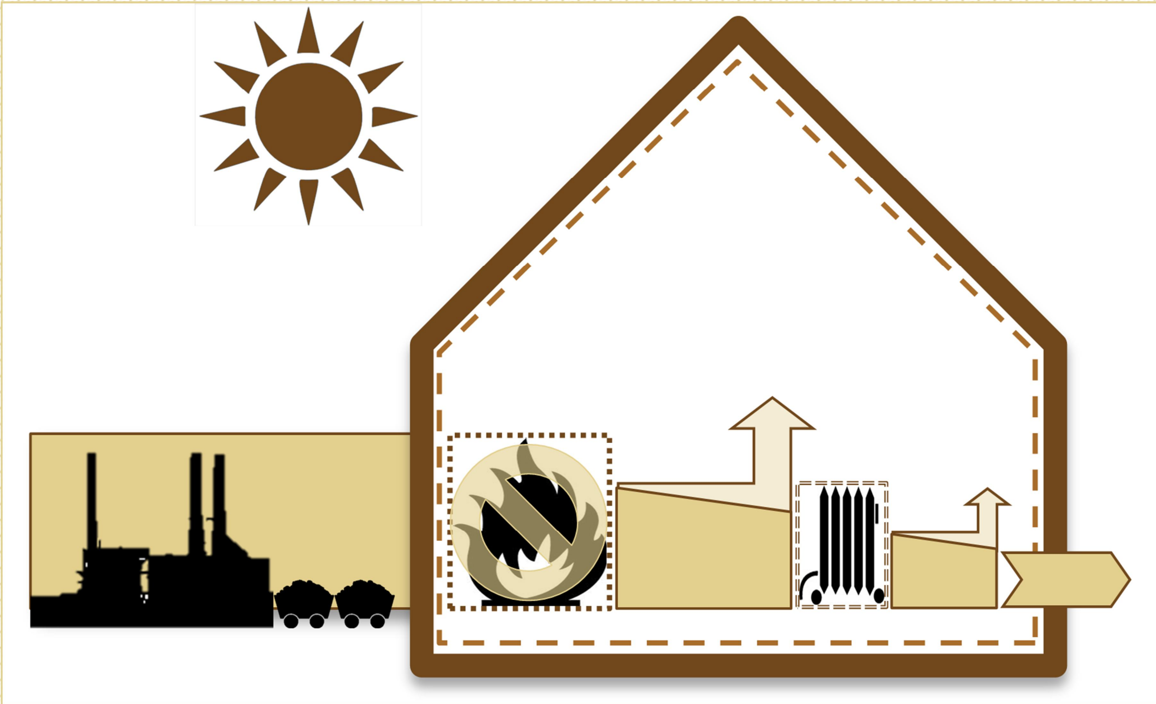

Pedro Manuel Ferreira Gonçalves

ENERGY AND EXERGY ASSESSMENTS FOR AN ENHANCED USE OF ENERGY IN BUILDINGS

Doctoral Thesis in Sustainable Energy Systems, supervised by Professor Manuel Carlos Gameiro da Silva and Professor Adélio Manuel Rodrigues Gaspar, submitted to the Department of Mechanical Engineering, Faculty of Sciences and Technology of the University of Coimbra

Coimbra, 2013

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Universidade de Coimbra

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PhD Thesis in Sustainable Energy Systems
Energy for Sustainability (EfS/MIT Portugal Program)

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Supervisors

Professor Doutor Manuel Carlos Gameiro da Silva

Professor Doutor Adélio Manuel Rodrigues Gaspar

Coimbra, November 2013

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ENERGIA PARA A SUSTENTABILIDADE ENERGY FOR SUSTAINABILITY

ADAI

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Preface

This thesis is submitted to the Mechanical Engineering Department of the University of Coimbra as a partial fulfilment of the requirements for the Doctoral degree on Sustainable Energy Systems. The studies described in the thesis have been carried out during the period from February 2009 to June 2013, and were funded by the fellowship SFRH/BD/51018/2010 from FCT, the Foundation for Science and Technology of the Portuguese Ministry of Education and Sciences, through the MIT PORTUGAL Program. The research was supervised by Professors Manuel Gameiro da Silva and Adélio Rodrigues Gaspar from the Mechanical Engineering Department at the University of Coimbra.

My interest in the topic “Exergy in buildings” started in January 2009 during the AGS Annual Meeting 2009 at ETH Zürich, after to listen the presentations of Professor Hansjürg Leibundgut from ETH Zürich, which presented the concept of “CO_2-free building” and the project “viaGialla”, designed based on concepts of Zero Emission and Low-exergy, and Professor Daniel Favrat, from Ecole Polytechnique Fédérale de Lausanne that recommended the need for further innovation on alternative indicators incorporating energy quality aspects for future energy assessments of buildings. Afterwards, I made an extensive literature review and proposed it as research topic in my Thesis Project, evaluated and approved by a jury in July 2009. I also realized that it could be of interest to the University of Coimbra, since never been studied in the context of doctoral research.

In this thesis, the exergy analysis was applied to different case studies, regarding to demonstrate it as a significant approach in comparison with conventional energy methods, able to provide complementary or exclusive information, finding a more rational or enhanced use of energy in buildings.

Coimbra, 19th June 2013

(Pedro Gonçalves)

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A special acknowledge to Giovanni Angrisani, with whom I shared ideas and knowledge that greatly contributed to the improvement of my work. I would like to thank also Carlo Roselli and Professor Maurizio Sasso, for their cooperation and support provided during my activities developed at *Università degli Studi del Sannio* in Italy.

To my advisors, Professor Manuel Gameiro da Silva and Professor Adélio Rodrigues Gaspar, I would to thank their suggestions and contributions; their serenity and positive thinking for believing that I could achieve the end of this long road.

I´m grateful to all my colleagues of the Doctoral Program on Sustainable Energy Systems, as well as, all other students and professors I have the opportunity to know during this PhD. In particular, I recognize Ehsan Asadi, Amir Safaei and Erica with whom I had the opportunity to cultivate a great friendship and improve my oral level of English. I also would like to acknowledge my laboratory mates: Cátia Augusto for her help and patience to listen my concerns; Luisa for her friendship and enjoyment; Vitor for his always ready availability and Nelson for his enthusiasm. To Sara, Prof. Almerindo and Carla, I appreciated their friendship and pleasant time we passed together. I also thank Ana Ramos that multiple times helped me to improve the level of English of my manuscripts.

I express my gratitude to my friends Nelson Alves and Luís Montelobo that multiple times gave me an extra reinforcement to carry on this work. To Doris, Ângela, Patrícia, Paulo and all my friends of A.F.S, I recognize their rapport and encouragement. I also thank all other persons that supported me in this work, but by lapse were not mentioned.

Last but not least, I would like to thank my parents, my brother and in particular my sister Goreti that follows closer my work. I recognize their affection and support, which brings me motivation and strength of mind in achieving my goals. Certainly, this thesis is dedicated to them.

Abstract

Exergy analysis has been found to be a useful method for improving the conversion efficiency of energy resources, since it helps to identify locations, types and true magnitudes of wastes and losses. It has also been applied for other purposes, such as distinguishing high- from low-quality energy sources or defining the engineering technological limits in designing more energy-efficient systems. In this doctoral thesis, the exergy analysis is widely applied in order to highlight and demonstrate it as a significant method of performing energy assessments of buildings and related energy supply systems. It aims to make the concept more familiar and accessible for building professionals and to encourage its wider use in engineering practice. This thesis is divided into five main cases studies, which have different scopes and follow slightly different approaches but all with the same common objective.

Case study I aims to show the importance of exergy analysis in the energy performance assessment of eight space heating building options evaluated under different outdoor environmental conditions. This study is concerned with the so-called “reference state”, which in this study is calculated using the average outdoor temperature for a given period of analysis. Primary energy and related exergy ratios are assessed and compared. Higher primary exergy ratios are obtained for low outdoor temperatures, while the primary energy ratios are assumed as constant for the same scenarios. The outcomes of this study demonstrate the significance of exergy analysis in comparison with energy analysis when different reference states are compared.

Case study II and Case study III present two energy and exergy assessment studies applied to a hotel and a student accommodation building, respectively. Case study II compares the energy and exergy performance of the main end uses of a hotel building located in Coimbra in central Portugal, using data derived from an energy audit. The results show that the most energy-efficient hotel end use does not necessarily correspond to the most exergy-efficient one. A diagram including information related to primary energy demand and energy and exergy efficiencies is proposed, revealing to be a very useful tool for including in future legislation on energy performance of buildings. Case study III uses data collected from energy utilities bills to estimate the energy and exergy performance

associated to each building end use. Furthermore, the building end uses are ranked by inefficiencies or exergy destruction levels, using the concept of “Exergy Destruction Ratio”. Additionally, a set of energy supply options are proposed and assessed as primary energy demand and exergy efficiency, showing it as a possible benchmarking method for future legislative frameworks regarding the energy performance assessment of buildings.

Case study IV proposes a set of complementary indicators for comparing cogeneration and separate heat and electricity production systems. It aims to identify the advantages of exergy analysis relative to energy analysis, giving particular examples where these advantages are significant. The results demonstrate that exergy analysis can reveal meaningful information that might not be accessible using a conventional energy analysis approach, which is particularly evident when cogeneration and separated systems provide heat at very different temperatures.

Case study V follows the exergy analysis method to evaluate the energy and exergy performance of a desiccant cooling system, aiming to assess and locate irreversibilities sources. The results reveal that natural gas boiler is the most inefficient component of the plant in question, followed by the chiller and heating coil. A set of alternative heating supply options for desiccant wheel regeneration is proposed, showing that, while some renewables may effectively reduce the primary energy demand of the plant, although this may not correspond to the optimum level of exergy efficiency. The thermal and chemical exergy components of moist air are also evaluated, as well as, the influence of outdoor environmental conditions on the energy/exergy performance of the plant.

This research provides knowledge that is essential for the future development of complementary energy- and exergy-based indicators, helping to improve the current methodologies on performance assessments of buildings, cogeneration and desiccant cooling systems. The significance of exergy analysis is demonstrated for different types of buildings, which may be located in different climates (reference states) and be supplied by different types of energy sources.

Keywords: Exergy analysis, Performance assessments, Buildings, Micro-cogeneration, Desiccant cooling systems, Exergy efficiency, Primary energy.

Resumo

A análise exergética tem sido usada como um método útil para melhorar a eficiência na utilização de recursos energéticos, uma vez que permite identificar os locais, tipos e magnitudes das perdas ou desperdícios de energia. Tem sido aplicada para outros fins, tais como, distinção entre recursos de alta e baixa qualidade energia, ou definir os limites tecnológicos de engenharia na concepção de sistemas mais eficientes. Nesta tese de doutoramento, a análise exergética é aplicada para demonstrar a sua importância na avaliação do desempenho energético de edifícios e sistemas de conversão de energia. Tem por objectivo tornar o conceito mais familiar e acessível entre os profissionais de energia em edifícios, incentivando o seu uso corrente em engenharia. Esta tese está dividida em cinco casos de estudos com diferentes orientações, seguindo abordagens ligeiramente distintas, mas procurando responder ao mesmo objectivo comum.

O caso de estudo I tem como objectivo mostrar a importância da análise exergética na avaliação do desempenho energético de oito opções de aquecimento, sob diferentes condições ambientais externas. O estudo está focado no chamado "estado de referência", que neste estudo é calculado usando a temperatura média exterior para um dado período de análise. Rácios de energia e exergia primária foram estimados e comparados. Como resultado, os rácios de exergia são mais elevados para níveis de temperaturas exteriores mais baixas, enquanto os rácios de energia primária são constantes nesses mesmos cenários. Os resultados deste estudo demonstram o valor da análise exergética por comparação à análise energética, quando diferentes estados de referência são considerados.

Os casos de estudo II and III apresentam duas avaliações do desempenho energético e exegético aplicadas a um hotel e de uma residência de estudantes, respectivamente. O caso de estudo II compara o desempenho energético e exegético de um hotel localizado em Coimbra, usando informação obtida por uma auditoria energética. Os resultados mostram que o utilizador final energeticamente mais eficiente do edifício não corresponde necessariamente ao mais eficiente em termos de exergia. Um diagrama incluindo informação de eficiência energética e exergética e consumos de energia primária por utilizador final é proposto, revelando ser uma ferramenta a incluir em legislação futura sobre o desempenho energético de edifícios. No caso de estudo III são usados dados de facturação de consumos para calcular o desempenho energético e exergético associado a cada utilizador final de energia do edifício. Adicionalmente, os diferentes utilizadores

foram classificados por níveis de ineficiências ou destruição de exergia, utilizando o conceito de "Exergy Destruction Ratio". Foram ainda propostas diferentes opções de fornecimento de energia, avaliadas e classificadas em termos de consumo de energia primária e eficiência exergética, revelando ser assim um possível método de "benchmarking" para futuros quadros legislativos sobre o desempenho energético de edifícios.

O caso de estudo IV propõe um conjunto de indicadores complementares para comparar sistemas de co-geração e sistemas de produção separada de calor e electricidade. Tem como objectivo identificar as vantagens da análise exergética comparativamente ao método de análise energética, mostrando exemplos particulares onde são mais evidentes. Os resultados demonstram que a exergia revela informação distinta face a uma abordagem energética convencional, sendo mais evidente em sistemas de co-geração e de produção separada com fornecimento de calor a temperaturas muito diferentes.

O caso de estudo V usa o método de análise exergética para avaliar o desempenho energético e exergético de um sistema de arrefecimento exsicante, tendo por objectivo principal avaliar e localizar fontes significativas de irreversibilidades. Os resultados revelam que a caldeira a gás natural é o componente mais ineficiente, seguindo-se o "chiller" e o permutador de aquecimento. Um conjunto de opções alternativas de aquecimento para regeneração da roda exsicante é também proposto, revelando que algumas fontes de energia renovável podem efectivamente reduzir o consumo de energia primária, embora possam não corresponder a eficiências exergéticas elevadas. As componentes térmicas e químicas do ar húmido são também avaliados, assim como a influência de condições ambientais externas no desempenho da unidade.

Este trabalho de investigação contém conhecimento essencial para o futuro desenvolvimento de indicadores complementares baseados em exergia, permitindo melhorar as metodologias convencionais de desempenho energético de edifícios, sistemas de co-geração e sistemas de arrefecimento dissecante. A importância da análise exergética é demonstrada para diferentes tipos de edifícios, que podem estar localizados em diferentes ambientais exteriores (estados de referência), e que podem ser fornecidos por diferentes fontes de energia.

Palavras-chave: Análise exergética; Avaliações de desempenho; Edifícios; Micro-cogeração; Sistemas de arrefecimento exsicante; Eficiência exergética; Energia primária.

Nomenclature[1]

Main Symbols

A_f	Floor conditioned area (hotel building), (m^2)
$E_{el,i}$	Energy demand of hotel electric end use *i*, (kWh)
E_p	Primary-fossil energy demand, (kWh m^{-2})
$\dot{E}_{p,vii}$	Primary energy load at the heating system of the desiccant wheel, (kW)
$E_{u,i}$	Useful energy demand related to the hotel end use *i*, (kWh)
EDR_k	Exergy destruction ratio for the end use *k*, (-)
$E_{f,i}$	Energy demand related to fossil sources (hotel building), (kWh)
$\dot{E}_p$	Primary energy input rate for a given space heating option, (kW)
EP	Specific Primary Energy demand of the hotel building, (kWh m^{-2})
$E_{p,i}$	Primary energy demand related to the hotel end, *i*, (kWh)
Ex_D	Useful exergy demand, (kWh)
$Ex_{des,i}$	Exergy desired related to the hotel end use, *i*, (kWh)
$\dot{E}x_{in,k}$	Exergy input rate of component *k* of the desiccant cooling plant, (kW)
$\dot{E}x_{iv}$	Space heating exergy demand at sub-system *iv*, (kW)
$\dot{E}x_{out,k}$	Exergy output rate of component *k* of the desiccant cooling plant, (kW)
$\dot{E}x_p$	Exergy rate related to the primary energy demand of a space heating option, (kW)
$Ex_{req,i}$	Exergy required related to the hotel end use *i*, (kWh)
Ex_S	Total exergy required at supply side, (kWh)
$F_{el,p}$, $F_{p,e}$	Conversion factor from electricity to primary energy, (-)
$F_{p,f}$	Conversion factor from fossil sources to primary energy, (-)
$\dot{I}_{chp}$	Irreversibility rate occurring at the cogeneration system, (kW)
I_k	Irreversibility associated to building end use *k*, (kWh)
$\dot{I}_k$	Irreversibility rate at the component *k* of the desiccant cooling plant, (kW)
$\dot{I}_p$	Primary irreversibility rate, (kW)
$I_{R,k}$	Relative irreversibility rate at the component *k* of the desiccant cooling plant, (-)
$\dot{I}_{p,ref}$	Primary irreversibility rate in the reference system, (kW)
$\dot{I}_{t,ref}$	Total irreversibility rate in the reference system, (kW)
PER	Primary Energy Ratio, (-)
PER_i	Primary Energy Ratio, related to the hotel final use *i*, (-)
PER_{ove}	Overall Primary Energy Ratio of the desiccant cooling system, (-)
PES	Primary Energy Savings, (-)

[1] The list of symbols presented in this section is only referred to the main five chapters of this dissertation. The complete list of symbols is individually presented in each Research Paper, included in the Appendix.

PExR	Primary Exergy Ratio, (-)
PIS	Primary Irreversibility Savings, (-)
$\dot{Q}_{H,iv}$	Space heating load at sub-system *iv*, (kW)
$Q_{h.k}$	Heating energy demand of the student housing end use *k*, (kWh)
$\dot{Q}_{c}$	Cooling load of the desiccant cooling plant, (kW)
TIS	Total Irreversibility Savings, (-)
$\dot{W}_{el,iv}$	Electricity load of chiller in the desiccant cooling plant, (kW)
$W_{el,j}$	Electricity demand of the hotel building end use, *j* (kWh)

Greek symbols

δ_k	Exergy efficiency defect related to the desiccant cooling plant component *k*, (-)
φ_{eg}	Fraction of electricity produced by renewable sources, (-)
φ_{hs} ; $\varphi_{h,k}$	Fraction of useful heat derived from renewable sources, (-)
$\eta_{e,chp}$	Electric-based efficiency of the cogeneration unit, (-)
η_{eg}	Averaged efficiency of the electricity production system, (-)
$\eta_{eg,f}$	Electric grid efficiency (powered by fossil sources), (-)
$\eta_{h,chp}$	Thermal-based efficiency of the cogeneration unit, (-)
$\eta_{hs,k}^{f}$	Fuel-based heating system efficiency, related to end use *k*, (-)
$\eta_{hs,f}$	Heating system efficiency powered by fossil sources, (-)
ψ	Exergy efficiency of a given heating option, (-)
ψ_k	Exergy efficiency of the desiccant plant component *k*, (-)

Acronyms

AC	Air Conditioning units
CHP	Combined Heat and Power
DCS	Desiccant Cooling System
DHW	Domestic Hot Water
EC	European Commission
ECBCS	Energy Conservation in Buildings and Community Systems
EPBD	Energy Performance of Buildings Directive
ESN	Energy Supplied Network
HVAC	Heat Ventilation and Air Conditioning
IEA	International Energy Agency
MCHP	Micro Combined Heat and Power
OCDE	Organisation for Economic Co-operation and Development
RSECE	Acronym in Portuguese: Regulation of the Climatization Energy Systems in Buildings
WBCSD	World Business Council for Sustainable Development

List of original publications

This thesis is based on the five following publications, mentioned in the text as **Research Paper I-V**, and that are included in the Appendix section.

Research Paper I Pedro Gonçalves, Adélio Rodrigues Gaspar, Manuel Gameiro da Silva, 2013a. *Comparative energy and exergy performance of heating options in buildings under different climatic conditions.* Energy and Buildings 61, 288–297.

Research Paper II Pedro Gonçalves, Adélio Rodrigues Gaspar, Manuel Gameiro da Silva, 2012. *Energy and exergy-based indicators for the energy performance assessment of a hotel building.* Energy and Buildings 52, 181–188.

Research Paper III Pedro Gonçalves, Adélio Rodrigues Gaspar, Manuel Gameiro da Silva, 2013d. *Energy-exergy benchmarks for energy performance assessment of buildings.* Energy efficiency 00 (Under revision).

Research Paper IV Pedro Gonçalves, Giovanni Angrisani, Carlo Roselli, Adélio Rodrigues Gaspar, Manuel Gameiro da Silva, 2013b. *Comparative energy and exergy performance assessments of a microcogenerator unit in different electricity mix scenarios.* Energy Conversion and Management 73, 195-206.

Research Paper V Pedro Gonçalves, Adélio Rodrigues Gaspar, Giovanni Angrisani, Maurizio Sasso, Manuel Gameiro da Silva, 2013c. *Exergetic analysis of a desiccant cooling system: searching for performance improvement opportunities.* International Journal of Energy Research, DOI: 10.1002/er.3076.

Additional publications made under this research topic:

1. Pedro Gonçalves, Adélio Rodrigues Gaspar, Manuel Gameiro da Silva, 2011. *Comparative exergy and energy performance analysis of a separated and combined heat and power system for a student housing building*, in Proceedings of MICROGEN II: 2nd International Conference on Microgeneration and Related Technologies. Glasgow, 4-6 April.

2. Pedro Gonçalves, Adélio Rodrigues Gaspar, Manuel Gameiro da Silva, 2011. *Performance assessment of building heating systems using exergy analysis methods*, in Proceedings of Climamed 2011: VI Congreso Mediterraneo de Climatización, Madrid 2-3 July.

3. Pedro Gonçalves, Giovanni Angrisani, Carlo Roselli, Adélio Rodrigues Gaspar, Manuel Gameiro da Silva, 2013. *Energy and exergy-based modeling and evaluation of a micro-combined heat and power unit for residential applications*, in Proceedings of MICROGEN III: 3rd International Conference on Microgeneration and Related Technologies. Naples, 15-17 April.

Contents

1. Introduction

1.1. Background and motivation

The World Business Council for Sustainable Development (WBCSD) identified buildings as one of the five main energy users with highest potential for the energy efficiency improvement in the short term (WBCSD, 2009). In the European Union (EU), buildings sector account for 40 % of total energy consumption and 36 % of CO_2 emissions, representing Europe's largest source of greenhouse gas emissions. Therefore, improving the energy performance of buildings is a key objective of the European policy framework for the transition to a low-carbon economy. To pursue this goal, an action plan for energy efficiency launched by the European Commission (EC, 2006) set a target for achieving by 2020: 20 % reduction in greenhouse gas emissions, 20 % energy savings; and renewable energy accounting for 20 % of EU overall energy consumption. The action plan also establishes that the highest energy savings need to be made in residential (households) and commercial buildings, with potential savings estimated to be about 27 % and 30 %, respectively, followed by the industrial and transport sectors. Also, the Sustainable Building and Construction Initiative of the United Nations Environment Programme (Houvila and UNEP, 2007) defined building and construction as a key sector for the sustainable development. This sector presents a considerable potential for positive changes in becoming more efficient in terms of the use of resources being less environmentally intensive and more profitable. Energy benchmarks for buildings were outlined as an important instrument in helping decision-makers take correct appropriate steps and encourage energy efficient and sustainable buildings, while influencing the market mechanisms and promoting research and developments projects.

The building sector is an activity sector with a complex industrial chain, which involves a wide variety of players and is dependent of an extended life cycle of products and user preferences, making it one of the most complex environmental policy targets groups (OCDE, 2003). Incentive instruments for energy efficiency in buildings, including economic and technical aspects, R&D programmes and other tools need to be implemented alongside governmental policies. Building regulations are crucial in helping to encourage energy efficiency improvements in the building sector, limiting buildings energy consumption. Within the European Union, the Energy Performance of Buildings Directive (EPBD) 2002/91/EC (EC, 2002) and the recast EPBD 2010/31/EU (EU, 2010) are currently the main policy instruments regarding the reduction of energy consumption in buildings across Europe. Attention should also be given to the energy sources used for space heating and cooling, giving preference to the renewable energy and high-efficiency technologies, such as, solar thermal, air- or ground-source heat pumps systems.

Besides to purely quantity aspects, the energy quality should also be considered, giving preference to the use of low-quality sources such as, ground heat source and district heat (IEA, 2008). The quality of energy is revealed by combining the First and Second Law of Thermodynamics, which is usually treated as “Exergy analysis”. In actual energy systems, part of the exergy supplied is consumed or destroyed, caused by the inherent irreversibilities associated to each energy conversion process (Bejan, 2006). For example, high energy-efficient boilers are widely used to meet low-temperature heat requirements, such as, space heating or domestic hot water applications. In these applications, the high exergetic potential of the fuels supplied is irretrievably lost, leading to high exergy destruction rates or low-exergy efficiencies (IEA, 2008).

Consequently, this PhD research is driven to encourage the energy efficiency in buildings with regard to the quantitative and qualitative aspects of energy use, highlighting the importance of moving towards low-exergy technologies, the use of renewable and low-temperature heat sources in accordance with the actual exergy requirements of buildings or system output. Additionally, the exergy analysis also plays a key role in the sustainable development, since it is one way to reduce the depletion of resources and decrease the exergy losses by increasing the exergy efficiency of the energy conversion systems (Dinçer and Rosen, 2007). Therefore, the exergy plays also an important role on the main topics of Energy for Sustainability (EfS) and MIT Portugal Program on Sustainable Energy Systems, of which this PhD is a part.

1.2. Statement of the problem

The conventional methods of assessment of the energy use in buildings are usually focused on purely energy quantity aspects (first law approach), generally interested on minimizing energy losses or reducing the related primary energy demand. Although, in this approach, the margins for efficiency improvement are generally narrow, contrasting with exergy analysis methods, involving both first and second law principles. Despite the need of exergy methods for performance assessment of buildings has been claimed by several authors Schmidt and Shukuya (2003), Shukuya and Hammach (2002), Tolga Balta et al. (2008), Schmidt (2009) and Hepbasli (2012), their widespread use and current practice among building professionals is an issue that still exists. This problem has been minimized throughout the use of conversion factors, converting energy quantities into primary energy or related CO_2 emissions, although it does not involve any energy quality considerations.

The building sector was also considered a sector with a high potential for improving the quality match between energy supply and demand (Ala-Juusela, 2004), especially when high exergy sources are used to fulfil low-temperature (or low-exergy) requirements. As different levels of energy quality are required for the different end users within a building, adequate energy sources should be chosen in order to minimize quality differences between supply and demand. As example, for space heating and cooling requirements, with temperatures around 20 – 25ºC, the quality levels at demand (q) are relatively low (q=0.07). On other hand, lower than household electric appliances and lighting applications, which are associated to high energy quality levels (q=1) (IEA, 2008).

Additionally, the energy supply structure is not as sophisticated as building demand requirements, therefore energy is supplied as electricity or high exergy sources, such as fossil fuels, applied to perform both high exergy tasks and low-temperature requirements. Since fossil fuels burn at very high (flame) temperatures up to 2000 K (Dincer and Cengel, 2001), the available work (energy) obtained from the fossil fuels is largely wasted when the fossil fuels are used to space heating, hot water or even industrial steam production. This problem is known for a long time, but has not yet been addressed, especially in the building sector, where a dominant share of annual energy consumed with very low exergy efficiency and thereby polluting the atmosphere in an unnecessary way (Sakulpipatsin, 2008). An way to address this issue is to use low-exergy sources or alternative energy resources, directly with temperature levels compatible with energy demand requirements.

1.3. Objectives and research questions

Exergy analysis method aims towards a deeper understanding of the nature of energy flows or conversion processes, maximizing the match between the supplied exergy and the useful energy at demand (Schmidt, 2009). In this doctoral research, energy and exergy analysis methods are applied to different scopes, such as, performance assessments of buildings (hotel and student housing); assessments of heating options in buildings; comparison between cogeneration and separate heat and electricity production; and performance assessment of desiccant cooling systems. The main objectives are to demonstrate by practical examples the exergy analysis as a significant method for the performance assessment of buildings, showing it as a complementary approach to the energy method, making the exergy concept more familiar and practical for building professionals and encouraging further utilization in engineering practice. Based on the objectives, four main Research Questions (RQ) were formulated that this research will attempt to answer.

RQ I *How to demonstrate that the exergy can be a significant method able to provide meaningful or even exclusive information relatively to the conventional energy approach?*

RQ II *How to distinguish building energy end uses by means of energy and exergy performance and how it can contribute for the overall performance improvement of buildings?*

RQ III *How to evaluate and rank building energy end uses (or sub-components in multi-component systems) by irreversibilities levels and how to optimize their energy and exergy performance?*

RQ IV *Can exergy indicators be useful to the usually applied Primary Energy Savings (PES) for comparing cogenerated and separated heat and electricity production systems?*

1.4. Outline of the thesis

This thesis is constituted by five chapters and an appendix section. The chapters present the review of the most relevant scientific literature, the methods performed, the results and discussion and finally the main conclusions of this doctoral research. After the current Introduction section, Chapter 2 summarizes the main literature review, including exergy definitions, reference environment, developed exergy tools with major focus on the most important key topics about exergy in buildings. Chapter 3 describes the main case studies and the related methods used in this research. Chapter 4 presents the main outcomes of this research and Chapter 5 summarizes the main conclusions of the thesis, including main contributions, unsolved issues and suggestions for further research. In the appendix section, the main five research papers written during this research are included, which are following summarized:

- **Research Paper I** (Gonçalves et al., 2013a) makes a comparison between different heating options in buildings, located in different outdoor environmental conditions. This paper aims to show the significance of the exergy analysis relatively to the energy method for comparing scenarios with different dead state conditions.

- **Research Paper II** (Gonçalves et al., 2012) uses energy and exergy indicators to assess the performance of a hotel building located in the city of Coimbra, using actual energy data derived from an energy audit. This study aims to demonstrate how exergy analysis could be applied together with conventional energy methods, distinguishing buildings according to the type of the energy end uses.

- **Research Paper III** (Gonçalves et al., 2013d) compares primary energy and exergy indicators and discusses their significance for inclusion on future buildings energy codes. Using actual energy data, the primary energy and exergy performances of a student housing building were evaluated. Based on the concept of Exergy Destruction Ratio (*EDR*), the main building end uses were ranked monthly by the respective levels of irreversibilities (inefficiencies). Additionally, various alternatives for the energy supply were performed and benchmarked using primary energy and exergy indicators.

- **Research Paper IV** (Gonçalves et al., 2013b) compares a micro-cogeneration (MCHP) unit with a set of reference scenarios, based on separate heat and electricity production. The paper highlights the limitations of using Primary Energy Savings (*PES*) indicator and identifies particular situations, where alternative indicators (based on the first and second laws of thermodynamics) could provide additional information not possible with a simple energy approach using *PES*.

- **Research Paper V** (Gonçalves et al., 2013c) examines in detail all the component of a Desiccant Cooling System (DCS), evaluating their energy and exergy performance for a typical summer week in a Mediterranean climate (Naples, Italy). Using the concept of exergy efficiency defect, the sub-components of the DCS were ranked by levels of irreversibilities. Additionally, for the most inefficient component of the plant (the boiler), alternative systems were proposed and their performances evaluated.

2. State of the art

Exergy analysis method has been applied since the early 1970s, aiming to find the most rational use of energy, reducing fossil fuels consumption for low-quality energy requirements and looking for a better match between quality levels of supply and demand (Torío et al., 2009). In buildings, most scientific efforts have been focused on reducing primary energy demand or related CO_2 emissions, which have been accomplished through the use of more efficient equipments, improvements on building envelope quality (better insulation, enhance glazing, etc) or even teaching the users to change their behaviours. High performance and sustainable buildings requires maximizing energy, exergy and comfort performances, while minimizing the environmental footprint. In buildings and HVAC technologies, the exergy has been a forgotten concept (Kilkis, 2010), and most of the analysis conducted has been purely based on first law of thermodynamics. The exergy analysis leads to a better understanding of the influence of thermodynamic phenomena on the process effectiveness, highlighting the importance of different thermodynamic factors and most effective ways for improving energy conversion processes. Without the inclusion of the exergy concept in the analysis, major environmental problems and solutions remain hidden in the building sector (Kilkis, 2010). In recent years, the exergy concept has been increasingly applied and developed in the study of built environment, where the original studies of the architectural engineer Shukuya, including studies on fenestration, building services and human body (Shukuya and Assada, 1993; Shukuya, 1994, 1996) are mentioned as the firsts on this field.

In this state-of-the art, a great quantity of research studies on exergy analysis of building was reviewed, with especial attention for those related to the exergy-based assessments and exergy indicators, which are the main topics of this dissertation. It is divided into eight sections organized as following. Section 2.1 describes various exergy definitions and introduces the low-exergy approach concept. In Section 2.2, the reference (dead state) environment issues are presented and discussed. Section 2.3 reviews the most important exergy calculation tools for exergy analysis of buildings. The important studies on exergy analysis of building are presented in Section 2.4, and the most significant indicators for exergy performance of buildings are presented in Section 2.5. Finally, in

Section 2.6 and Section 2.7 are presented the main studies on exergy analysis of cogeneration systems and desiccant cooling systems, respectively.

2.1. Exergy definitions and low-exergy approach

Many researchers and engineers have applied exergy methods for performance assessment, design or improvement of energy systems or conversion processes. When compared with the conventional energy method, the benefits of the exergy analysis are numerous. The concept is often perceived as highly complex and some practicing engineers disbelieved exergy to achieve tangible and useful results (Hepbasli, 2012). For a better understanding of the concept, a review of the definitions given by the different authors was conducted and the respective results are presented in Table 1.

Table 1: Different exergy definitions.

Author (s)	**Exergy definition**
(Kotas, 1995)	The work equivalent of a given form of energy is a measure of its exergy, which is defined as the maximum work, which can be obtained from a given form of energy using the environmental parameters as the reference state.
(Szargut, 2005)	Exergy is a measure of a quality of various kinds of energy and is defined as the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes.
(Bejan, 2006)	Exergy is the minimum theoretical useful work required to form a quantity of matter from substance present in the environment and to bring the matter to a specified state. Exergy is a measure of the departure of the state of the system from that to the environment, and is therefore an attribute of the system and environment together.
(Tsatsaronis, 2007)	Exergy of a thermodynamic system is the maximum theoretical useful work (shaft work or electrical work) obtainable as the system is brought into complete thermodynamic equilibrium with the thermodynamic environment while the system interacts with this environment only.
(Moran and Shapiro, 2008)	Exergy is the maximum theoretical work that can be extracted from a combined system consisting of the system under study and the environment as the system passes from a given state to equilibrium with the environment.

Terms like “maximum theoretical work”, “reference environment” and “energy quality” are used by the different authors for the definition of exergy. Furthermore, Kotas (1995), Wark (1995) and Bejan (2006) described exergy as constituted by four main components: the physical exergy (mechanical and thermal), chemical exergy, kinetic and potential exergy. The physical exergy is related with deviation of temperature and pressure relatively to the reference environment. The chemical exergy is associated to the deviation of chemical composition of the system relatively to a given reference state. The kinetic and potential exergy is associated to the system velocity and height, respectively measured relative to a given reference point.

The introduction of the exergy concept in built environment aims to improve the quality match between supply and demand (Sakulpipatsin, 2008), since in most of cases, high energy sources are used to satisfy low temperature and thereby low exergy needs. In this way, concerning the concept applied to buildings, the most of suitable concepts are: exergy as “a measure of a quality of various kinds of energy”, for supplied exergy assessment (e.g. electricity, fossil and renewable resources); and exergy as ”the minimum theoretical useful work required to form a quantity of matter from substance present in the environment and to bring the matter to a specified state”, applied to evaluate the exergy building end uses (e.g. space heating, hot water, food preparation, etc).

In Figure 1, a scheme of the energy quality flows in buildings is represented at supply and demand side. The fossil energy supply and related energy use at building demand are represented. The size of each arrow gives an indication about the magnitude of each energy flow. A high match between supply and demand levels could be achieved through the use of suitable energy sources chosen according to the buildings demand, increasing significantly its overall exergy performance (Torío and Schmidt, 2010).

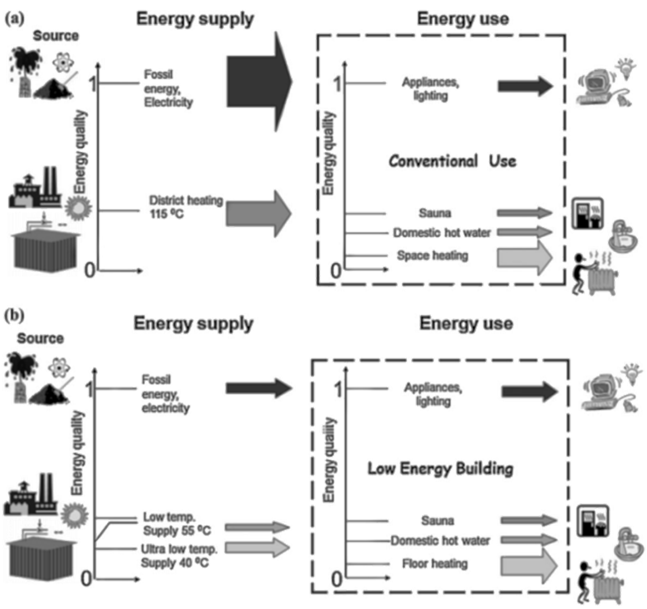


Figure 1: Schematic view of energy quality flows in buildings:

(a) Conventional building;

(b) Low-temperature building.

(Schmidt, 2009).

There are huge varieties of technical solutions on the market able to provide low temperature levels for heating (or high temperature for cooling), although this is not the main concern of engineers, who are mostly concerned on designing building systems based on pure energy quantitative aspects. To overcome this issue, the next generation of buildings should be planned to operate with sustainable energy sources for heating and cooling with adequate temperature levels. Therefore, the development of low-temperature heating systems or high-temperature cooling systems is a necessary pre-requisite for the use of alternative energy sources. These ideas lead to the concept of "Low-Exergy" or simply 'LowEx', which is found in the following studies Shukuya and Hammach (2002), Ala-Juusela (2004), CostExergy (2004), Schmidt and Ala-Juusela (2004), Cost24 (2007), Schmidt (2009). LowEx systems differ from "passive systems" that are designed to take profit of various "potentials" in the immediate environment. Low-exergy systems are "active" systems that allow the use of low valued energy, which is (easily) delivered by sustainable energy sources (e.g. by using heat pumps, solar collectors, either separate or linked to waste heat, energy storage, etc.) (Schmidt, 2004). The use of low-exergy supply systems is able to deliver heat/cool in environments relatively close to comfort conditions, and also provides many benefits, such as, improving the thermal comfort and indoor air quality and also the reduction of the exergy consumption (Gu, 2007).

2.2. Reference environment

The significance of the dead state definition for the exergy analysis was studied in detail by Rosen and Dincer (2004), Krakow (2007) and Utlu and Hepbasli (2007). The authors classified the exergy analysis as a relevant tool to compare actual and ideal (reversible) thermal systems, once two or more systems to be compared must have "basic similarities and equivalent boundary conditions" (Krakow, 2007).

From the previous definitions, exergy is associated to the work potential (or quality changes of energy and matter) always defined relatively to a given reference environment (or dead state). When a system is in equilibrium with the environment, the state of the system is called 'dead state' and its exergetic value is zero. At this state, mechanical, thermal and chemical conditions between the system and the environment are in equilibrium. The system has also no motion or elevation relative to the environment coordinates (Bejan and Mamut, 1999). Under this state, there is neither the possibility of a spontaneous change within the system or the environment nor an interaction between them. A particular dead state is called 'restricted dead state', when only mechanical and thermal equilibrium occur between the system and its environment. In the restricted dead state, a given system has no mass flow exchanges, both velocity and elevation relative to the environment coordinates are zero and the reference temperature and atmospheric pressure are respectively T_0 = 25 ºC and p_0 = 101 325 Pa (Moran, 1982).

The exergy analysis results are usually sensitive to variations of the dead state conditions. Some authors conducted some sensitivity analyses on the effect of varying dead state of engineering systems. Rosen and Dincer (2004) described the sensitivity exergy parameter with the reference environment based on pressure and temperature. The results indicate that, when the state is significantly different from the chosen dead-state, the exergy flows are not very sensible to the reference state choice (e.g. power plants). However, when the properties of the system are close to the reference environment (e.g. space heating and cooling of buildings) strong variations are obtained.

Concerning exergy analysis studies on dead state issues in built environment, some authors proposed that the dead state should be defined based on outdoor environment surrounding to the building (Alpuche et al., 2005; Angelotti and Caputo, 2007; Sakulpipatsin, 2008; Torío and Schmidt, 2010). Despite this definition requires the use of dynamic energy and exergy analysis, the major part of the papers reviewed apply the steady-state approach, using seasonal mean values and annual mean values (Torío et al., 2009). Also, Sakulpipatsin (2008) evaluated exergy flows through the building envelope, including the air humidity in the definition of both the building and its reference environment. The author investigated two climatic conditions: Bangkok (Thailand) as hot and humid climate and De Bilt (The Netherlands) as cold and dry climate. Chengqin et al. (2002) suggested an unusual selection of the dead-state novel of HVAC systems, which simplifies the exergy analysis by excluding the need of calculating the exergy of water at ambient temperature. An exergetic modelling and experimental performance assessment study of a novel desiccant cooling system conducted by Hürdoğan et al. (2011) found that exergetic efficiency of the whole system ranges from 32 % to 10 %, for variations on dead state temperatures from 0 to 30 ºC. Finally, in the study conducted by Utlu and Hepbasli (2007), the effect of the reference (dead) state on energy and exergy efficiencies of the residential-commercial sectors was investigated. The authors concluded that exergy efficiency values vary from 8.11 to 11.92 % with the dead state temperatures from 25 to 0 ºC. From all reviewed studies, it could be concluded that the choice of the reference environments greatly influences the exergy analysis results, which is a strong stimulus for the definition a common dead state framework for further exergy analysis studies.

2.3. Exergy calculation tools

The ECBCS Annex 49 (IEA, 2008) developed a huge variety of tools and diagrams, showing exergy analysis results in buildings and communities from different perspectives. An overview of tools developed during ECBCS Annex 49 is presented in Table 2. The "IEA Annex 49 pre-design tool" was originally developed by Schmidt D. (2003) and was used and improved during the research project ECBCS Annex 37 (Ala-Juusela, 2004). It is a MS Excel tool, based on a steady-state heat demand that performs the calculations for a design point defined by the user of outdoor/indoor conditions, solar radiation, internal gains and air exchange rate.

Table 2: Summary of tools for exergy analysis in built environment, developed during ECBCS Annex 49 (IEA, 2008).

Tool	Recommended user	Interface/ Programing	Licence	Scope
Annex 49 pre-design tool	Engineer Architect	Excel/Basic	Open source	System/building
Cascadia	Engineer Energy planner	Excel/Basic	Open source	Community
SEPE	Engineer	Excel/Basic	Open source	System/component
DPV	Engineer Architect	GUI/C	Private	Building
Human body	Engineer	GUI/Fortran	Open source	Occupant
Decision Tree	Owner Energy planner	Graphical	Open source	System/building

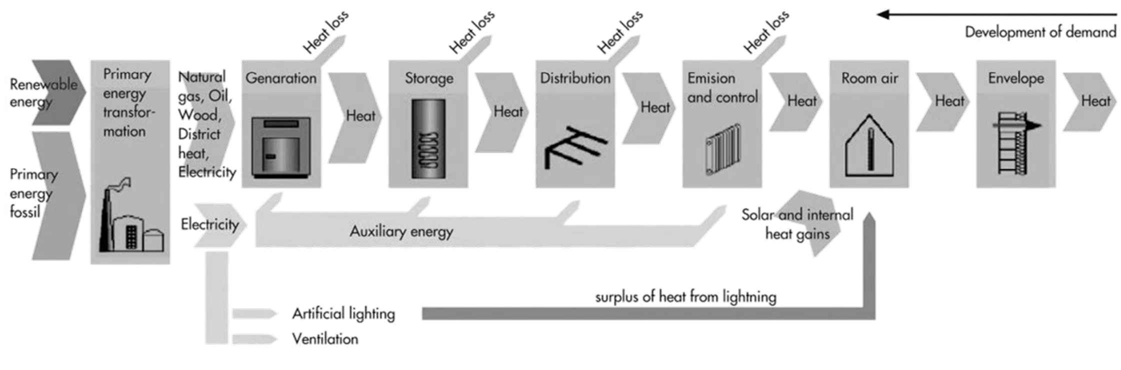


Figure 2: Energy supply chain for space heating in buildings, from primary energy transformation to final energy (Schmidt D., 2003).

The pre-design tool is divided into seven blocks and sub--systems as illustrated in Figure 2. It is able to assess the overall energy and exergy performance of the supply systems and individual components (e.g. boiler, solar collectors, floor heating systems, etc). More information about this tool may be found in IEA (2008). As output results, a set of diagrams may be presented showing the energy/exergy flows and energy/exergy losses that occur in each component of the energy supply chain.

As previously stated, exergy analysis has been used to locate sources of inefficiencies and identify the potential for energy systems improvement (Szargut, 2005), allowing also a common and scientifically grounded approach for analysing different energy sources (fossil or renewable). However, the exergy analysis by itself does not provide any information about renewability of a given energy source. Therefore, in IEA (2008), the link between these two aspects requires an additional parameter called Primary Energy Ratio (*PER*) that calculated as the ratio between the useful energy demand and the fossil energy input. High *PER* values indicate that the proportion of fossil energy in the supply is low (high efficient systems or high share of renewables). The combined use of *PER* and exergy efficiency, led to the concept of '*PER*-exergy efficiency diagram', developed by CHRI-Cauberg Huygen, in Netherlands. These diagrams were applied in the case studies of Annex 49 (IEA, 2008) for community supply systems, aiming to describe the exergy performance together with the use of renewable sources in communities.

2.4. Synopses of exergy studies in buildings

In the last few years, several exergy analysis studies about built environment have been conducted. As result of an initiative initiated by the International Society for Low Exergy Systems in Buildings, a guidebook on low-exergy heating and cooling systems was published (LowEx, 2003). Three additional international research projects on this topic have been conducted: IEA ECBCS Annex 37 (Ala-Juusela, 2004), IEA ECBCS Annex 49 (IEA, 2008) and COSTeXergy (CostExergy, 2004). These projects aimed to promote the rational use of energy in buildings by encouraging the use of low temperature heating systems and high temperature cooling systems in buildings. Xydis et al. (2009) dealt with energy and exergy assessments in hotels. The authors demonstrated that the exergy analysis results in four typical hotels in Northern and Southern Greece could assist to define the most appropriate energy sources to be used in non-residential buildings (e.g. hotels). Balta et al. (2008) exploited the exergetic analysis for the assessment of a low-exergy heating system from the power plant through a ground-source heat pump till the building envelope. Yucer and Hepbasli (2011) performed an exergy assessment study of an educational building heated by a conventional boiler. The energy and exergy flows between the stages were obtained using a pre-design tool (Schmidt D., 2003) for an optimized building design. Sakulpipatsin et al. (2010) presented an extended method for exergy analysis of buildings and HVAC, according to an energy demand build-up model from the building side to energy supply side. The two considered case studies meet the standard Dutch energy performance regulations, nevertheless their overall exergy efficiencies are low in both cases (17.15 % and 6.81 %). A summary including the main exergy analysis studies conducted in built environment and the main outcomes is presented in Table 3.

Table 3: Main review studies on the use of exergy for buildings and related energy systems

Authors/References	Scope	Main features or outcomes
(Ala-Juusela, 2004)	Low exergy solutions by case studies	Guidebook about the design of low-exergy technologies; new concepts/system solutions and recommendations for innovative strategies and policies
(IEA, 2008)	Exergy metrics for performance and sustainability	Exergy tools for building design and performance assessment; demonstration projects; framework for policy measures
(Sakulpipatsin et al., 2005, 2010; Sakulpipatsin, 2008)	Exergy efficient building design	Method for exergy analysis of buildings; thermal exergy and energy demand/losses in HVAC systems
(Schmidt D., 2003; Tolga Balta et al., 2008; Schmidt, 2009)	Overall energy chain analysis	Methodology based on a pre-design analysis tool; energy and exergy flows investigated from power plant to building envelope
(Ozgener and Hepbasli, 2005; Ozgener et al., 2006, 2007; Ozgener and Ozgener, 2009, 2010)	Geothermal district heating systems	Exergy efficiencies; exergy flow diagrams; exergoeconomic analysis; reference state sensibility
(Kilkis, 2007, 2012)	Exergy concerns on net-zero buildings	Two case studies; net-zero exergy building concept; exergy-aware energy chain for greater sustainability in green cities of the future

2.5. Energy-exergy performance indicators

In this section, a review on exergy based indicators for building analysis was conducted. The Directive 2010/31/EU (EU, 2010) proposes that energy performance of buildings shall be clearly expressed by an Energy Performance indicator relating the primary energy use or CO_2, which are calculated by means conversion factors per energy carrier. Far from being fixed, these indicators are dependent on particular conditions of a country and huge variations are expected on account of differences on the share of renewable energy in the energy supply systems at a global scale. Additionally, they are only based upon the first law principles, neglecting any issue concerned with quality or exergy quantities. To overcome these issues, different types of indicators have been proposed. Kanoglu et al. (2012) define efficiency as a measure of effectiveness and/or performance of a system, which may take different forms and designations, depending on the type and objective of the analysis. The concept of energy efficiency is usually applied and based on the first law of thermodynamic principles and may be simply described as the ratio of energy output to the energy input. In turn, the exergy efficiency is based on both first and second law of thermodynamics, and may be named as second law efficiency, exergetic efficiency or even effectiveness (Cornelissen, 1997). Similarly to other efficiency definitions, the exergy efficiency is defined as the ratio of the final (or useful) exergy output to the required exergy input. Usually, two types of exergy efficiencies are used: “simple/universal” and “rational/functional”. Detailed literature about these terms can be found in Kotas (1995), Cornelissen (1997), Bejan (2006), Torío et al. (2009). The main difference between these two exergy efficiencies is the way the exergy output is defined by (Kanoglu et al., 2012). The rational efficiency considers the difference between “desired output” and other kind of outflow from the system. In turn, the simple exergy efficiency considers any kind of outflow from the system. In most of buildings, undesirable outputs are presented (e.g. return flows of heat/cold systems), although the simple exergy efficiency works better when input/outputs flow are transformed into some kind of desired/required quantities (Kanoglu et al., 2012).

Boelman and Sakulpipatsin (2004) and Sakulpipatsin (2008) conducted a critical analysis of exergy efficiency definitions with better potential to be used in built environment. Having a simple heat exchanger operating near environmental conditions as case-study, Sakulpipatsin (2008) studied the sensitivity of both the simple and rational efficiencies to outdoor temperature, fluid inlet temperature and thermal effectiveness of the heat exchanger. As result, the study indicated that the rational efficiency is more sensitive to these parameters than the simple energy efficiency. Furthermore, the exergy efficiency has been also applied as an indicator for the performance assessment of buildings by the following authors: Zmeureanu and Yuwu (2007), Tolga Balta et al. (2008), Wei and Zmeureanu (2009), Xydis et al. (2009), Balta et al. (2010) and Bingöl et al. (2011).

Despite some attempts to use the exergy approach in legislative codes on energy performance of buildings, it has not been completely addressed. Favrat et al. (2008)

presented a description of the exergy efficiency, including exergy-based parameters for the new energy regulation of Geneva (Swiss canton). The authors exploited the use of exergy efficiency as a new parameter to characterize the exergy performance of buildings. For simplicity, the overall supply system was divided into a structure formed by four subsystems, including the room convector, the plant of the building, a possible district heating and cooling plant and an external power plant. In this proposal, the overall exergy efficiency is the chosen parameter to describe the performance of the building and its energy supply chain. Another benchmarking proposal for the assessment of the performance of energy building systems was done by Schmidt et al. (2007). The author defined the concept of “exergy expenditure figure”, which is calculated as the ratio of the exergy required at supply (effort) to the useful energy at demand (use) side. This parameter could be seen as a kind of quality factor (energy to exergy ratio) of the energy processes occurring at a given component (Torío et al., 2009). Some other exergy key indicators have been used to compare buildings and quality energy use and, in a certain way, information about sustainability (Cornelissen, 1997).

The sustainable development requires not only green and affordable supply sources, but also a right and efficient use of the resources. In this field, exergy analysis has revealed to be a very useful tool for improving the efficiency and sustainability (Cornelissen, 1997), reducing the use of resources and thus minimizing the undesired environmental effects. Rosen et al. (2008) defined the relation between exergy efficiency and sustainability through the sustainability index. Van Gool (1997) recommended the concept of “Exergetic improvement potential” to compare different processes or sectors in the economy. The maximum improvement in the exergy efficiency for a process or system is achieved when the exergy loss and irreversibilities are minimized (Hepbasli and Arif, 2008). Some other thermodynamic exergy related parameters were applied in the study of Xiang et al. (2004), namely the fuel depletion ratio, the relative irreversibility, the productivity lack, the productivity lack and the exergetic factor.

2.6. Exergy analysis of CHP plants

Micro-combined heat and power (MCHP) systems have been investigated as an emerging technology with a high potential in residential and commercial sectors. Despite, the current scenario characterized by technologic improvements on electricity power plants, and the high integration of renewables into electric current grids, some doubts exist about the advantages of cogeneration systems. Analyses of performance covering several MCHP units, coupled with an extensive model development and testing work were conducted within the International Energy Agency (IEA) Annex 42 by Ferguson (2005), Beausoleil-Morrison and Ferguson (2007), Sasso et al. (2007) and Beausoleil-Morrison (2008). Additionally, several studies on energy performance of cogeneration systems were review. Rosato and Sibilio (2012) calibrated and validated the performance of a 6 kW_{el} MCHP unit, Kelly et al. (2008) elaborated an approach to model a domestic microcogenerator using a building simulation tool and Roselli et al. (2011) reported the energetic, economic and environmental implications of using small scale cogeneration systems, by means of an experimental research activity performed by the authors and other researchers. These studies are however based on methods involving only first law principles. In addition, involving both first and second laws of thermodynamics, the following studies were reviewed: Abusoglu and Kanoglu (2008) performed a thermodynamic analysis of an existing diesel engine cogeneration system; Kanoglu and Dincer (2009) assessed various building cogeneration plants through energy and exergy efficiencies, and Gonçalves et al. (2011) made a comparative study between a MCHP and a reference system, using actual energy demand data of a student housing building located in Coimbra (Portugal). Some other studies reviewed about exergy analysis of CHP systems are summarized in Table 4.

Table 4: Review studies on the use of exergy for CHP plants.

Reference	Scope	Main features/outcomes
(Smith and Few, 2001)	Second-law analysis cogeneration plant and heat pump	Exergy analysis to assess the plant performance and indicate areas of improvement
(Rosen et al., 2005)	Cogeneration-based district energy systems	Energy and exergy efficiency analysis; Case study in Edmonton, Canada; Exergy efficiencies found to be more meaningful
(Balli et al., 2007)	Performance evaluation of CHP system in Turkey	Ways to improve the exergy efficiency of this system; Exergy balance for each component and whole CHP system.
(Ertesvag, 2007)	Comparison of energy and exergy indicators	Limitations of legislative regulations; Relative avoided irreversibility; Industrial cogeneration cases studies.
(Kanoglu et al., 2007)	Performance assessment of building cogeneration systems	Exergy analysis revealed to be an useful tool; Allows meaningful comparisons of different cogeneration systems.
(Barelli et al., 2011)	Cogeneration systems based on fuel cells	Performance evaluation of the optimal operating conditions that ensures the most efficient use of the energy and exergy inputs

2.7. Exergy analysis of desiccant cooling systems

Desiccant Cooling Systems (DCS) are heat-driven systems designed to provide cooled and dehumidified air for indoor environments. They can be used as an alternative or complement to conventional vapour compression or absorption cooling systems. Several research works involving DCS have been conducted in the last years. La et al. (2010) studied a modified regenerative evaporative cooling coupled with a rotary desiccant cooling process, delivering both dry air and chilled water simultaneously. Furthermore, Angrisani et al. (2010, 2011a, 2011b, 2011c, 2012) conducted a set experimental-based studies on small scale poly-generation system, constituted by a natural gas microcogenerator connected to a desiccant cooling system. The authors experimentally assessed the parameters and technical features of the system components, and calibrated a model of the system in TRNSYS (Klein et al., 1976).

Most of the studies reviewed are designed based on an energy approach, nevertheless thanks to the growing interest towards exergy methods, the exergy concept has been applied to DCS. In Table 5, the main exergy analysis studies reviewed on heat-driven DCS are presented. As shown, the exergy analysis has been mostly applied for performance assessments, to evaluate the potential for improvement and to locate irreversibilities sources.

Table 5: Review studies on the use of exergy for heat-driven desiccant cooling systems.

Reference	Scope	Main features and outcomes
(Lavan et al., 1989)	Second-law analysis	Introduction of an equivalent Carnot temperature for evaluating the reversible *COP*
(Kanoglu, 2004)	Experimental open-cycle Desiccant cooling system	Exergy destruction and exergy efficiency Theoretical performance system limit; Identification and quantification of the exergy losses
(Hürdoğan et al., 2011)	Exergetic modelling and experimental performance assessment	Exergy efficiencies of the system were determined to assess individual performances and potential for improvements

3. Methods

3.1. Overview

In this section, the methodology adopted in this doctoral research is described. Despite constituted by different case studies, its main structure is common and constituted by three main blocks (A, B and C), as shown in Figure 3. The left and right arrows characterize the exergy requirements at supply and demand side, respectively. Their relative dimensions show that the exergy supplied to a system is always higher than exergy at demand (useful), as occurs in actual energy conversion systems, where part of the exergy input is irretrievably lost due to irreversibilities (exergy destruction). In Table 6, the main points, targets and tools involved in the blocks A, B and C are described in detail.

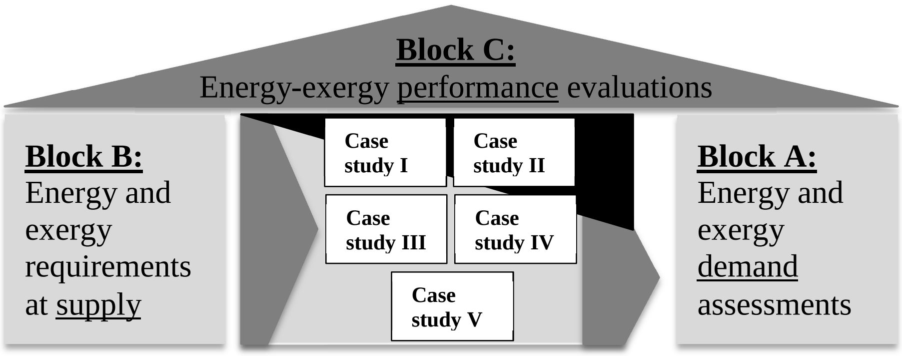


Figure 3: Main structure adopted by this research work.

Table 6: Description of topics, targets and methods addressed by the Blocks A, B and C

Block A: Energy and exergy demand assessments	
Topics	- Evaluate the energy and exergy demand (useful) for different building end uses; - Distinguish thermal, mechanical and chemical energy forms; - Evaluate the exergy requirements for different reference environments states.
Targets	- Building end uses (space heating and cooling; domestic hot water; electric appliances; food preparation); - Delivered heat and electricity (cogenerated or produced separately); - Moist air flows.
Tools	- Energy assessments: energy audits, energy utilities bills, simulated results, experimental data; - Exergy calculations: analytical methods based on thermodynamics fundamentals.
Block B: Energy and exergy supply requirements	
Topics	- Evaluate energy and exergy requirements at supply side; - Assess different sources according to their energy quality values; - Distinguish between primary-fossil and renewable energy sources.

Targets	- Fossil energy sources (e.g. natural gas, coal, fuel oil); renewable energy sources (biomass and biofuels; hydro, wind, solar, geothermal); low-temperature thermal sources (e.g. solar thermal).
Tools	- Energy assessments: energy audits, energy utilities bills, simulated results, experimental data; - Exergy calculations: analytical methods based on thermodynamics fundamentals.
Block C: Energy-exergy performance evaluations	
Topics	- Comparing energy and exergy indicators for performance assessments; - assessing thermodynamic inefficiencies (exergy destruction); - Finding indicators for potential improvement of energy systems.
Targets	- Building end uses; - Buildings as a whole; - Micro-combined heat and power; - Desiccant cooling systems; - Components of a desiccant cooling system.
Tools	- Energy-exergy indicators: Primary energy ratio; Primary energy demand; Exergy efficiency; Primary Exergy Ratio; Exergy efficiency. - Parameters for potential improvement: Exergy efficiency defect; Relative irreversibility rate; - Parametric and sensitivity analysis.

Based on these three blocks, five main case studies were performed and applied to different scales, from single energy systems to buildings as whole. The methods followed by each case study are following presented. Furthermore, a summary-table of the main indicators and related definitions used by each case study is presented in Table 7.

Table 7: Main indicators addressed in each case study.

Indicator	Definition	Mathematical Formula
Case study I		
PER	**Primary Energy Ratio:** Ratio of useful energy for space heating to the primary-fossil energy supplied	$PER = \frac{\dot{Q}_{H,iv}}{\dot{E}_p}$
$PExR$	**Primary Exergy Ratio:** Ratio of useful exergy for space heating to the primary-fossil energy supplied, evaluated as exergy values.	$PExR = \frac{\dot{E}x_{iv}}{\dot{E}x_p}$
$\dot{I}_p$	**Primary Irreversibility rate** (whole supply chain): difference between primary exergy supplied and exergy desired at the last sub-system of the supply chain.	$\dot{I}_p = \dot{E}x_p - \dot{E}x_{iv}$ $\dot{I}_p = \dot{E}x_p\left(1 - PExR\right)$
Case study II		
EP	***EP* indicator:** Specific primary energy demand per square meter of floor area.	$EP = \frac{\sum_i E_{f,i} + W_{el,j}/\eta_{eg}}{A_f}$
PER_i	**Primary Energy Ratio** (final user, *i*): Ratio of the useful energy to the primary energy supplied, related to the final user *i*.	$PER_i = \frac{E_{u,i}}{E_{p,i}}$
ψ_i	**Exergy efficiency:** Ratio of the exergy desired (output) to the exergy required (input), related to the final user *i*.	$\psi_i = \frac{Ex_{des,i}}{Ex_{req,i}}$

Case study III		
E_P	**Primary-fossil energy demand:** Sum of primary energy demand associated to each building final user, (excluding the fraction of heat produced by renewable sources).	$E_P = \sum_k F_{p,k}^f \frac{Q_{h,k}}{\eta_{hs,k}^f}\left(1-\varphi_{h,k}\right) + F_p^e \sum_k W_{e,k}$
ψ_{ove}	**Exergy efficiency:** Ratio of the (useful) exergy at building final user to the exergy supplied.	$\psi_{ove} = \frac{Ex_D}{Ex_S}$
EDR_k	**Exergy Destruction Ratio:** Ratio of the irreversibility associated to each final user and the total exergy supplied.	$EDR_k = \frac{I_k}{Ex_S}$
Case study IV		
PES	**Primary Energy Savings:** Relative primary energy difference between a cogeneration and a reference system for separate heat and electricity production.	$PES = 1 - \frac{1}{\eta_{e,chp}\frac{1-\varphi_{eg}}{\eta_{eg,f}} + \eta_{h,chp}\frac{1-\varphi_{hs}}{\eta_{hs,f}}}$
PIS	**Primary Irreversibility Savings:** Relative primary-based irreversibility difference between a cogeneration and a reference system for separate heat and electricity production.	$PIS = 1 - \frac{\dot{I}_{chp}}{\dot{I}_{p,ref}}$
TIS	**Total Irreversibility Savings:** Relative total irreversibility difference between a cogeneration and a reference system for separate heat and electricity production.	$TIS = 1 - \frac{\dot{I}_{chp}}{\dot{I}_{t,ref}}$
Case study V		
PER_{ove}	**Primary Energy Ratio:** Ratio of the cooling capacity to the total primary fossil energy input.	$PER_{ove} = \frac{\dot{Q}_c}{E_{p,vii} + F_{el}^p W_{el,iv}}$
ψ_k	**Exergy efficiency** (component, *k*): Ratio of exergy output (or desired) to exergy input (or required), associated to the component *k*.	$\psi_k = \frac{\dot{E}x_{out,k}}{\dot{E}x_{in,k}} = 1 - \frac{\dot{I}_k}{\dot{E}x_{in,k}}$
δ_k	**Exergy efficiency defect:** Ratio of exergy destruction at the *k*-th component to the total exergy input.	$\delta_k = \frac{\dot{I}_k}{\sum_k \dot{E}x_{in,k}}$
$I_{R,k}$	**Relative irreversibility:** Ratio of the exergy destruction at the *k*-th component to the total irreversibility ratio occurring in the plant.	$I_{R,k} = \frac{\dot{I}_k}{\sum_k \dot{I}_k}$

3.2. Case study I: Comparison of heating options in buildings

The objective of this case study is to assess the energy and exergy performance of different building heating options located at different outdoor environmental conditions. The advantages of the exergy analysis in comparison with the conventional energy approach are highlighted in this study. Eight different space heating supply options are compared and the related performance evaluated using energy and exergy-based indicators.

The heating load of the building for different environmental conditions was predicted by modelling and simulation using the software package TRNSYS, using different built-in weather files. The methodology follows an approach from "Demand" to "Supply" side, similarly to the pre-design tool developed by Schmidt D. (2003), although the current approach includes some new features, such as, renewables and non-renewable energy sources and considers the hourly heat load demand at building envelope (demand side). A schematic illustration of this approach is presented in Figure 4.

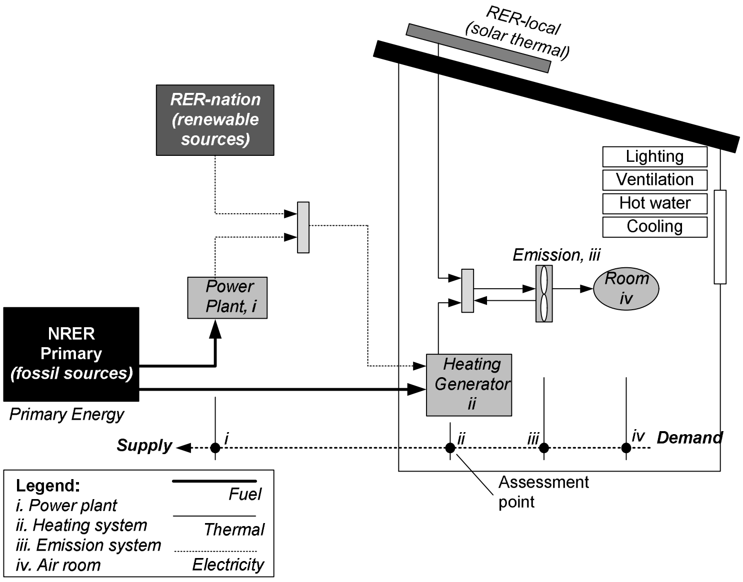


Figure 4: Schematic of the Case-study I methodology.

Each heating option is associated to the so-called "Energy Supply Network" (ESN) that is defined as a combination of four sub-systems: (*i*) power plant; (*ii*) heat generator; (*iii*) emission system; and (*iv*) room. The heat generator could be powered by electricity, fossil or renewable fuel sources. As summarized in Table 7, two main indicators were proposed and used in this study: the Primary Energy Ratio (*PER*) and the Primary Exergy Ratio (*PExR*). Additionally, the irreversibility rate occurring in each sub-system (*i*-*iv*) was also evaluated. More detailed information about the followed methodology, model characterization, operating conditions, indicators and characterization of each ESN can be found in **Research Paper I**.

3.3. Case Study II: Hotel building

3.3.1. Building description and methods

This case study involves an energy-exergy performance assessment of a four star hotel building located in Coimbra, Portugal. It has a maximum capacity of 180 guests, one hundred and twenty bedrooms and thirteen suites, distributed along seven floors. The hotel has 6531 m^2 of conditioned area, 3443 m^2 reserved for parking and 596 m^2 for other non-useful areas. The HVAC plant is constituted by a natural gas boiler, providing heat for space heating and Domestic Hot Water (DHW), and an air-to-water chiller for the space cooling requirements of the hotel. Additionally, some individual Air Conditioning (AC) units are installed, working as auxiliary systems of the central system, mainly used for space cooling. Air handling units and extraction fans are installed in the roof of the building, ensuring the air quality requirements. A detailed energy audit was conducted regarding to identify the energy consumption patterns of the building and the related breakdown by final users. The energy audit is a procedure recommended by the Portuguese building certification scheme (RSECE, 2006) aiming to evaluate the energy performance of buildings. Figure 5 shows a scheme of the main end users and energy flows considered in this analysis.

3.3.2. Energy and exergy indicators

Three main indicators were used in this analysis: Primary energy consumption (*EP*), Primary Energy Ratio (*PER*) and exergy efficiency. *EP* is given by the annual primary energy consumption of the building per unit of floor of the conditioned area. Different primary energy factors are applied depending of source type (e.g. natural gas) or energy carrier (e.g. electricity). These indicators are summarized in Table 7 and detailed presented in **Research Paper II.**

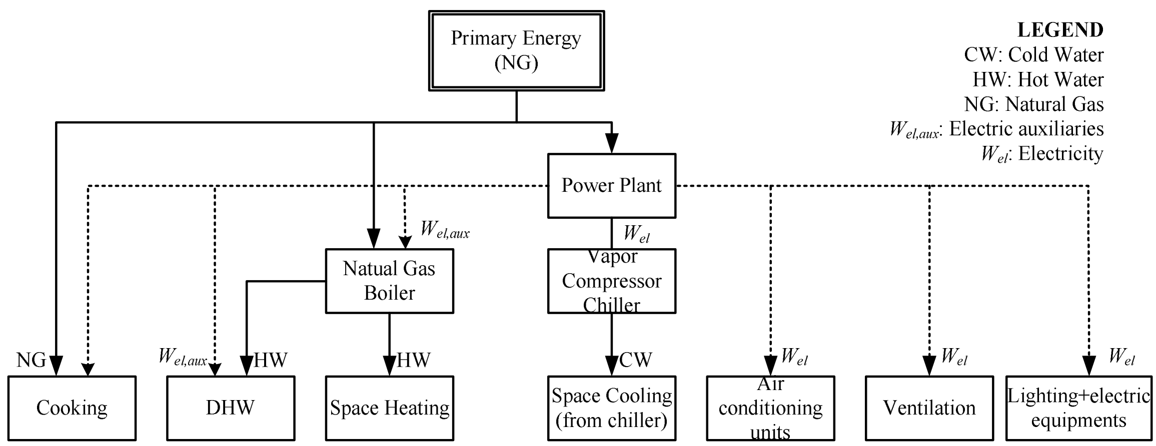


Figure 5: Schematic of the Case-study II methodology.

3.4. Case Study III: Student housing building

In this case-study, the student housing building shown in Figure 6 was studied using principles based on both first and second laws of thermodynamics. Actual energy consumption data derived from utilities bills (natural gas and electricity) and information about the efficiencies of the installed systems were used to estimate the energy demand of each building end use (space heating, domestic hot water, food preparation and electric appliances). The building performance was described using energy and exergy indicators. The contribution of each building end use for the overall inefficiencies was also evaluated, using the indicator “Exergy Destruction Ratio”, as defined in Table 7. Additionally, a set of alternative supply options were proposed regarding to compare them from energy and exergy perspectives. The methodology proposed in this study follows an approach from the “demand” to the “supply side”, where the demand is evaluated at building end uses and the supply is evaluated at fossil or renewable energy inputs.

Figure 6: Student housing building, Campus II, University of Coimbra (Case study III).

3.4.1. Building description and key indicators

The student housing building is located at Campus II of University of Coimbra and has an overall conditioned area of 1807 m^2. The building has a rectangular shape, with main facade south-oriented. Each floor is composed by a kitchen, living room, a study room and eighteen double bedrooms (with a private bathroom). The building has a maximum capacity of 144 students and operates 24 hours per day. The building is closed in August, on account of the calendar holidays. Natural gas is the main energy source used for space heating requirements, domestic hot water and food preparation. Electricity is exclusively used for lighting and other electric appliances. Concerning the primary energy assessments, natural gas was assumed as primary-fossil energy source. On the other hand, the primary energy factor associated to electricity production was estimated based on actual Portuguese electric grid performance.

In this study, three main performance indicators were assessed: the Primary Energy Ratio (*PER*), the exergy efficiency and the exergy destruction ratio. As defined in Table 7, *PER* gives information about the ratio between useful energy to the total primary energy input, the exergy efficiency measures the exergy performance of the building, providing information about the irreversibility degree that occurs in the building conversion processes, and the exergy destruction ratio is defined as the ratio of irreversibility associated to each end use to the total exergy input, aiming to identify and locate the building end users by inefficiencies. Detailed formulations of these indicators are reported in **Research Paper III**.

3.5. Case Study IV: Micro-cogeneration technologies

3.5.1. MCHP description and research approach

In this case study, the schematically 6 kW_{el} MCHP unit presented in Figure 7 was experimentally tested and its performance compared with a set of different heat and electricity supply options, including the actual electric mixes of Portugal and Italy.

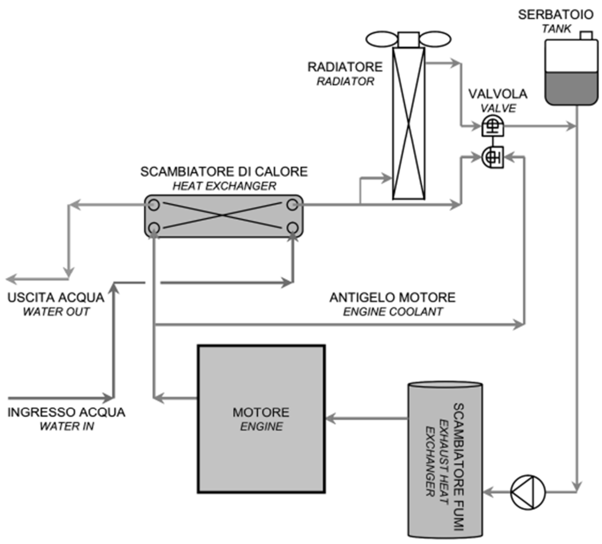


Figure 7: Schematic of the internal circuits of the cogeneration system under analysis.

The unit is powered by a three cylinders water cooled internal combustion engine that has a displacement volume of 952 cm^3. The engine is connected to an electronically controlled 16 poles synchronous generator, with an inverter automatically synchronized in phase and frequency. The electrical output can vary from 0.3 to 6 kW according to the user's demand in electric following mode. The manufacturer indicates a rated heat output rate of 11.7 kW (considering 33.5 litre per minute water flow rate, with supply and return temperatures of 65 ºC and 60 ºC, respectively). The heat is recovered from exhaust gases and engine jacket, being afterwards transferred to an external water flow circuit in a plate heat exchanger.

Additionally, a schematic layout of the comparative analysis done between the cogeneration and reference system (separate electric and heat system) is shown in Figure 8. This analysis is exclusively designed for CHP systems powered by primary-fossil energy sources, however the reference (separated electricity and heat production) may be fuelled by both fossil (FS) and renewable sources (RS). The MCHP performance was experimentally tested for different electric-heat loads and operating temperature conditions. The reference was assumed to have different share of renewable sources, efficiencies and delivered temperatures.

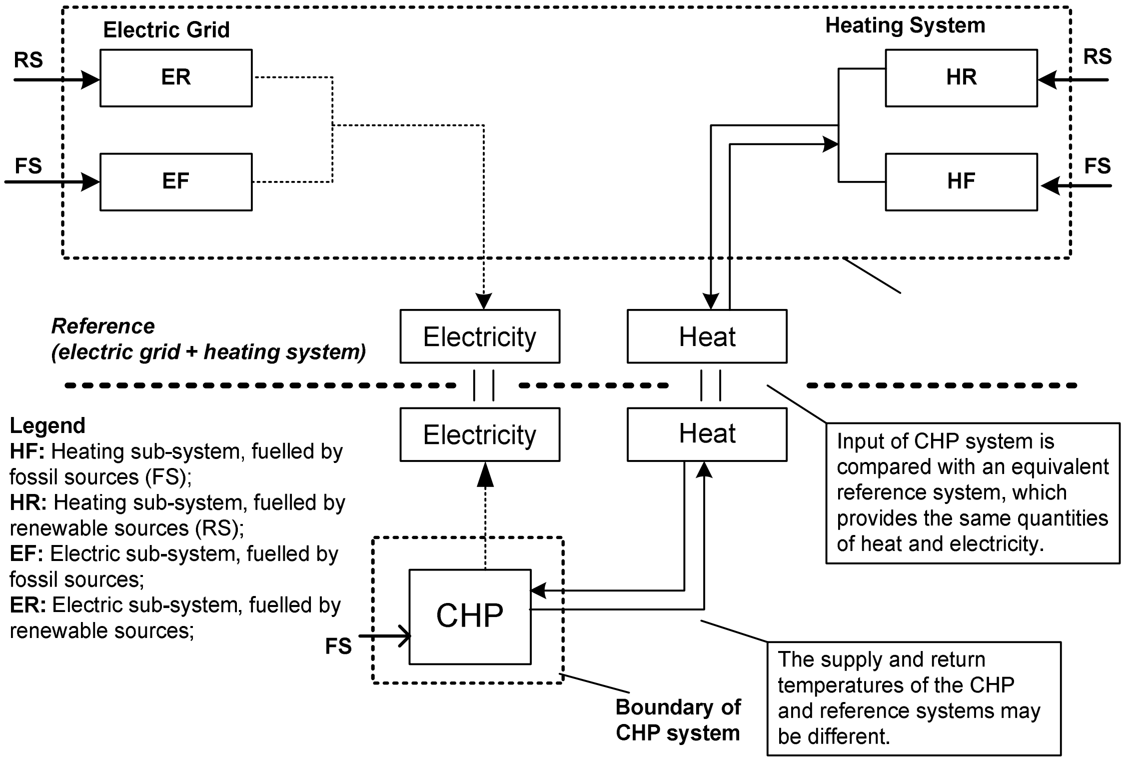


Figure 8: Schematic layout of energy flows and sub-systems considered in Case-study IV

3.5.2. Main proposed indicators

The main three indicators *PES*, *PIS* and *TIS* in use in this case study are presented in Table 7. The main objective of this analysis is to reveal the limitations of the current indicator *PES* and show particular examples where the indicators based on first and second laws of thermodynamics (*PIS* and *TIS*) can provide significant or even exclusive information for the comparison of cogeneration and separated heat and electricity production systems. *PES* is proposed by the European Directive 2004/8/CE (EC, 2004) and quantifies the primary energy savings of cogeneration relatively to the reference system. On the same order, *PIS* and *TIS* compare the relative irreversibilities (or inefficiencies) savings of a CHP with an equivalent reference system. The irreversibility concept is widely used in exergy analysis and it is related to part of exergy supplied that is destroyed (not recovered) in conversion processes. Regarding the assessment of the energy and exergy performances related to renewable sources, two additional indicators are also applied: the Energetic Renewability Ratio (*EnRR*) and Exergetic Renewability Ratio (*ExRR*). More detailed information about these two indicators can be found in **Research Paper IV**.

3.6. Case Study V: Desiccant cooling systems

3.6.1. System description

In this case study, a Desiccant Cooling System (DCS) located at *Università degli Studi del Sannio* in Benevento (Italy) is studied. The DCS is constituted by a desiccant wheel, an air-to-air heat exchanger, an evaporative cooler, heating and cooling coils. As heating system, a natural gas boiler produces hot air for the desiccant wheel regeneration process. After pass through the desiccant wheel, the process air passes through the air-to-air heat exchanger and cooling coil, which is connected to a compressed chiller that produces cold water. The schematic layout of the DCS is shown in Figure 9.

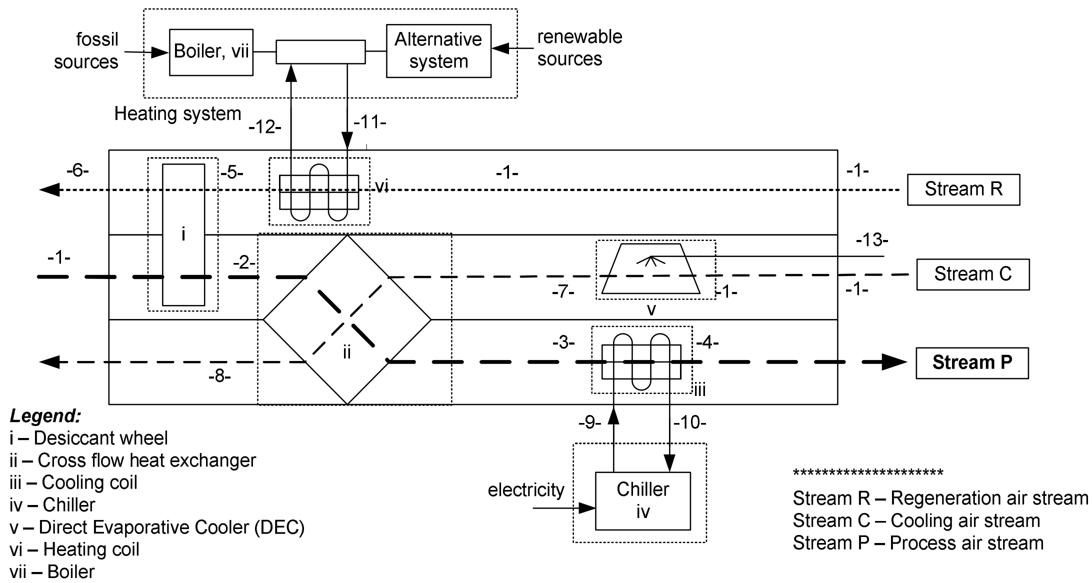


Figure 9: Schematic view of the desiccant cooling system.

The system is divided into seven components (*i-vii*) and thirteen assessment points (1-13), where the specific properties of moist air are evaluated. Three main air flows (R, C and P) are represented: - "*Stream R*" is used for regeneration of the desiccant wheel (5-6). The air flow is warmed up in the heating coil (1-5), which is connected to the heating system (*vii*); - "*Stream P*" is the process air, which is dehumidified in the desiccant wheel (1-2), pre-cooled at the cross flow heat exchanger (2-3) and cooled down for the desired temperature at the cooling coil (3-4); - "*Stream C*" is an auxiliary air flow used to pre-cool down the process air. It crosses an evaporative cooler at (1-7), absorbing heat from the process air at the heat exchanger (7-8).

3.6.2. Operation conditions and main parameters addressed

This study is focused on the period from 1st to 7th August (9h00 to 18h00), using the weather data corresponding to the city of Naples (Italy). Using averaged values in this period, the energy and exergy rates were estimated for the assessment points (1-13). The following energy performance parameters were addressed for the components of DCS: thermal efficiency and *COP* were calculated for the boiler and chiller, respectively; the effectiveness was estimated for the desiccant wheel, heat exchanger, evaporative cooler, heating and cooling coil. Similarly considering exergy, the exergy efficiency was assessed for all sub-systems of the DCS. In addition, a set of alternative heating systems providing the heat required for the regeneration process was also considered. They include high efficient (e.g. heat pump or cogeneration) or systems that make use renewable energy sources (e.g. solar thermal, waste). The overall performances of the DCS was evaluated by the indicators Primary Energy Ratio (*PER*) and exergy efficiency. More information about the methodology and mathematical formulations used in this study are detailed in **Research Paper V.**

3.7. Inter-Connection between blocks, case studies and research questions

In this section is made the inter-connection between the three blocks (defined in Section 3.1), the case studies and the research questions, previously addressed. The objective is to make easier understand the differences between case studies, and how they are linked with the main structure of the thesis. In Table 8 is summarized these inter-connections, where is shown that both fossil and renewable energy sources are usually considered at supply side (Block B); different energy final uses or energy sub-products are considered in Block A; and *PER* and exergy efficiency are the main indicators in use by all case studies (excluding Case study III). Concerning the research questions: RQ I is transversal to all the studies; RQ II is addressed in Case study II and III; RQ III is answered in Case study III and V and RQ IV is mostly replied in Case study IV.

Table 8: Inter-connections between case-studies, main topics addressed and research questions associated

	Block A	**Block B**	**Block C**	**Research questions**
Case Study I	Space heating	Fossil and renewable sources	*PExR*; *PER*	RQ I
Case study II	Space heating-cooling; DHW; food preparation; electric appliances	Primary-fossil sources	Primary energy demand; *PER*; Exergy efficiency	RQ I, II
Case Study III	Space heating; DHW; food preparation; electric appliances	Fossil and renewable sources	*PER*, Exergy efficiency; Exergy destruction ratio	RQ I, II, III
Case study IV	Heat and electricity rate delivered	Fossil and renewable sources	*PES*, *PIS*, *TIS*, energetic/exergetic renewability ratios	RQ I, IV
Case study V	Heating and cooling processes of moist air	Fossil and renewable sources; electricity	*PER*; Exergy efficiency; Exergy efficiency defect	RQ I, III

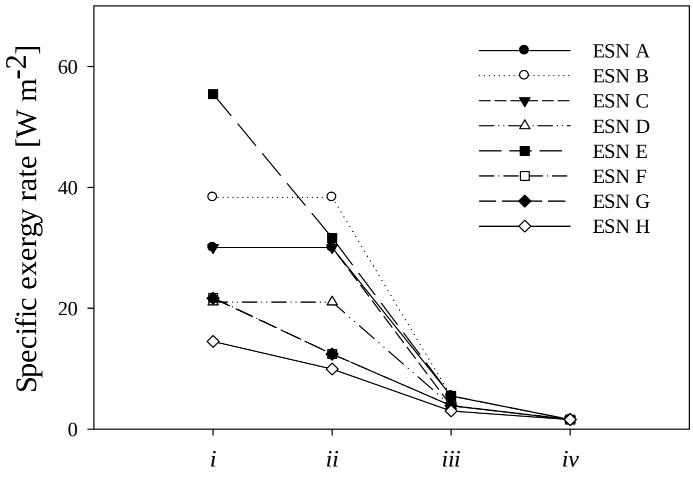
4. Results and Discussion

In this chapter, the main results of the case studies conducted are presented. It is divided into five sections, each one corresponding to a given case study. Only the main outcomes were selected to be presented here, although the complete results and detailed discussions are presented in the Appendix in **Research Papers I** to **V**.

4.1. Case study I: Comparison of heating options in buildings

The exergy load at each component of the ESN, corresponding to the winter day 12th January in Coimbra, is presented in Figure 10. Each ESN is constituted by *i*) room air space; *ii*) emission system (high, medium, low temperature); *iii*) heating system (fuel or electric based) and *iv*) primary energy plant. This diagram provides information about the magnitude and location of the high exergy rates, occurring at each component (*i-iv*) of the ESN, quickly finding where the exergy differences (exergy destruction rate or high irreversibility rate) between components are higher.

Figure 10: Specific exergy rate at each component of ESN A to H (weather data corresponding to Coimbra on 12th January).



Comparing ESN A and B, the results indicate that most of the exergy losses occur in the conversion from the heating system, (*ii*) to the emission, (*iii*). However, from an energy perspective (as shown in Figure 11), relatively low energy losses occur in the same conversion, due to high energy efficiency of the heating system (95 % and 80 %, respectively). Moreover, comparing ESN E from both perspectives, the energy viewpoint indicates that the major inefficiencies occur at power plant, although as shown in Figure 10, similar exergy destruction occurs at both power plant and heat generator.

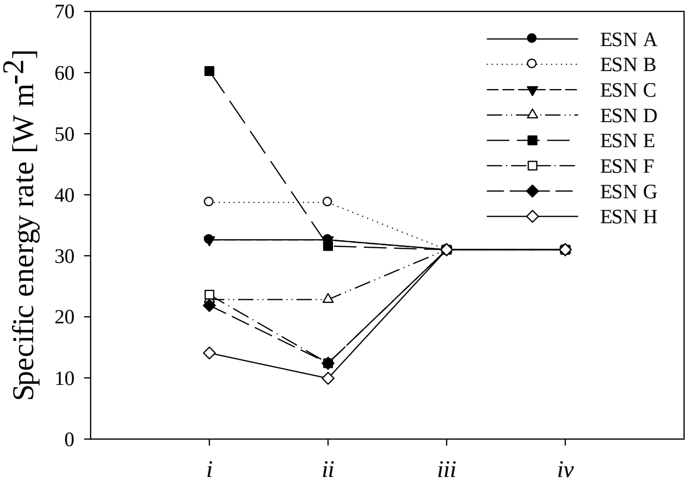


Figure 11: Specific energy rate at each component of ESN A to H (weather data corresponding to Coimbra on 12th January).

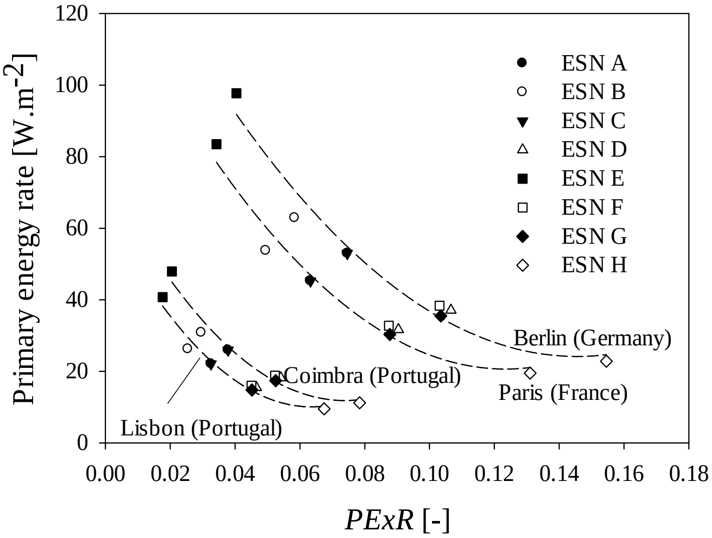


Figure 12: Specific primary energy rate as a function of *PExR* for ESN A-H in four different locations (averaged weather data of January).

In order to evaluate the relationship between primary energy demand and energy and exergy performance indicators, Figure 12 presents the primary energy rate as function of *PExR*. As shown, *PExR* depends of the outdoor conditions (that defines the reference dead state), however, the energy efficiency (*PER*) of each ESN sub-components is constant for different outdoor conditions (as shown in Section 5.2 of **Research Paper I**). As example, for the weather conditions of Coimbra, *PExR* of ESN H is about 0.08, while for Berlin *PExR* is about 0.155. The indicator *PExR* can be applied whenever possible for the performance evaluation of heating options in buildings, especially when different reference weather conditions are compared or when *PER* assumes the same value, not allowing the comparison between options.

Furthermore, the irreversibility rate at each sub-system was also assessed for January outdoors conditions at Coimbra, Lisbon, Berlin and Paris and is published in Section 5.3 of **Research Paper I**. For fuel based heating systems (ESN A-D), the highest irreversibility rate occurs at heat generator, while for electric ESN E, the irreversibilities are equally shared between heat generator and power plant. For the ESN with higher primary exergy demand (ESN E), the heat generator accounts for 49 % of total irreversibility, while the power plant and emission contributes with 44 % and 7.2 %, respectively.

4.2. Case Study II: Hotel building

In this section, the main results derived from the Case study II are presented. This case study aims to assess the overall energy-exergy performance of a hotel building located in Coimbra and the related performance associated to each final user.

The monthly energy demand associated to natural gas and electricity and related breakdown by energy end uses were obtained through an energy audit conducted in the building. The annual natural gas and electricity demand was estimated as 706 080 kWh and 250 628 kWh, corresponding to an estimated primary energy of 2 918 500 kWh. In Figure 13, the specific annual exergy demand and exergy efficiency associated to each building end use are shown. The electric equipments have the highest exergy demand, followed by the space heating and cooling and Domestic Hot Water (DHW) needs. Electric equipments, ventilation and food preparation (cooking) have the highest (primary) exergy performance, while the values associated to low-temperature air conditioning requirements are associated to very low-exergy efficiencies.

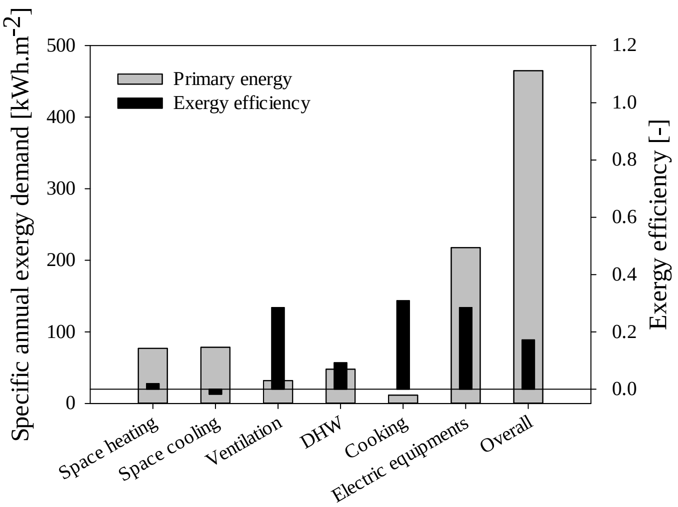


Figure 13: Annual primary exergy demand and exergy efficiency of hotel's end uses and building as whole.

The energy and exergy performance "picture" of the building, including relative information about the primary energy consumption, *PER* and the exergy efficiency of each building energy end use is shown in Figure 14. In this diagram, the differences between energy and exergy performances (*PER* and exergy efficiency, respectively) are easily identified, as well as, the higher contributors for the primary energy consumption of the building. In this building, the electric appliances (including lighting, ventilation and other electric devices) are the main primary energy consumption contributors of the hotel, are associated to a low-*PER*, although a relatively high exergy efficiency. In turn, the space heating and cooling have a high-*PER* value, although low exergy efficiencies. More detailed results may be found in **Research Paper II**.

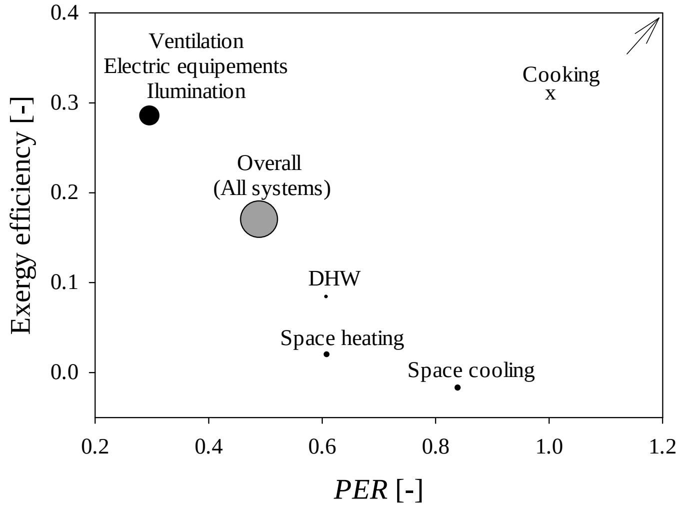


Figure 14: Exergy efficiency vs. *PER* diagram for Hotel´s end-uses energy consumers.

4.3. Case Study III: Student housing building

In this section, the main energy-exergy results of the student housing building handled in Case Study III are presented. The monthly energy breakdown by final user was predicted based on natural gas and electricity bills related to the year 2009, occupancy patterns, systems efficiency and other information provided by the technical staff of the building. The installed heating system is constituted by a boiler with 90 % thermal efficiency that satisfies the space heating and DHW requirements. Considering the estimated useful energy of each building final user, the primary energy demand and the related exergy supplied are compared for the actual supply chain and for a set of proposed alternative options.

The energy and exergy performances were evaluated using the indicators *PER* and exergy efficiency, respectively. The results show significant differences between primary energy and exergy performances. Thus, high *PER* values are obtained in the winter season, while high exergy efficiency values are obtained in the summer season. It occurs since the low-exergy requirements associated to space heating demand (in winter) are mostly fulfilled by high exergy sources (e.g. natural gas). On other hand, the exergy efficiency has its maximum value in July, corresponding to low-thermal loads together with high reference dead states.

As overall results, the annual primary energy demand of the building is 353 kWh m^{-2} and the overall annual exergy efficiency is 27 %. For an ideal match between exergy levels of supply and demand, the ideal exergy performance was defined as 100 %. Therefore, for this building, the difference between the current and an ideal building reveals a potential for improvement at about 73 %. Having such high value, a possible question arises "What is the contribution of each building end use or task for this level of inefficiencies?" This question can be answered through an indicator named Exergy Destruction Ratio (*EDR*), where the corresponding results are presented in Figure 15. The results show that in winter season, the main contributors for building inefficiencies are the space heating, followed by hot water needs and electric appliances. Even though the fact that space heating and hot water preparation are produced in the boiler that has a high energy efficiency (90 %), the exergy analysis indicates them as the lowest exergy efficient end users, because it applies of high exergy sources to perform low-temperature required tasks. *EDR* is found as a significant indicator able to identify the most important contributors for the building inefficiencies, helping to find their locations and potential for the overall improvement.

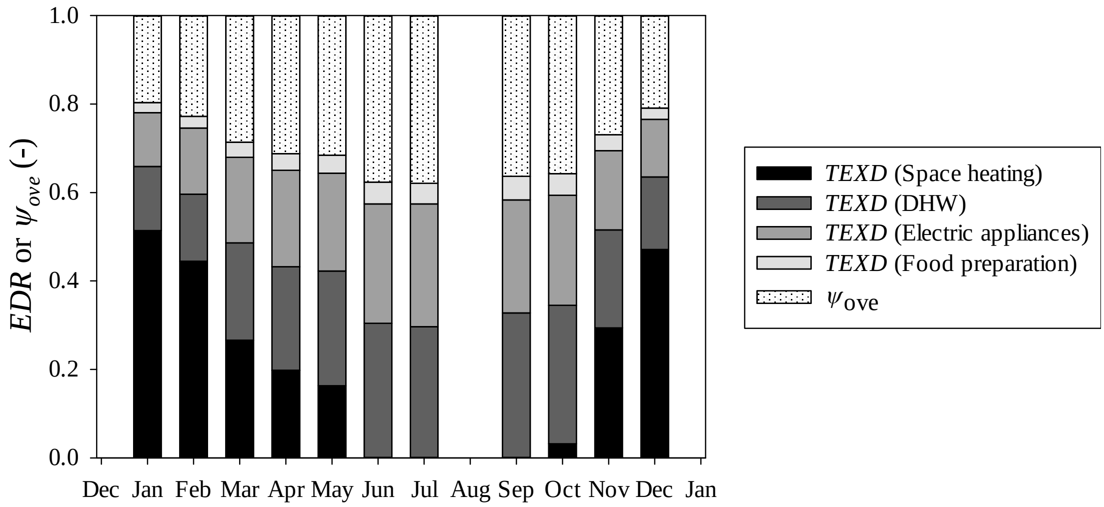


Figure 15: Exergy efficiency and *EDR* related to the end uses of the student housing building.

Furthermore, the proposed alternative supply options are presented in Table 9 and the corresponding primary energy demand and exergy efficiency results are shown in Table 10. Concerning the energy building benchmark scheme in Portugal, the primary energy demand is commonly compared with a given reference value that is defined by a legislative code. For student housing buildings in Portugal, the reference value is 220 kWh m^{-2} (RSECE, 2006). Following a similar approach for the exergy analysis and assuming 100 % as reference, the lowest primary energy demand scenario (B-IV) presents a value close to the reference (240 kWh m^{-2}), while the related exergy efficiency is only 33 %, therefore far from the ideal scenario. These results indicate that assessing buildings exclusively by a simple primary energy analysis is not enough for a complete description of the overall performance. Moreover, the exergy efficiency was identified as a possible indicator to be included in future energy performance benchmarks of buildings and able to rank similar scenarios from both primary energy and exergy viewpoints. More detailed results can be found in **Research Paper III**.

Table 9: Description of the different alternative supply scenarios for the student housing building.

Scenario	Description	Parameter
A-I	Integration of renewable sources into the electric system	$\varphi_e = 0.0$
A-II		$\varphi_e = 0.2$
A-III		$\varphi_e = 0.4$
A-IV		$\varphi_e = 0.6$
B-I	Fuelled-based heating system	$\eta_{hs} = 0.80$
B-II		$\eta_{hs} = 0.92$
B-III	Electric-based heating system	$\eta_{hs} = 0.98$
B-IV	Air source heat pump	$\eta_{hs} = 2.50$ (COP)
C-I	Integration of renewables into the heating system	$\varphi_h = 0.10$
C-II		$\varphi_h = 0.20$
C-III		$\varphi_h = 0.50$
D-I	Space heating decreasing	$Q_h =$ - 20 %
D-II		$Q_h =$ - 40 %
D-III	Space heating increasing	$Q_h =$ + 50 %
D-IV		$Q_h =$ + 100 %

Table 10: Proposed scenarios ranked by primary energy use and related exergy efficiency.

Scenario	E_P (kWh.m^{-2})	ψ (-)
Reference	**220**	**1.00**
B-IV	240	0.33
C-III	254	0.34
D-II	309	0.30
A-IV	310	0.29
C-II	312	0.30
C-I	328	0.29
D-I	331	0.29
B-II	335	0.28
Student housing	**353**	**0.27**
A-III	353	0.27
B-I	379	0.26
A-II	388	0.26
B-III	391	0.21
D-III	408	0.24
A-I	427	0.25
D-IV	463	0.22

4.4. Case Study IV: Micro-cogeneration technologies

In this section, the main results of the comparisons performed in Case Study IV between MCHP and a reference separate heat and electricity production system are presented. *PES* iso-lines diagrams were built in order to quickly find scenarios, where the MCHP can result in primary energy savings relatively to the reference system. Additionally, the indicators *PIS* and *TIS* were compared for different scenarios, aiming to demonstrate by particular examples, the cases where their use is advantageous comparatively to the "conventional" *PES*. Considering MCHP unit operating at its maximum electrical power (6 kW) and the Portuguese and Italian electric grids as electrical references, Figure 16 shows *PES* and *PIS* for different fractions of heat (produced from renewable solar thermal). The scenarios PT-I to PT-III are related to the Portuguese electric grid, and the roman numbers I, II and III correspond to different renewable heat fractions produced by solar thermal panels of 0 %, 30 % and 60 %, respectively. The main heating system is the same – a natural gas boiler, with 90 % efficiency. The same assumptions are applied for the scenarios IT-I to IT-III, but assuming the Italian electric grid as reference. Comparing PT-I and IT-I, *PES* presents a value about 10 % for Italian electric grid as reference, and 3 % assuming the Portuguese electric grid. Additionally, *PIS* presents different numerical values than *PES*, giving information about relative irreversibilities differences between MCHP and reference for different scenarios.

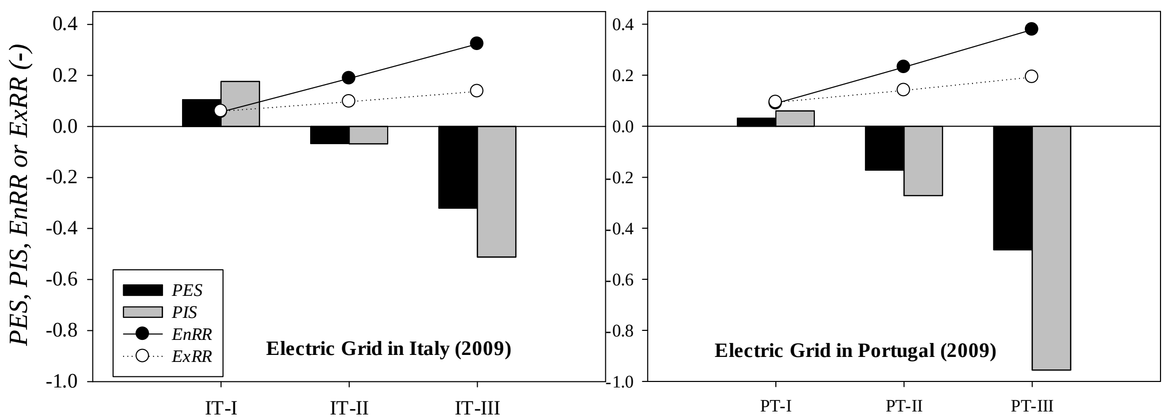


Figure 16: *PES*, *PIS*, *EnRR* and *ExRR* assessments assuming different fraction of heat delivered from renewables and considering the actual performance of electric grid of Portugal and Italy.

Finally, the Energy and Exergetic Renewability Ratios (*EnRR* and *ExRR*, respectively) provide information about the integration of renewables in the reference system, so the difference between *EnRR* and *ExRR* evaluates the energy quality of the renewables delivered by the reference system. In the current example, the obtained values indicate that low-quality renewable energy is being produced.

Depending on the heating system technology, different supply/return temperatures options are possible. Maximum temperatures are usually established for the different systems: boiler, air source or ground source heat pump and solar thermal collectors (IEA, 2008). Therefore, for similar thermal loads produced by different technologies, different exergy output levels may result. The same assumptions are still valid for the MCHP, although it operates under a very limited range of supply/return water temperatures. In the current analysis three levels of supply/return temperatures were tested for the MCHP: trial #1, 65/60 ºC; trial #2, 59/54 ºC and trial #3, 72/67 ºC. In Figure 17, *PES* and *PIS* are presented for all trials #1, #2 and #3, considering as a reference system an electric fossil efficiency, 52.5 % and a fossil-based heating efficiency, 90 %; both without inputs from renewables. Concerning *PES*, similar values are obtained for the trials #1 and #2, because similar MCHP performances were obtained for these two experimental tests. However, looking at *PIS*, since the heat is released at different temperatures for trial #1 and #2, *PIS* assume different values. For lower supply/return temperatures (trial #2) high irreversibilities are generated at MCHP, leading to low irreversibilities savings (*PIS*). The low thermal efficiency of the MCHP at trial #3 leads to a reduction of both *PES* and *PIS*, although trial #3 it is not comparable with two others, because *PES* is not the same. More detailed information and complete results are included in **Research Paper IV**.

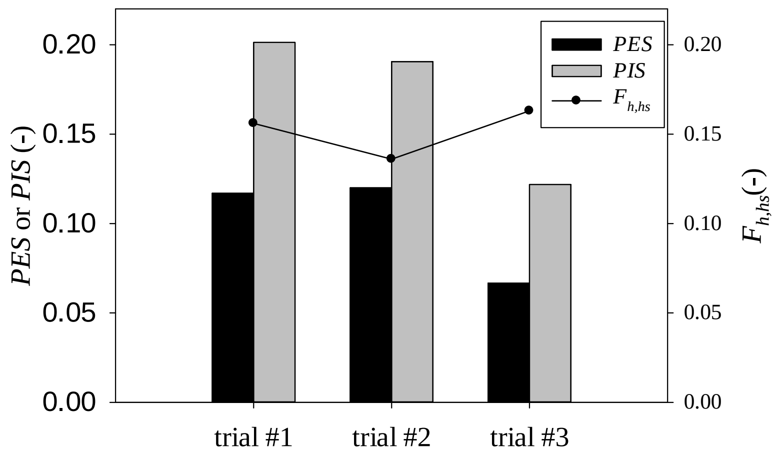
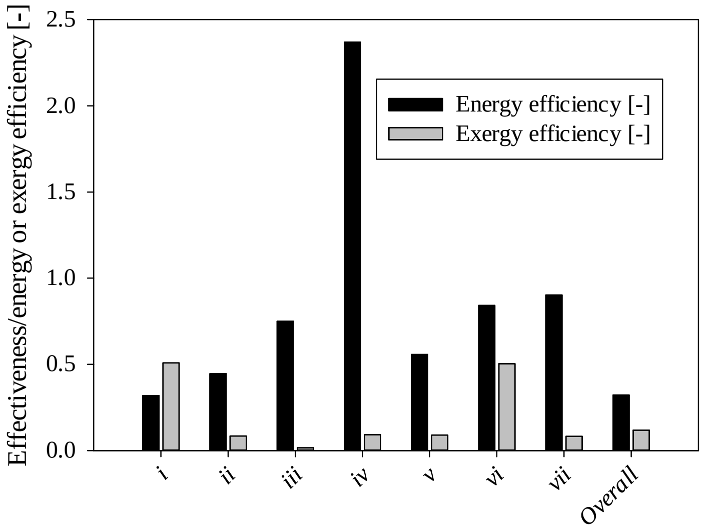


Figure 17: *PES* and *PIS* assuming the MCHP performance at part-load ratio 1 for trials #1, #2 and #3.

4.5. Case Study V: Desiccant Cooling Systems

The results of the analysis of a DCS are presented in this section and were derived from simulations performed for a summer week from 1st to 7th August, using the Meteonorm weather data for the city of Naples, Italy. During this period, the DCS unit operates from 9h00 to 18h00, with the outdoor temperature varying from 21 to 29 ºC and the humidity ratio from 0.008 to 0.017 kg/kg. The dead state was calculated based on averaged outdoor conditions during the period, T_0 = 26.1 ºC; ω_0 = 0.0114 kg/kg and p_0 = 101 325 Pa. The energy and exergy-based efficiencies were calculated for all sub-components of the DCS and huge differences were found, as shown in Figure 18.

Figure 18: Energy and exergy efficiency of sub-components of DCS and overall system.



Despite the fact that the exergy efficiency indicator identifies the most inefficient components of the plant, this indicator alone is not sufficient to identify and assess the individual contribution of each one for the overall inefficiencies of the plant, since each one has different exergy inputs. In this way, the parameter Exergy Efficiency Defect was applied. The results derived from its application to all components of the DCS are shown in Figure 19, showing that the most inefficient component of the plant (higher exergy efficiency defect) is the boiler (69.0 %), followed by the chiller (12.3 %) and the heating coil (3.1 %). The overall exergy efficiency defect is about 88.2 %, indicating a huge potential for improvement. Therefore, concerning the exergy performance improvement of the plant, the results indicate that the boiler should be the first component to be replaced.

Additionally, a set of additional scenarios were proposed to evaluate the energy-exergy performance differences among heating technologies, including those fuelled by renewable sources. The results show that there are options which make lower use of primary-fossil energy sources, although do not necessarily correspond to high exergy efficiency scenarios. Moreover, when high efficient heating systems are considered, the exergy efficiency defect indicates that the chiller becomes the most inefficient component of the plant. Considering the variability of the plant performance with the environmental conditions, the results show that the irreversibility rate is highly dependent of the inlet operating conditions, having its maximum value for high inlet/outlet temperature and humidity ratio differences (points 1 and 4). More detailed examples and discussions can be found in **Research Paper V**.

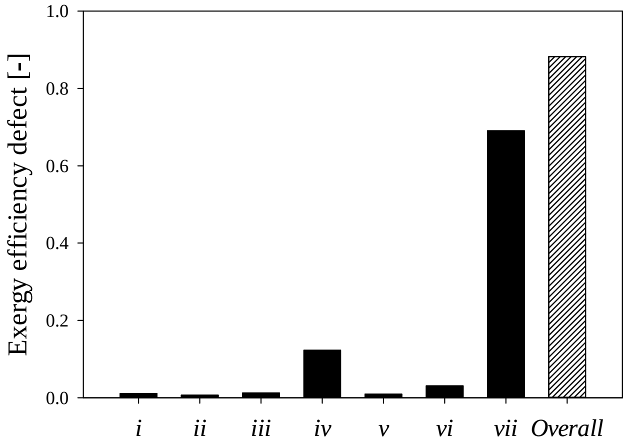


Figure 19: Exergy efficiency defect for the components (i-vii) of DCS.

5. Conclusions and further work

5.1. Contributions provided by this dissertation

The exergy topic has been applied worldwide, mostly in universities or research institutions, although on the scope of doctoral studies, this thesis is the first work addressing the topic “exergy analysis of buildings”, carried out at the University of Coimbra. This dissertation presents a set of new perspectives of using the exergy method to assess the energy performance of buildings and related energy systems, helping to identify and locate inefficiency sources and improve the rational use of energy in buildings. It is expected to overcome the established idea outside of the scientific community that the exergy methods are complex and do no provide significant add-value comparatively to the conventional energy methods. In this thesis, the exergy analysis method was mainly applied to buildings as a whole system, including a building hotel, a student housing building and a building simulated model. Concerning individual systems, it also involves the exergy performance of a DCS and a MCHP. New exergy calculation tools, methodologies and indicators were developed and applied through different case studies. The individual contribution provided by each one is following summarized.

The Case study I showed that the exergy-based performance indicator, *PExR* is more suitable to distinguish different heating options than the energy-based indicator, *PER*. Through the exergy analysis, it was also possible to assess in detail the irreversibility rate of each sub-component of the energy supply network that would not be possible using a simple conventional energy analysis approach.

The Case studies II and III showed how to evaluate the energy and exergy performance of buildings, using actual energy consumption data. The results were presented for the whole building and individually for each energy final user. The values of the exergy performance are very low, especially for end uses with low-temperature heat requirements (e.g. space heating and DWH), notwithstanding they are usually associated to high energy efficiencies (e.g. condensing boilers or heat pump systems). The use of renewable sources may reduce effectively the levels of primary energy demand, although may not conduct to high exergy performances. The use of diagrams “primary energy demand vs. exergy efficiency” allows to show the differences from both perspectives in a better way, clearly identifying the most important contributors of the building inefficiencies.

In Case study IV, the values of the exergy-based indicators developed to compare cogeneration and separated heat and electricity production systems are discussed. Through a set of particular examples, an experimental tested MCHP unit was compared with different reference scenarios, demonstrating how exergy-based indicators are different and significant relatively to the commonly used parameter, *PES*. Moreover, in the Case study V, the exergy method was applied to a DCS, providing information about the overall performance of the plant in the actual setup, and considering other alternatives for the desiccant wheel regeneration. Through the indicator "exergy efficiency defect", it was also possible to assess the irreversibility levels that occur in each component of the plant and thus identify the most inefficient components of the plant.

The multi-effect of this research includes the share of knowledge among the scientific community through the published journal papers and attended conferences, the development of new skills, including the use of modelling and simulation tools, data energy analysis, and practice in experimental and analytical methods. Moreover, it is expected that the indicators developed may be applied or at least their use recommended in future legislative frameworks on energy performance of buildings.

5.2. Answers for the research questions

The answers to the four research questions formulated in the Section 1.3 are following presented. Some of them are generic and related to all case studies, and others more directed to a particular one.

RQ I *How to demonstrate that the exergy can be a significant method able to provide meaningful or even exclusive information relatively to the conventional energy approach?*

The RQ I is entirely related to the overall objectives of this dissertation and consequently is transversal to all the studies. For example, the differences between energy and exergy indicators are highlighted in Case study I, when different ESN options are evaluated for different outdoor conditions. The energy ratios (*PER*) were assumed as constant for the different scenarios, while the related exergy-based index *PExR* changed according to the assumed "dead state" point. The results demonstrated that the use of exergy-based indicators allowed to distinguish different supply options, which would not be possible using purely energy-based methods. Also, in all the other case studies, the effective the effective advantages of the exergy relatively to energy approach were demonstrated.

RQ II *How to distinguish building energy end uses by means of energy and exergy performance and how it can contribute for the overall performance improvement of buildings?*

The RQ II is answered in Case studies II and III, where a building hotel and a student housing were examined. In Case study II, the differences between primary energy and exergy efficiency indicators of the various final users and for the building as a whole were highlighted. Moreover, in Case study III, the building was assess by means primary energy and exergy performance and its end uses were classified by the indicator *EDR*, helping to evaluate which of them can contribute more for the performance improvement of the building.

RQ III *How to evaluate and rank building energy end uses (or sub-components in multi-component systems) by irreversibilities levels and how to optimize their energy and exergy performance?*

The RQ III is entirely related with the irreversibility rate parameter and how it changes for the various building end uses or components of a stand-alone system. In Case study III, using the concept of *EDR*, the various building end uses were evaluated and ranked by inefficiency levels, helping to identify those that more contribute for the irreversibilities levels of the building. Additional, in Case study V, each sub-component of the DCS are also ranked by irreversibilities levels, using the concept of “exergy efficiency defect”, providing important information about the performance improvement of the plant.

RQ IV *Can exergy indicators be useful to the usually applied Primary Energy Savings (PES) for comparing cogenerated and separated heat and electricity production systems?*

The RQ IV is entirely related to Case Study IV, which aims to demonstrate the significance of using exergy-based indicators to compare cogeneration and equivalent reference heat and electricity production systems. In this study, a MCHP system was compared with a set of alternative reference scenarios, showing that exergy indicators (e.g. *PIS* and *TIS*) may provide more significant information not possible by the use of *PES*.

5.3. Unsolved issues and recommendations for future research

In this section, the main unsolved issues found in each case study and the recommendations for future research are addressed. The Case study I highlights the importance of the reference environment when different space heating options are compared. To easily understand the analysis, some simplifications were considered, although, in future studies a more complete approach is recommended, including efficiencies varying with outdoor environmental conditions, different envelope U-values, defined according the building codes of the country or region where the building is located; more detailed analysis, including moist air and chemical exergy considerations.

In Case study II and III, the energy and exergy performances of two different types of buildings and related final users are evaluated. For future research, more detailed energy audits should be conducted, especially concerned on a detailed energy breakdown by building final users and exergy requirements levels. Additionally, similarly to primary energy reference values for building benchmarks, also standard exergy efficiency values should also be defined. It would overcome the issue raised in Case study III, where was assumed as reference exergy efficiency 100 %, which may be too high and not realistic.

The Case study IV compared the energy and exergy performance of cogeneration and separated heat and electricity production system. One limitation of those analyses is that the cogeneration system was assumed to be fuelled exclusively by fossil energy sources, despite the reference could be fuelled by both fossil and renewables. *PES* and *PIS* are able to compare levels of primary energy between the two systems, although for renewable-based cogeneration systems, alternative indicators should be defined.

As future work in Case study V, additional weather conditions should be considered (e.g. different dry bulb air temperature and relative humidity pairs) in order have more robust conclusions about the conditions where DCS are more suitable and identify the operating conditions that can maximize its both energy and exergy performance.

For closing, covering all the studies, it was demonstrated that the limitations of conventional energy methods can be overcome or significantly reduced following an approach based on exergy analysis. However, as further studies, more complex exergy analysis involving the trade-offs between exergy efficiency and cost of the system, usually so-called “exergo-economic” analysis is recommended, aiming to find the best compromise between energy/exergy performance and cost.

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Appendix

RESEARCH PAPER I

Comparative energy and exergy performance of heating options in buildings under different climatic conditions

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Comparative energy and exergy performance of heating options in buildings under different climatic conditions

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Abstract

The energy assessments of buildings are usually performed based on fundamentals of the First Law of Thermodynamics, especially concerned on quantitative energy aspects. This approach does not provide however a faithful thermodynamic evaluation of the overall energy conversion processes that occur in buildings and a more detailed approach should be followed. The exergy analysis is a useful method that combines First Law and Second Law perspectives and has been applied in many related engineering fields, such as, power plants analysis, CHP systems, heat pumps or building energy systems. In this study, the overall energy and exergy performance of eight space heating options are compared for different outdoor environmental conditions. The methodology follows an approach from demand (at building envelope) to supply side (primary energy supplied), assuming that each energy supply network (ESN) or heating option is divided into the following sub-systems: room, emission, heat generator and power plant. The related energy and exergy performance of each ESN are evaluated through the following indicators: primary energy ratio (*PER*) and primary exergy ratio (*PExR*). The results show that for similar primary energy performance, *PExR* may assume distinct values depending of outdoor environmental conditions. The highest energy efficient ESN has a *PER* of 2.2, while the related *PExR* changes from 7 % to 16 % for Lisbon and Berlin, respectively. Furthermore, the assessment of irreversibility rate associated to each ESN sub-system reveals that the inefficiency sources could be pinpointed and measured, leading to tangible suggestions for further improvements.

Keywords: Exergy analysis; TRNSYS; Primary energy ratio; Primary exergy ratio; Irreversibility rate.

Nomenclature

$\dot{E}$	Specific energy rate [W m^{-2}]
$\dot{E}x$	Specific exergy rate [W m^{-2}]
$f_{th,RER}$	Fraction of renewable energy resources for thermal production
$f_{el,RER}$	Fraction of renewable energy resources for electrical production
F_q	Quality factor [-]
$\dot{I}$	Irreversibility rate [W. m^{-2}]
PER	Primary energy ratio [-]
PExR	Primary exergy ratio [-]
$\dot{Q}$	Thermal load [W. m^{-2}]
T_0	Reference (dead) state temperature
T	Temperature [K]
$\dot{W}_{el}$	Specific electricity rate [W. m^{-2}]

Greek symbol

η	Energy efficiency

Subscripts

i	Power plant
ii	Heat generator
iii	Emission
iv	Room
p	Primary
ret	Return
s	Supplied
th	Thermal

1 Introduction

Since 1970s, many energy computational modelling tools and building energy codes have been developed, although mostly based on mathematical models based on First Law of Thermodynamics. The Energy Conservation Law states that energy is conserved in any energy conversion process and cannot be destroyed. However, from an engineering perspective, the conservation principle alone is not adequate to handle some important aspects related with energy utilization [1]. Therefore, the exergy is then employed as complementary method to the energy conservation principle. The exergy analysis applies the conservation of mass and energy principles together with the Second Law of Thermodynamics, concerning quantity and quality aspects of energy utilization [1-2].

Exergy is defined as the maximum theoretical work that can be obtainable from a system at a given specified state relatively to its reference (dead) state [1]. Alternatively, it may be defined as the magnitude of the minimum theoretical work required to bring a given system from a reference (dead) state to a given required one [1]. At the dead-state, the system is at the temperature and pressure of its environment or in thermal and mechanical equilibrium. There is no kinetic and potential energy relative to the environment, and it does not react with the environment (chemical inert). Unlike energy, exergy can be destroyed during an energy conversion due to the irreversibility nature of processes (such as, heat transfer throughout a finite temperature difference, friction, unrestrained expansion of fluids and others). Exergy analysis is a useful tool for achieving the goal of a more efficient energy-resource use and addressing the environmental impacts of the energy resource utilization, since it can provide information about the match between supply (e.g. fossil fuels) and energy demand (e.g. low-temperature space heating, domestic hot water) [3]. It provides the locations, types and true magnitudes of wastes and losses and rank them by the order of significance [4].

Some authors have evaluated the exergy in buildings and their related energy systems to identify their potential for improvement and understand some important aspects of the different building energy conversion processes [5]. The International Energy Agency (IEA) launched two international research projects related with exergy efficiency in buildings. The main objective of ECBCS-Annex 37 (Low Exergy Systems for Heating and Cooling) [6] is to increase the knowledge of the different exergy flows in buildings and find possibilities for further improvements in their final energy utilization. In the same line, under ECBCS Annex 49 (Low Exergy Systems for High-Performance Buildings and Communities) [7] a set of tools for exergy analysis of buildings were developed, providing guidelines, recommendations and best-practice examples for building designers, engineers or decision makers. Some other studies on this topic were conducted. Schmidt et al. [8], [9] and [10] proposed and applied a method based on a pre-design tool to design low exergy buildings. It can be applied to assess and compare different energy flows exist in buildings, distinguishing them according to their quantity and quality values, from supplied primary energy to its final utilization. A similar approach was also conducted by Balta et al. [11] that applied the exergy analysis method to assess and compare four different energy options for a building space heating application. The exergy efficiency of heat pump, condensing boiler, conventional boiler and solar heating was evaluated as 66 %, 3.31 %, 2.99 % and 12.64 %, respectively. Using the methodology based on a pre-design analysis tool developed in [6], Balta et al. [12] performed an exergy analysis of a low-exergy heating system from the power plant through the ground-source heat pump to the building envelope. The energy and exergy demand were quantified and the exergy destructions were investigated and illustrated throughout the overall system. Favrat et al. [13] developed a procedure to include the calculation of an exergy indicator for the “Canton of Geneva” in Switzerland to introduce the exergy concept in building energy codes. The overall system was divided into a supply structure formed by four sub-systems: room convector, plant of the building, a possible district heating and cooling plant and an external power plant. The exergy method has been also applied for the assessment of ventilation systems in buildings. Zmeureanu and Yuwu [14] studied the impact of separated mechanical ventilation system on the annual energy and exergy performance of several design alternatives of residential heating systems in Montreal (Canada). Wei et al. [15] applied the exergy analysis to variable air volume (VAV) systems in office buildings for air-conditioning. The energy and exergy efficiency and related equivalent-CO_2 emissions, associated to electricity generation of used by the VAV system were assessed and presented. Additionally, Lohani and Schmidt [16], Sakulpipatsin [17] and Gonçalves et al. [18] studied the combination of simulation tools with the exergy analysis.

In the previous studies [8-12], the energy and exergy method are used to assess or compare different energy options, showing differences between the energy and exergy performance indicators. However, and especially in the cases where the energy performance indicators fail, the importance of the exergy indicator to compared different energy options were not completely highlighted. Furthermore, the exergy analysis of hybrid systems (i.e. conventional systems + renewables), systems powered by electricity that may be partly generated by renewables (e.g. hydro, wind, solar) and other poly-generation systems have not been addressed, namely when different outdoor environmental conditions are compared. Taking into account the limitations found in the literature, this study aims to apply the energy and exergy method to assess the performance of different building heating options located at different outdoor environmental conditions. Furthermore, the advantages of the exergy approach in compare to the conventional energy method are investigated in this work. As a case study, eight different energy supply options for a building space heating are compared using energy and exergy indicators. A building model and eight different systems are modelled in TRNSYS simulation engine. Each option is simulated for different outdoor environmental conditions, using different weather files. The energy systems may be powered by both fossil and renewable sources. The primary energy and exergy demand, primary energy ratio (*PER*), primary exergy ratio (*PExR*) and irreversibility rates were calculated and compared for each proposed scenario.

2 The exergy method applied to HVAC systems

Schmidt [8] developed a methodology for exergy analysis of buildings based on an approach from demand to supply side. As demand, the author defined the useful energy demand required to satisfy the various energy building end uses (e.g. space heating tasks or hot water requirements), and as supply, the energy and exergy demand are evaluated at primary energy sub-system. Further studies [11-12, 16-17] also have used this method for energy and exergy steady-state calculations. In this study, the basis of this method was included into a model developed in TRNSYS, introducing some features, such as renewable and non-renewable energy considerations and dynamic assessment of the energy and exergy loads. The method is illustrated in Figure 1 and the related mathematical model is described in this section.

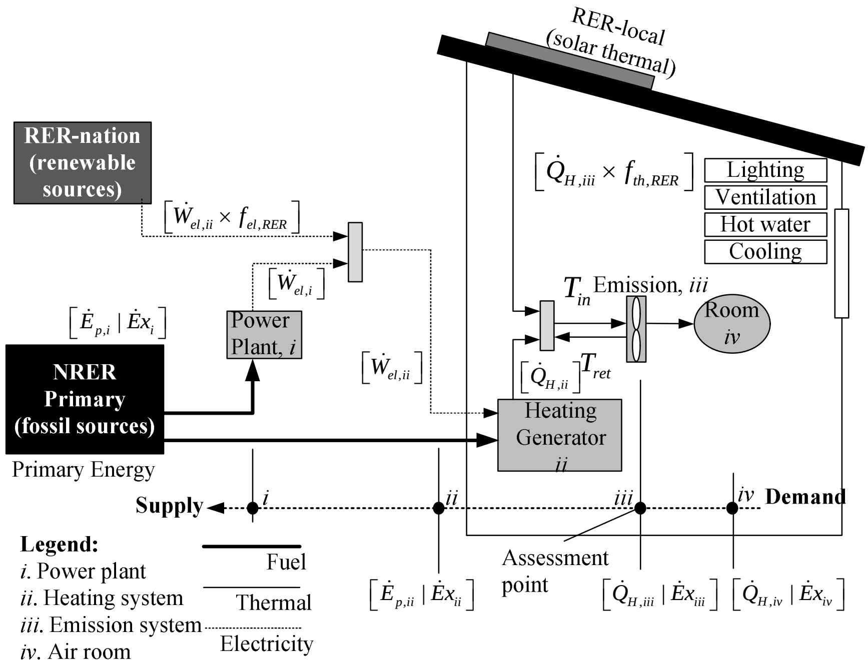


Figure 1: Schematic representation of the systems (i–iv) and their connections.

According to Figure 1, "Demand" corresponds to the thermal energy required for the space heating requirements of the building, assuming an indoor air temperature of 20 °C. "Supply" refers to the primary (fossil) energy demand, after efficiencies and energy losses of all sub-systems are taken into account. Each heating option is associated to a so-called "Energy Supply Network" (ESN), which is defined as a combination of four sub-systems: power plant (*i*), heat generator (*ii*), emission system (*iii*) and air room (*iv*). The heat generator could be powered directly by fuel or electricity, which is "generated" at the power plant (*i*). Two different energy resources are considered as the inputs: renewable energy resources (RER-local + RER-nation) and non-renewable energy resources (NRER), according to the schematic of Figure 1. In the current study, only primary energy flows derived from NRER were included into the energy and exergy assessments, therefore the integration of RER into sub-systems (*i*) or (*ii*) is only treated as reduction of demand associated to NRER.

In Figure 1, the room (*iv*) is the ultimate sub-system of the ESN, corresponding to the sub-system with the minimum exergy requirement to perform the space heating task. Conceptually, it corresponds to the mechanical work required to power a reversible heat pump device, operating between indoor and outdoor conditions. The evaluation of the exergy demand at room (*iv*), $\dot{E}x_{iv}$ is given by Eq. (1).

$$\dot{E}x_{iv} = \dot{Q}_{H,iv}\left(1 - T_0/T_{iv}\right) \quad (1)$$

where, $\dot{Q}_{H,iv}$ is the space heating load at room (*iv*), T_0 is the reference (dead state) temperature and T_{iv} is the required room air temperature (in this study, 20 °C was assumed). The heating load at room may be obtained by a static approach, using established conventional methods or, using dynamic simulation tools. In this study, TRNSYS 16 [19] was used to assess the hourly heating load of the building, using the weather data provided by the software's database, corresponding to different outdoor environments. The emission system (*iii*) corresponds to a conventional water-to-air heat exchange, usually called as "radiator" or "fan coil" in HVAC terminology. At this sub-system, no energy losses were considered, so from the energy conservation principle applied to the systems (*iii*) and (iv), $\dot{Q}_{H,iii} = \dot{Q}_{H,iv}$. Although, the exergy rate at the emission (*iii*) is given by Eq. (2).

$$\dot{E}x_{iii} = \dot{Q}_{H,iii}\left(1 - \frac{T_0}{\left(T_{in} - T_{ret}\right)}\ln\frac{T_{in}}{T_{ret}}\right) \quad (2)$$

where, $\dot{Q}_{H,iii}$ is the heating load at emission (*iii*), T_{in} and T_{ret} are the inlet and return water temperature, respectively, T_0 is the reference temperature. Since, there is not information related to the electric auxiliaries' loads were neglected by the current analysis.

The heating system at (*ii*) may be powered directly by fuels (including both fossil and renewable sources) or electricity. The energy supplied rate at (*ii*), $\dot{E}_{s,ii}$, is given by Eq. (3), where $\dot{Q}_{H,iii}$ is the thermal load at emission (*iii*), $f_{th,RER}$ is the thermal fraction derived from RER, and η_{ii} is the thermal efficiency of the heat generator (or COP, for heat pump technologies). From Figure 1, the thermal load produced by the heat generator (*ii*) is given by $\dot{Q}_{H,ii} = \dot{Q}_{H,iii}\left(1 - f_{th,RER}\right)$.

$$\dot{E}_{s,ii} = \frac{\dot{Q}_{H,iii}}{\eta_{ii}}\left(1 - f_{th,RER}\right) \qquad (3)$$

The energy supplied at (*ii*) could be assumed as primary energy, when the system is powered directly by primary-fossil sources, $\left(\dot{E}_{s,ii} = \dot{E}_{p,ii}\right)$ or simply as an electric load, $\left(\dot{E}_{s,ii} = \dot{W}_{el,ii}\right)$ for electric based heating systems. The term $\left(1 - f_{th,RER}\right)$ outlines that inputs derived from RER are not accounted as input. For fuel based heating systems, the related primary exergy rate at (*ii*), $\dot{E}x_{ii}$ is given by the product of $\dot{E}_{p,ii}$ and the quality factor of the fuel, $F_{q,ii}$ as given by Eq. (4). For electric based heating generators, $\dot{E}x_{in} = \dot{W}_{el,ii}$.

$$\dot{E}x_{ii} = F_{q,ii}\dot{E}_{p,ii} \qquad (4)$$

For electric based heating systems, regarding an equivalent comparison based on same type of supplied fuel, the primary energy associated to electricity production should to be accounted. Therefore, the related performance of the electric power plant should be incorporated into the analysis. The primary energy and exergy load at the power plant for electric-based heating systems are given by Eqs. (5) and (6), respectively.

$$\dot{E}_{p,i} = \frac{\dot{W}_{el,ii}}{\eta_{i}}\left(1 - f_{el,RER}\right) \qquad (5)$$

$$\dot{E}x_{i} = F_{q,i}\dot{E}_{p,i} \qquad (6)$$

where, $\dot{W}_{el,ii}$ is the electricity demand at heat generator (ii), η_i is the thermal efficiency of the power plant and $F_{q,i}$ is the quality factor of the supply source and the parameter $f_{el,RER}$ is the fraction of electricity produced by RER.

3 Energy and exergy performance indicators

The exergy analysis can provide several advantages when compared to the conventional energy approach; however, it is not widely adopted by the building industry, energy building-modelling professionals or even in building energy standards. In the Portuguese energy building code RCCTE [20], as well as, in the European Directive for the Energy Performance of Buildings, EU 2002/91/CE [21], the exergy concept is not mentioned or even its use recommended. In the procedure followed by RCCTE, the energy performance of buildings is quantified by their related primary energy demand, simply using primary energy conversion factors. In this study, two new indicators are proposed: primary energy ratio (*PER*) and an equivalent index based on exergy – the primary exergy ratio (*PExR*). In the following sub-sections, the mathematical formulations of these indicators are presented.

3.1 Primary Energy Ratio

Primary Energy Ratio (*PER*) is defined as the ratio of delivered useful energy (thermal, electric, mechanic) to the primary-fossil energy supplied (derived from natural gas, fuel oil or coal). This indicator provides information about the efficiency of employing NRER to fulfil the space heating requirements of the building. Taking into account the symbols of Figure 1, *PER* is given by the Eq. (7), where $\dot{Q}_{H,iv}$ is the heating load at (*iv*) and $\dot{E}_p$ is the required total primary energy. For fuel based heat generators, $\dot{E}_p = \dot{E}_{p,ii}$ and for electric based heating systems, $\dot{E}_p = \dot{E}_{p,i}$.

$$PER = \frac{\dot{Q}_{H,iv}}{\dot{E}_p} \tag{7}$$

3.2 Primary exergy ratio

The overall exergy performance of an energy conversion system is usually given by the exergy efficiency, which is defined as the ratio of the output exergy to the total exergy required. This indicator quantifies how well the exergy input is converted, or looking from the reverse direction, shows the irreversibility level generated during the conversion process. For the current study, primary exergy ratio is defined as the useful exergy demand to the primary exergy input rate, expressed by Eq. (8):

$$PExR = \frac{\dot{E}x_{iv}}{\dot{E}x_p} \tag{8}$$

where, $\dot{E}x_{iv}$ is the exergy heat demand at room (*iv*) and $\dot{E}x_p$ is the primary energy input, expressed as exergy values. Similarly, for heat generators powered by fossil fuels, $\dot{E}x_p = \dot{E}x_{p,ii}$ and for systems powered by electricity, $\dot{E}x_p = \dot{E}x_{p,i}$.

3.3 Primary irreversibility rate

The potential work lost during an energy conversion process is commonly defined as the irreversibility rate or exergy destruction rate [2]. It is given by the difference between the exergy input or required and the exergy output or desired at a given system or sub-system. Using the symbols of Figure 1, the overall irreversibility rate for a given ESN is given by Eq. (9). Furthermore, the relationship between irreversibility rate and *PExR* is expressed by Eq. (10).

$$\dot{I}_p = \dot{E}x_p - \dot{E}x_{iv} \tag{9}$$

$$\dot{I}_p = \dot{E}x_p \left(1 - PExR\right) \tag{10}$$

As previously, for heat generators powered by fossil fuels, $\dot{E}x_p = \dot{E}x_{p,ii}$ and for systems powered by electricity, $\dot{E}x_p = \dot{E}x_{p,i}$. The irreversibility rate evaluated for each sub-system presented in Figure 1 is given by Eqs. 11 to 14. For the emission (*iii*),

$$\dot{I}_{p,iii} = \dot{E}x_{iii} - \dot{E}x_{iv} \tag{11}$$

where, $\dot{E}x_{iii}$ is the exergy demand at emission (*iii*) and $\dot{E}x_{iv}$ is the exergy demand at room (*iv*). For fuel based heat generators (*ii*),

$$\dot{I}_{p,ii} = \dot{E}x_{p,ii} - \dot{E}x_{iii} \tag{12}$$

where, $\dot{E}x_{p,ii}$ is the exergy related to the primary energy input to (*ii*). For electric driven heat generators (*ii*),

$$\dot{I}_{p,ii} = \dot{W}_{el,ii} - \dot{E}x_{iii} \tag{13}$$

where, $\dot{W}_{el,ii}$ is the electricity rate input to (*ii*). For the power plants (*i*), the irreversibility related rate is given by Eq. (14).

$$\dot{I}_{p,i} = \dot{E}x_{p,i} - \dot{W}_{el,ii} \qquad (14)$$

where, $\dot{E}x_{p,i}$ is the exergy rate related to the primary energy supplied to the power plant (*i*).

4 Model characterization and simulation scenarios

In this study, eight ESN are described using different types of emission system (low, medium and high temperature), heat generators (powered by fuel, electric resistance and air source heat pump) and power plants technologies (natural gas, oil or coal). Part of heat or electricity delivered may be produced by RER, therefore reducing the demand of NRER. Using the same building model, the energy and exergy performance of each ESN was evaluated under different outdoor environmental conditions. Different simulations were conducted using Meteonorm weather files for the following locations: Coimbra and Lisbon in Portugal, Paris in France and Berlin in Germany. In this section, the building model and energy supply networks (ESN) are described, as well as, the main parameters and assumptions made.

4.1 Building model description and operating conditions

The building model is describe as single thermal zone, rectangular shaped with main façade south-orientated and was modelled in TRNSYS using the components Type 109 and Type 56. It has a total floor area of 336 m^2 and volume of 907.2 m^3. For the ventilation rate, it was assumed 0.6 air changes per hour (value established by RCCTE [20]). The sensible heat demand was calculated assuming an indoor set-point temperature of 20 °C. No humidity loads were considered into the analysis. The main envelope parameters are presented in Table 1.

Table 1: Building model envelope characterization

Type of façade	Orientation	U-value [W m^{-2} K^{-1}]	Area [m^2]
Exterior Walls	North and South	0.870	304
Exterior Walls	East and West	0.870	37.8
Roof	Horizontal	0.493	336
Ground	Horizontal	1.323	336
Glazing	South	2.83 (g = 0.755)	14.0

The U-values of the construction elements are in agreement with the reference or recommended values established for new residential buildings in Portugal, which are defined by the building code RCCTE [20]. The standard also outlines maximum admissible U-values for the envelope performance of new buildings. They change according type of construction (walls, roofs or pavements), boundary conditions (contact with exterior or non-conditioned spaces) and climatic zone (three climatic zones are defined in Portugal). For locations with more severe climate than Portugal (e.g. France or Germany), lower U-values are recommended, although in this study, the same building model (and related U-values) was applied for all the heating options proposed and outdoor environmental conditions proposed. The main objective of the study is not to assess the heating demand and related primary energy consumption of the building model, respecting the building codes of each country, but to address the energy and exergy performance variations for different outdoor environmental conditions.

4.2 Characterization of the energy supply networks (ESN)

The different combinations of emission systems, heat generators and power plants are described in Tables 2 to 4, respectively. The thermal efficiencies of the heating systems presented in Table 3 were defined according to pre-design tool developed by Schmidt [8], widely used in the projects: IEA-ECBCS Annex 37 [6] and Annex 49 [7]. Since most of the systems installed in buildings do not operate at their maximum capacity, thermal efficiencies are defined at part-load ratio as 30 %. Furthermore, the related power plant efficiencies were retrieved from Ref. [25], using recommended values by power plant technology. In Tables 3 and 4 are also shown the quality factors related to each fuel source or carrier and were also retrieved from Ref.s [22-24]. Combining the sub-systems presented in Tables 2-4, the definition of each ESN is presented in Table 5. As example, “ESN G” is a supply network constituted by an “Air source heat pump (HG4)”, where the heat is released by “Medium temperature (50/40 °C) (E2)” emission system. Furthermore, 30 % of electricity is produced by RER and the remainder (70 %) is generated in a conventional “Power plant fuelled by oil (PP2)”.

5 Results and discussion

In this section, the results of the energy and exergy analyses applied to each ESN are presented. They are organized in three main sections. In Section 5.1, the energy and exergy demand is evaluated individually for each sub-system of the ESN. In Section 5.2, the energy-exergy performance indicators and primary energy demand are compared for different outdoors environmental conditions. To close, in Section 5.3, the irreversibility rate is evaluated for the different sub-system of the ESN. For the exergy analysis, the definition of the reference (dead) state temperatures for all considered outdoor environmental scenarios are presented in Table 6. They were calculated based on the average temperature for each period (day or month), using the weather's data at each location (city).

Table 2: Description of the emission systems, operating temperatures and type of technology

Code	Emission system	Technology
E1	Low temperature (40/30 ºC)	Floor heating or large convector areas
E2	Medium temperature (50/40 ºC)	Convectors/Fan coils
E3	High temperature (70/60 ºC)	Convectors/Fan coils

Table 3: Technologies and efficiencies for the heat generators

Code	Heat generator	Thermal efficiency (based on Ref. [7])	Quality factor of the source [-]
HG1	Condensing boiler (Natural Gas)	95%	0.92
HG2	Standard oil boiler	80%	0.99
HG3	Electric Boiler	98%	1.00
HG4	Air source heat pump	2.5 (COP)	1.00

Table 4: Description of power plant types and technologies

Code	Fuel	Efficiency [a]	Quality factor [-]
PP1	Coal	42.3 %	1.03
PP2	Fuel Oil	39.7 %	0.99
PP3	Natural gas (Combined Cycle)	52.5 %	0.92

[a] Efficiencies reference values in application for Directive 2004/8/EC [25]

Table 5: Different combinations of sub-systems for the definition of ESN A-H

	ESN	Power plant	Heat generator	Emission	RER-local (Thermal)	RER-nation (Electric)
Fuel	A	-	HG1	E3	0	0
	B	-	HG2	E3	0	0
	C	-	HG1	E2	0	0
	D	-	HG1	E2	0.30	0
Electric	E	PP3	HG3	E3	0	0
	F	PP3	HG4	E2	0	0
	G	PP2	HG4	E2	0	0.30
	H	PP1	HG4	E1	0.20	0.40

Table 6: Reference (dead) state temperature for the outdoor environments examined.

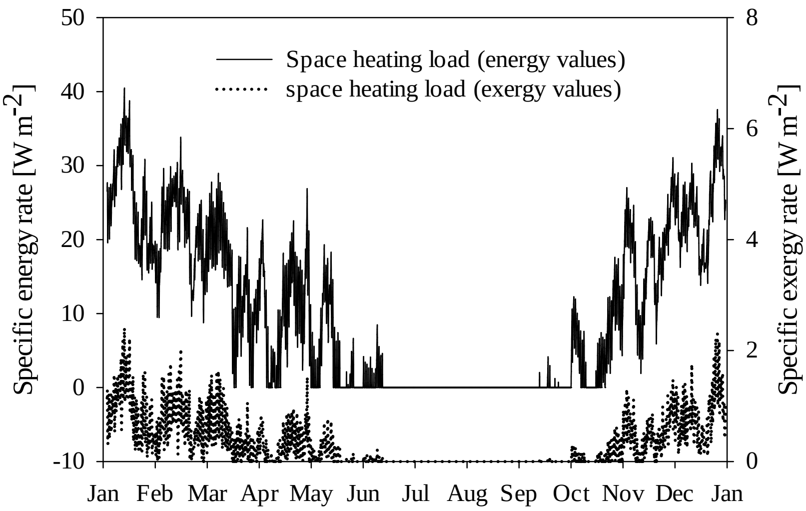
Weather's file	Reference period	T_0 (K)[b]
Coimbra, Portugal	12th January (day)	278.42
	January (month)	283.11
	February (month)	284.11
	March (month)	285.66
	November (month)	286.03
	December (month)	283.55
Lisbon, Portugal	January (month)	284.57
Paris, France	January (month)	275.99
Berlin, Germany	January (month)	272.99

[b] Calculation method: daily or monthly averaged temperature.

5.1 Energy and exergy demand

Having as reference the weather outdoor conditions of Coimbra's city (Portugal), annual dynamic simulations were conducted to evaluate the space heating thermal demand and related exergy load of the building model. The results for the subsystem room (*i*) are presented in Figure 2.

Figure 2: Space heating energy and related exergy demand of the building (simulated results for weather data corresponding to Coimbra).



Two different lines are presented: one corresponding to the space heating thermal demand (directly derived from the simulation output results); and second one associated to the space heating related exergy demand at room (*iv*). For a conceptual point of view, the exergy curve represents the minimum equivalent work required to run a reversible heat pump system operating between outdoor and indoor air temperature. The differences between the two parameters show that exergy of a low-temperature requirements task (such as space heating) is very low when compared with the related energy value. Considering a single day analysis (12th January at Coimbra), the energy and exergy average demand at each sub-system of each ESN, are presented in Figure 3-A and 3-B, respectively.

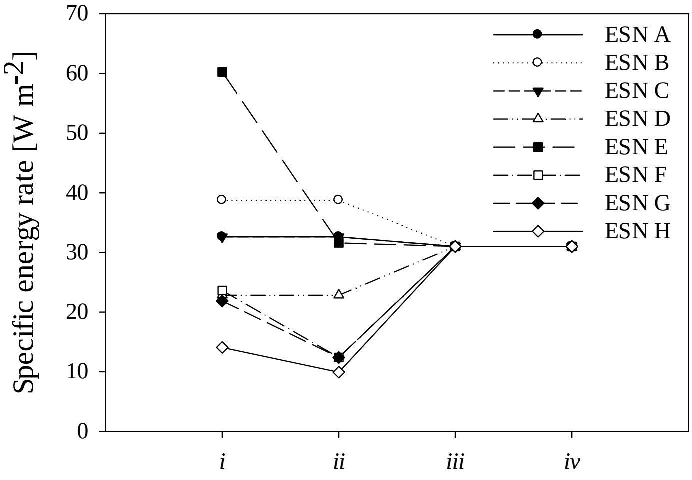


Figure 3-A: Specific heating energy rate at each sub-system for ESN A–H (weather data corresponding to Coimbra on 12th January).

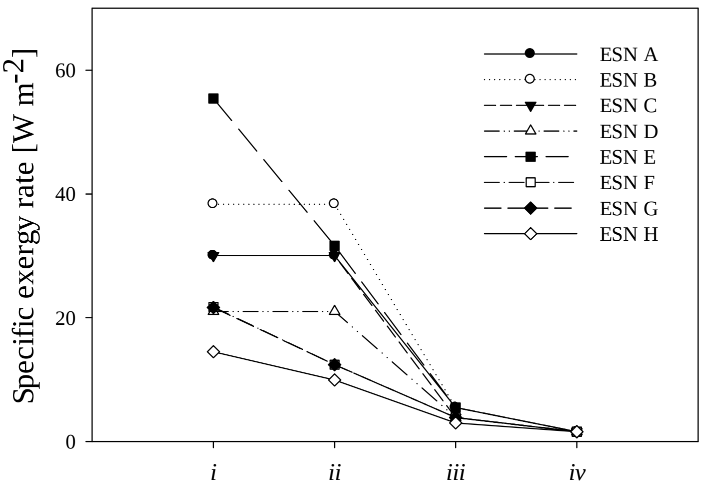


Figure 3-B: Specific exergy rate at each sub-system for ESN A–H (weather data corresponding to Coimbra on 12th January).

The energy and exergy differences at sub-system room (*iv*) were discussed previously and they are equivalent for all ESN, since the same building model was applied. Concerning the emission system (*iii*), since different type of systems were assumed, the exergy demand at (*iii*) changes accordingly. The lowest exergy demand value occurs for ESN H, which involves a low temperature (40/30 °C) emission system. The exergy differences among ESN at (*iii*) are almost imperceptible, when compared with differences verified at (*ii*) or (*i*). The related energy load at (*iii*) is the same for all ESN analysed, because no thermal losses were assumed in that sub-system.

The energy and exergy demand at heat generator (*ii*) show high differences from both perspectives. Comparing the differences between (*ii*) and (*iii*), the exergy requirements at (*ii*) are always higher than (*iii*), showing the presence of irreversibilities at the conversion from (*ii*) to (*iii*). Concerning energy, some of the ESN present lower demand values at heat generator (*iii*) than at emission (*iii*). This means that RER are considered as source or the heat generators may have energy efficiency higher that unit (heat pumps), which occurs for ESN D, F, G and H.

Furthermore, for ESN A–D, the heat generator is powered directly by fuels sources, so the last value is located at (*ii*). Although, in order to have a facilitated comparison among other options, the energy–exergy for ESN A–D demand at (*ii*) were extended to (*i*). These diagrams are particularly useful for evaluating and comparing the major inefficiencies or exergy losses at the ESN. The slope of the lines provides useful information regarding the mentioned fact, although from an energy perspective, due to the presence of slopes in different directions, it is more difficult to extract consistent conclusions about the sub-system where the major inefficiencies occur. As an example, comparing ESN A and B, from an energy perspective both supply systems indicate relatively low-energy losses at the heating system, but from an exergy point of view, most of exergy losses (about 40 W m^{-2}) occur in the transformation from (*ii*) to (*iii*). Moreover, for the ESN E, the energy diagram (Figure 3-A) indicates that the major inefficiencies occur at power plant, but from exergy diagram (Figure 3-B), they are shared between power plant and electric heat generator. Comparing the results from Figure 3-A and Figure 3-B, the differences between energy and exergy approaches are highlighted. From an overall perspective, these diagrams reveal that major source of irreversibilities occur at the heating system (*i*) and power plant (*ii*).

5.2 Energy and exergy indicators

The energy and exergy performance of ESN A–H are evaluated through the indicators *PER* and *PExR*. In Figure 4, these two indicators are presented using averaged values for the typical winter day of 12th January. Since constant heating efficiencies and quality factor were assumed, the results show a linear correlation between the indicators *PER* and *PExR*, both having the same performance ranking: ESN H, G, D, F, C, A, B. Despite a different numerical value, these results do not show the main advantages of *PExR* relatively to *PER*. However, in Figure 5, these differences are highlighted when different outdoor environmental conditions are compared. Each point represents the monthly averaged energy and exergy performance (*PER* and *PExR*, respectively) for ESN A–H for different winter months, using as reference outdoors conditions of Coimbra. The related reference (dead) state temperatures are presented in Table 6.

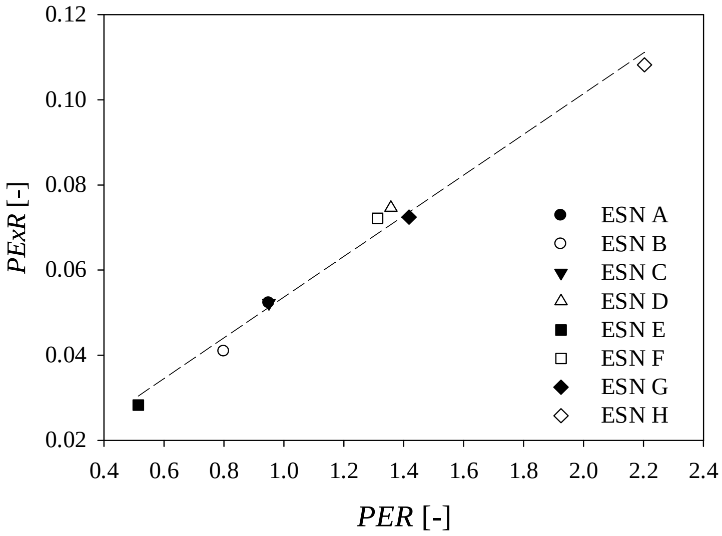


Figure 4: *PExR* as a function of *PER* for ESN A–H (weather data corresponding to Coimbra on 12th January).

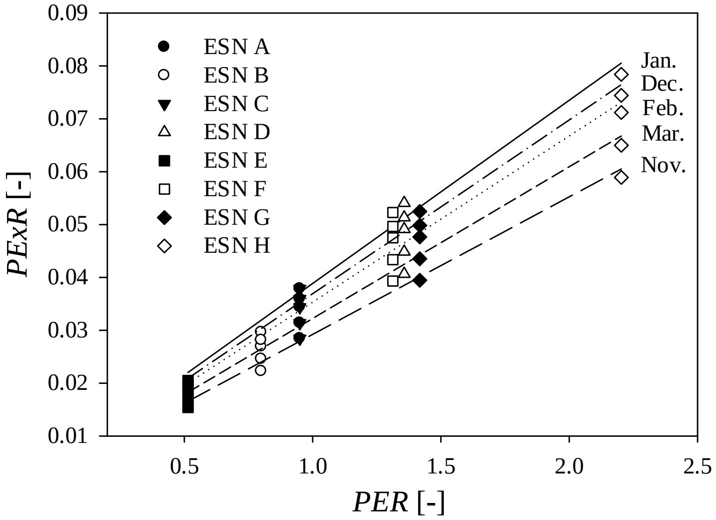
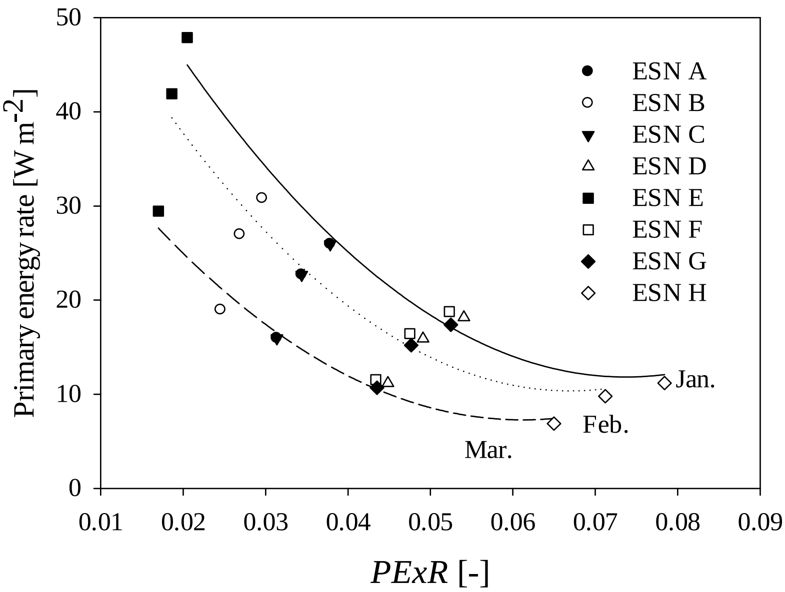


Figure 5: *PExR* as a function of *PER* for ESN A–H for typical winter's months (weather data corresponding to Coimbra).

The results show that *PExR* of each ESN changes according to different months, while *PER* remains constant. It clearly shows the limitation of *PER* for the performance assessment of each ESN, when different outdoor conditions are compared. The exergy performance (*PExR*) of each ESN assumes the highest value for January, following December, February, March and November. It shows that *PExR* is higher for “cold” months, which are associated to low reference (dead) state temperatures, T_0. Low T_0 leads to slightly high exergy requirements at demand, therefore for the same system's efficiency, high exergy performance is achieved. High exergy efficiencies indicate a more rational use of the resources, indicating a match between exergy levels between supply and demand.

Since the *PER* and/or *PExR* indicators are non-dimensional ratios, they give information about the primary energy and exergy efficiency of the heating conversion process, but no information concerning the actual primary energy demand of the building. The primary energy demand (or related CO_2 emissions) is the commonly indicator recommended to measure the energy performance of buildings. Combining *PER* and *PExR* with primary energy consumption of buildings a more complete information about the building energy performance is granted. In Figure 6, the specific primary energy rate is presented as a function of *PExR*, for Coimbra's winter months from January to March. The primary energy demand is higher for low efficient ESN and more severe outdoor environmental conditions: $\dot{E}_p(\text{January}) > \dot{E}_p(\text{February}) > \dot{E}_p(\text{March})$. Concerning exergy performance of each ESN, the higher *PExR* value is also obtained for January, followed by February and March, and the differences more relevant for ESN with low primary energy demand. These results also reveal the "ability" of *PExR* to distinguish systems' performance for different reference outdoor conditions.

Figure 6: Specific primary energy rate as function of *PExR* for ESN A–H (weather data corresponding to Coimbra).



In the previous approach, the heating performance of the building model proposed was assessed for different European cities: Coimbra (Portugal) and Lisbon (Portugal), Paris (France) and Berlin (Germany). The same building envelope, ventilation requirements, and related U-values were applied for all the weather reference conditions. U-value influences the space heating demand and related primary energy/exergy rate of the building model. In this study, U-values of the building model are the recommended values for the Portuguese weather's conditions, although considering more severe climate conditions (e.g. Berlin and Paris), lower U-values are recommended, reducing the primary energy demand. In this study, the same U-values applied to all the different climatic conditions are considered, regarding to assess only the ESN performance, and not the envelope.

In Figure 7-A and 7-B, the specific primary energy rates as function of *PER* and *PExR* are shown, respectively. These diagrams could provide useful information about the energy or exergy performance of the supply systems, together with the primary energy demand associated. Since constant efficiencies were defined for heat generator and related power plant sub-systems, *PER* of each ESN is constant for the different weather conditions. As an example, *PER* of ESN E is about 0.5 for all scenarios, and the same occurs for ESN H, where *PER* = 2.2. On other hand, concerning the exergy performance, it changes according to the reference weather conditions. Thus, for ESN H, *PExR* is about 0.07 for Coimbra's weather and about 0.155 for Berlin's outdoor environment. Since different exergy requirements at demand (room, *iv*) are obtained for each weather conditions, the exergy performance is a very sensitive parameter, especially for ESN with low primary energy demand.

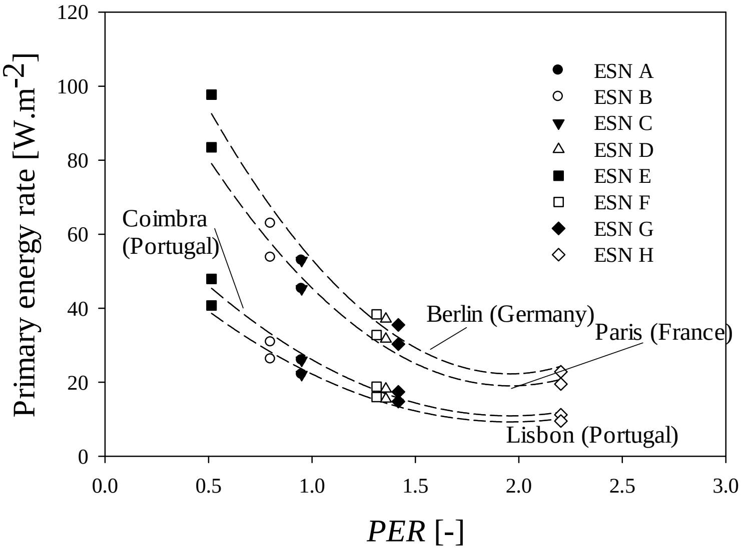


Figure 7-A: Specific primary energy rate as function of *PER* for ESN A–H in four different locations (weather data corresponding to January).

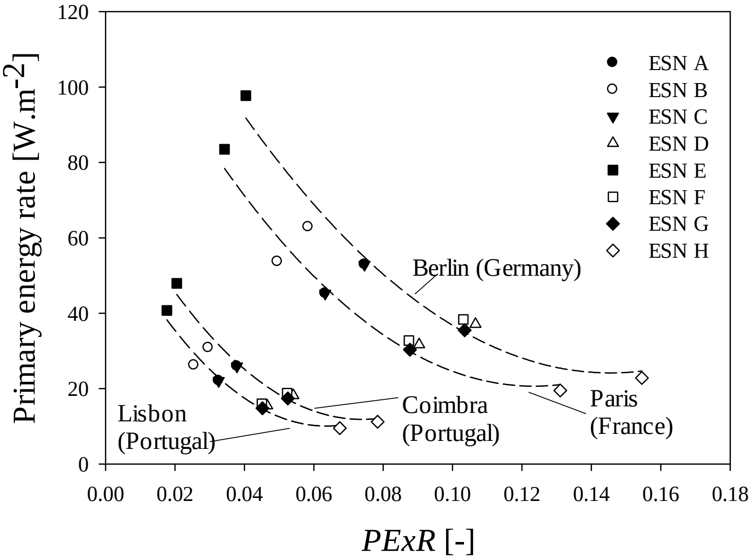


Figure 7-B: Specific primary energy rate as function of *PExR* for ESN A–H in four different locations (weather data corresponding to January).

These diagrams are also very useful for comparing buildings performances when the same primary energy demand is achieved, but with different energy and exergy performance results, depending of the reference outdoor environmental conditions. From results derived from Figure 7-A and 7-B, considering ESN E in Lisbon and ESN F in

Berlin, approximately the same primary energy demand is achieved (40 W m^{-2}). Therefore, the related *PER* is higher for Berlin (about 1.4) than for Lisbon (about 0.5). Comparing the two options, for these two scenarios, *PER* of ESN F is 1.8 times more efficient than ESN E. Doing the same comparison ($\dot{E}_p$ = 40 W m^{-2}), but considering exergy performance (*PExR*), the following results are derived: *PExR* for ESN E in Lisbon is about 0.02, while the related value for ESN F in Berlin is 0.105. It indicates that ESN F is 4.25 times more (exergy) efficient than ESN E, which is a very different result than the one obtained for *PER*. Considering the accuracy of *PExR* from thermodynamic perspective, it is suggested that *PExR* should be used as a valid indicator rather than *PER*.

5.4 Irreversibility rate: breakdown by sub-system

The primary irreversibility rate or exergy destroyed in each ESN is directly related with the primary exergy rate input and its exergy performance *PExR*, as expressed by Eq. (10). Furthermore, the related exergy destruction or irreversibility rate associated to each individual component is given by Eq.s 11-14. The irreversibility rate for each ESNs sub-system is presented in Figures 8-A to 8-D, using average results for January weather's outdoors conditions of Coimbra, Lisbon, Berlin and Paris, respectively. In Figures 8-A to 8-D, it is possible to assess and specify the most inefficient components of each ESN, as well as, the minimum exergy required to perform the space heating task for each outdoor environmental condition. For fuel based heating systems (ESN A–D), the most of irreversibility rates occur at heat generator, while for electric-based options, the irreversibilities are shared between the heat generator and power plant. Concerning emission system (iii), as it operates near to the space heating temperature, its associated exergy destruction is relatively low when compared with the related value at heat generator or power plant). However, it is possible to distinguish irreversibility rate differences among emission systems, depending if they are high, medium or low temperature systems: the irreversibility rate at high-temperature emission systems (ESN A, B, E) is higher than medium-temperature systems (ESN C, D, F and G), and these two higher than low-temperature emission system (ESN H).

Taking into attention the values of exergy required at demand (building room, iv), its value is too low when compared with total exergy supply, revealing low-exergy efficient processes, especially for ESNs with high primary exergy demand. From the Figures 8-A to 8-D, it is also possible to distinguish different exergy requirements at room for the different outdoor environmental conditions. Thus, for locations with a low reference (dead state) temperature, such as Berlin or Paris, the exergy demand at room is higher than in Coimbra or Lisbon. Concerning the overall primary exergy rate, this value is also very different for the different outdoor climate conditions, because the same U-values were considered for all of them. Therefore, by improving the envelope quality for more severe outdoor conditions, low primary exergy rate could be obtained, as well as, the related primary irreversibility rate associated to each system.

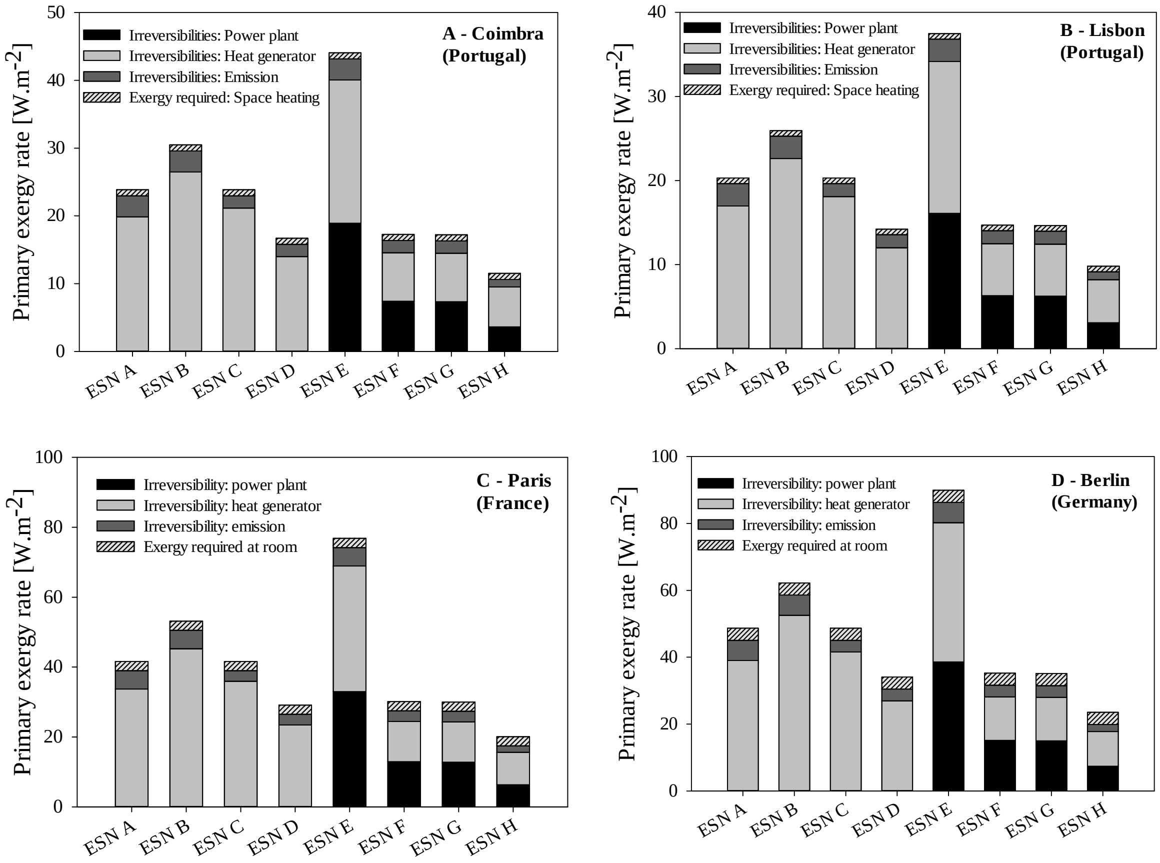
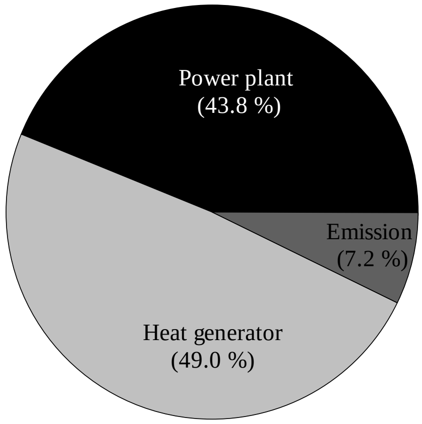


Fig. 8. Primary exergy rate required for ESN A–H and its allocation by irreversibilities and exergy required; weather data for January in (A) Coimbra, (B) Lisbon, (C) Paris and (D) Berlin.

Fig. 9 shows the irreversibility breakdown (in %) by each subsystem, that is relative irreversibility associated to each sub-system of ESN E, which have higher primary exergy demand. As shown, the heat generator accounts with 49 % for the total irreversibility rate, the power plant with about 44 % and the emission with 7.2 %. Following a simple energy approach, these values are hidden, since the thermal efficiency of the heat generator is 98 %, showing only inefficiency at powered plant (PP3), which has an associated efficiency of 52.5 %.

Figure 9: Allocation of the primary irreversibilities of the sub-systems related to ESN E (weather data corresponding to Berlin in January).



6 Conclusions

In this study, the energy and exergy performance of eight heating supply options were compared for different outdoor environmental conditions. Since the space heating is usually associated to low-exergy task, huge differences were found between energy and related heating exergy demand at sub-system *iv* (room). Therefore, it leads to significant variations between energy and exergy performances for each ESN evaluated. However, the exergy performance (*PExR*) is the indicator with more thermodynamic significance, since it includes both quantitative and qualitative energy aspects.

For a given outdoor environmental condition, a linear relationship between energy and exergy performance indicators is found for all ESN. However, when different outdoor conditions are compared, higher exergy performances (*PExR*) are obtained for lower outdoor temperatures, while *PER* remains the same.

For low outdoor temperature conditions, the exergy at demand side (room) is higher, than when high outdoor temperatures are considered, therefore for the same resource (or exergy input), better performances are achieved. This approach reveals that the exergy is an useful method for comparing of thermal-based energy options, with similar primary energy performances and located at different outdoor environmental conditions.

Furthermore, the use of primary exergy demand and related irreversibilities or exergy destruction occurring at the sub-systems revealed to be a practical outcome, since it helps to quantify and locate the true thermodynamic inefficiencies associated to each ESN. The authors expect that the outcomes of this work may be used as basis of further comparison studies on energy performance of buildings, located at different outdoors conditions.

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RESEARCH PAPER II

Energy and exergy-based indicators for the energy performance assessment of a hotel building

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Join author statement

As this PhD thesis contains articles made in collaboration with other researches, a join author statement about the contribution of PhD student and each co-authors for the article is recommended.

Title of the article	Energy and exergy-based indicators for the energy performance assessment of a hotel building
Authors	Pedro Gonçalves, Adélio Rodrigues Gaspar, Manuel Gameiro da Silva

PhD Student	Pedro Gonçalves	**Number:** 2006158070
Course	PhD on Sustainable Energy Systems (Doutoramento em Sistemas Sustentáveis de Energia)	

Description the contribution of each author to the above-mentioned article

	Design of research	Development of the method	Literature review	Data collection	Discussion of results	Reporting	Principal authorship
Pedro Gonçalves	X	X	X	X	X	X	X
Adélio Rodrigues Gaspar		X		X	X	X	
Manuel Gameiro da Silva			X		X	X	

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Energy and exergy-based indicators for the energy performance assessment of a hotel building

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Abstract

Buildings account for 40 % of total energy consumption in the European Union. The sector is expanding, which will lead to an increase of its energy consumption, if no additional measures are taken. The Directives 2002/91/EC and 2010/31/EU (recast) on the energy performance of buildings have as objective to reinforce the improvement of the energy performance of buildings, proposing the use of energy performance indicators, based on primary energy use or CO_2 emissions. In this study, the limitations of the actual method are identified and a new indicator, based on exergy, is proposed, aiming to give new insights about the energy use in buildings. As a case study, a hotel building located in Coimbra (Portugal) is analysed using actual energy consumption data derived from a conducted energy audit. Besides primary energy based indicators, two more indicators were used: the primary energy ratio (*PER*) and exergy efficiency. Results show an estimated overall primary energy consumption of 446 kWh m^{-2} $year^{-1}$, and 49 % and 17 %, found as *PER* and exergy efficiency, respectively. From an individual analysis, the electric equipments were found as the main contributors for the primary energy consumption of the hotel; however, they present the highest exergy efficiency when compared to processes related with space air conditioning.

Keywords: Exergy analysis; Energy audits; Energy performance of buildings; Energy labelling

Nomenclature

A_f	Floor Area [m^2]
$\bar{C}OP$	Coefficient of Performance (averaged) [-]
E	Energy demand [kWh]

EP	Energy performance indicator, based on primary energy use
Ex	Exergy demand [kWh]
F_q	Quality factor
PER	Primary energy ratio
T	Temperature [°C]
W_{el}	Electricity demand [kWh]

Subscripts

0	reference
acc	air conditioning for cooling
ach	air conditioning for heating
aux	electric auxiliaries loads
ch	chiller
ck	cooking
cs	cooling system
de	distribution and emission system
des	desired
ds	distribution and storage
DHW	domestic hot water
ee	electric appliances
eg	electric grid
f	fossil fuel (primary energy)
hg	heat generator
hs	heating system
i	energy end-user
ove	overall
p	primary
req	required
u	useful energy (at last user of the energy supply chain)

Greek symbols

η	Energy efficiency
ψ	Exergy efficiency

Acronyms

DHW	domestic hot water
EPBD	Energy Performance of Buildings Directive
EU	European Union
HVAC	Heating Ventilation and Air Conditioning

RCCTE	acronym in Portuguese, “Regulation of the Buildings Thermal Behaviour Characteristics”
RSECE	acronym in Portuguese, “Regulation of the Energy Systems in Buildings”
SCE	acronym in Portuguese, “Energy and Indoor Air Quality Certification of Buildings”

1 Introduction

In the European Union (EU) the building sector is responsible for 40 % of energy consumption and 36 % of CO_2 emissions [1]. The related regulation on energy performance of buildings is an important instrument to achieve the EU Climate and Energy objectives. The Directive 2002/91/EC [2] on energy performance of buildings (EPB) is the main legislative instrument at EU level to promote the improvement of the energy performance of buildings. Under this directive, each member state must apply minimum requirements regarding the energy performance of new and existing buildings, ensuring the certification of their energy performance and requiring the regular inspection of boilers and air conditioning systems in buildings. Portugal adopted a series of measures to implement Directive 2002/91/EC [2] into the national law. In this scope, three decrees were officially published on April 2006 [3-5], which configure simultaneously the minimum requirements and the corrective measures for IAQ and energy efficiency, in either new or existing buildings. Decree 78/2006 creates and defines the operational rules for the National System for Energy and Indoor Air Quality Certification of Buildings (SCE). Decree 79/2006 establishes the new revision of the Regulation for HVAC Systems, including requirements for regular inspection of boilers and air-conditioning equipments and systems (RSECE) and Decree 80/2006 establishes the new revision of the regulations regarding the Thermal Behaviour of Buildings (RCCTE).

In 2010, the European Commission published Directive 2010/31/EU [6], a recast directive on EPB, in order to reinforce the energy performance requirements and to clarify and streamline some of its provisions. The adoption of a methodology for a detailed evaluation of the EPB is one of the directive's requirements. EPB shall be clearly expressed by an energy performance (*EP*) numerical indicator of primary energy use, based on conversion factors per energy carrier. These factors may be based on national or regional yearly average values or may take into account relevant European standards [6]. Some authors have studied the implementation of the European directive in different member state. Maldonado [7] contains extended summaries on the main outcomes of five topics: certification of buildings, inspections of boilers and air-conditioning systems, training of experts, procedures for characterisation of energy performance, information campaigns. Moreover, the survey undertaken by Economidou [8], from Buildings Institute Europe showed large variations in the approaches adopted by different countries. Ballarini and Corrado [9] applied the EPBD through the energy assessment of some residential buildings in Turin (Italy). The energy use for heating/cooling is calculated through the application of the overall system efficiency and expressed through *EP* indices, based on annual primary energy demand per square meter. Similar studies were accomplished in Ireland [10], Portugal [11], Spain [12] and Greece [13], [14] and [15]. A software tool (EPA-ED) that can be used to perform building energy audits and assess buildings in a uniform way is proposed by Poel et al. [16]. The output results include monthly energy consumption for heating and cooling; calculated energy demand for domestic hot water (DHW), a summary with calculated savings (fuel consumption, electricity, CO_2 emissions, energy indicator) and cost (investment cost, payback period). Similarly, the authors Rey et al. [17] proposed a new energy certification method called Building Energy Analysis (BEA) [18] to assess the building energy labelling, valid for residential and non-residential buildings, where the quantitative indicator is based on the energy required by the building, taking into account the instantaneous consumption energy demand and HVAC performance.

Despite some differences verified in the various methodologies reviewed, the *EP* indicators are related with the primary energy use in buildings or, in some cases, with the associated CO_2 emissions. However, from all the indicators proposed by either the European Directives or National Laws none distinguishes energy flows according to their quality levels. For example, one unit of energy for heating, expressed as thermal energy, is treated in the same way as one unit of electricity for lighting or electric equipments. However, from a thermodynamic point of view, the potential conversion value of one unit of electricity is completely different from the same unit value associated to the thermal energy, for space heating or hot water. Thus, the buildings as energy consumers with multiple quality requirements (space heating and cooling, hot water, illumination, ventilation and others), should include quality related aspects into its energy performance.

From the reference literature [19-22], the energy quality associated to an energy state of flow is evaluated throughout the thermodynamic property “Exergy”, which relates the principles of mass and energy conservation together with the second law of thermodynamics, for design or analysis of thermal systems. The exergy analysis is particularly suited for furthering the goal of more efficient resource use, since it enables the locations, types, and true magnitudes of waste and loss to be determined. The method has been applied in many fields, from industrial sector [23], [24] and [25] to buildings and their energy systems [22], [23], [26], [27], [28], [29] and [30]. Despite the add-value of the exergy analysis in the building context, the concept was not referred in the actual legislative frameworks on EPB. However, Favrat et al. [31] proposed a procedure for the calculation of an exergy indicator, regarding its inclusion into a new law for the “Canton of Geneva” in Switzerland. Nevertheless, this indicator is only related with HVAC analysis and does not account for other energy users, such as: lighting, electric services, hot water or ventilation.

The present study aims to show the importance of additional energy and exergy based indicators for a better energy use description on EPB. Besides the conventional *EP* indicators, based on primary energy use, the primary energy ratio and exergy efficiency are proposed as extra indicators for an improved overall and individual (by energy end-user) energy use description of buildings. For the application of the methodology proposed, a four star hotel building located in Coimbra (Portugal) was analysed. Data derived from the energy [32] and indoor air quality audit [33] conducted during the energy labelling process of the building was used. The primary energy use, exergy efficiency and primary energy ratio were calculated for the overall building and for the following energy end-users: space heating and cooling, cooking, domestic hot water (DHW), ventilation, lighting and electric powered equipments. A “map” of the building is then presented, including information on energy and exergy performance of the hotel, indicating good-practices for the improvement of the energy performance of the building.

2 Energy and exergy indicators

2.1 Primary based energy indicators

The *EP* indicator recommended by the Portuguese Law on EPB is expressed as the annual primary energy demand per square meter of conditioned area, in [kgep m^{-2} $year^{-1}$]. The conversion factors between final and primary energy established for solid, liquid and gas fuels is 0.086 kgep per kWh and 0.290 kgep per kWh for electricity. These values assume that fuels are considered primary energy sources and electricity as a transformed product. Thus, it is assumed that the overall electric grid efficiency (power plant + distribution) is of 30 % for the electricity production.

In this study, a similar based procedure is conducted. Thus, the primary energy demand associated to the final user *i*, $E_{p,i}$ is given by Eq. (1), where E_f is the annual fossil fuel demand (assumed as direct primary energy); W_{el} is the annual electricity input and η_{eg} is the overall energy efficiency of the electric grid (electric power plant + distribution). The specific primary energy or *EP* indicator is then calculated using the primary energy input, taking into account the building floor area, A_f, expressed by Eq. (2).

$$E_{p,i} = E_{f,i} + \frac{W_{el,i}}{\eta_{eg}} \quad (1)$$

$$EP = \sum_i \frac{E_{p,i}}{A_f} \quad (2)$$

Different procedures are used for the assessment of E_f and W_{el}, depending on the type of buildings. For new buildings with floor areas smaller than 1000 m^2, the Portuguese regulation RCCTE [4] defines a procedure for the calculation of the useful energy at the building's envelope, and according to the type and efficiency of the energy supply systems, E_f and W_{el} are predicted. For new buildings, with floor areas larger than 1000 m^2, the use of dynamic simulation energy tools for the prediction of the building's energy requirements is done through the patterns defined by the type of building. For existing buildings, the energy bills for the last three years of the building operation, an energy audit and the use of dynamic simulation tools are some of the procedures defined in [5], for the assessment of the annual energy demand of the building.

2.2 Primary energy ratio

The *EP* indicator defined by Eq. (2) E_p is based on the primary energy consumption of the building and includes information on envelope performance and systems' efficiency. However, this approach does not distinguish between systems' efficiency, including the use of renewables in the supply, and envelope performance. It is also important to consider whether improvements should be made either on the building's envelope or on its systems. Thus, on this study, the indicator Primary Energy Ratio (*PER*) is used to provide information on the overall efficiency of the energy supply systems, including information on the integration of renewables on the energy supply systems. For a given energy use *i*, PER_i is defined as the ratio of useful energy at demand $\left(E_{u,i}\right)$ and primary energy supplied

$\left(E_{p,i}\right)$, as given by Eq. (3). $E_{p,i}$ is calculated by Eq. (1) and $E_{u,i}$ is defined according to the type of final energy use. In this study, as an existing hotel building was considered as a case study, the assessment of the useful energy $E_{u,i}$ is presented according to energy end-users present in the hotel.

$$PER_i = \frac{E_{u,i}}{E_{p,i}} \tag{3}$$

For the heating system, constituted by a conventional heat generator (power by fuel), hydraulic distribution-emission system and/or air conditioning heating units (*ach*), the useful energy is given by Eq. (4).

$$E_{u,hs} = \underbrace{\sum E_{f,hg}\eta_{hg}\eta_{de}}_{A} + \underbrace{\sum W_{el,ach}\bar{C}OP_{ach}}_{B} + \underbrace{\sum W_{el,aux}}_{C} \tag{4}$$

The terms *A* and *B* are related to the useful energy provided by the heat generator and air conditioning heating units, respectively; and *C* with the electric auxiliaries for the heating tasks. $E_{f,hg}$ is the fuel input of the heat generator; η_{hg} is the thermal efficiency of the heat generator and η_{de} is the efficiency of distribution network and emission system. $W_{el,ach}$ and $\bar{C}OP_{ach}$ are the supplied electricity and the averaged *COP* of the heating air conditioning units, respectively and $W_{el,aux}$ is the electricity load required for the auxiliaries of space heating process (e.g. pumps, fans).

For the cooling system $\left(cs\right)$, a chiller for cold water production/hydraulic distribution-emission distribution system and air conditioning cooling units are used. The formulation is given by

$$E_{u,cs} = \underbrace{W_{el,ch}\bar{C}OP_{ch}\eta_{de}}_{D} + \underbrace{\sum W_{el,acc}\bar{C}OP_{acc}}_{E} + \underbrace{\sum W_{el,aux}}_{F} \tag{5}$$

The expressions *D* and *E* are related to the useful energy provided by the chiller and air conditioning cooling units, respectively. and *F* with the electric auxiliaries for the cooling tasks. $W_{el,ch}$ and $\bar{C}OP_{ch}$ are the supplied electricity and the averaged Coefficient of Performance for the chiller; $W_{el,acc}$ and $\bar{C}OP_{acc}$ are the supplied electricity and the averaged Coefficient of Performance of the cooling air conditioning units and $W_{el,aux}$ is the electricity load required for the auxiliaries of space heating process (e.g. pumps, fans).

For the domestic hot water (DHW) production system, the useful energy is given by Eq. (6).

$$E_{u,\mathrm{DHW}} = \sum E_{f,hg}\eta_{hg}\eta_{ds} + \sum W_{el,aux} \tag{6}$$

where, $E_{f,hg}$ is the fuel supplied to the generator; η_{hg} and η_{ds} are the energy efficiency of the heat generator and hot water distribution and storage system, respectively. $W_{el,aux}$ is the electric auxiliaries loads required for the cooling system.

For cooking applications (ck), powered by fuel (primary energy source) and/or electricity, the useful energy was assumed as equivalent to the fuel or electricity demand, as given by Eq. (7).

$$E_{u,ck} = \sum E_{f,ck} + \sum W_{el,ck} \tag{7}$$

For electricity powered equipments (ee) (excluding heating and cooling equipments), such as lighting, ventilation and other hotel's electric equipments, the useful energy is given by Eq. (8).

$$E_{u,ee} = \sum W_{el} \tag{8}$$

The overall *PER* for the building, (PER_{ove}) is given by Eq. (9), formulated as the ratio of the sum of the ratios of useful energy to primary energy inputs.

$$PER_{ove} = \sum_i \frac{E_{u,i}}{E_{p,i}} \tag{9}$$

2.3 Exergy efficiency

The previously formulated *PER* gives an indication of the primary energy used by a system to perform a given task. However, *PER* does not take into account the thermodynamic considerations in the energy usage of a system. Energy is conserved in every device or process and cannot be destroyed [22]. Thus, the exergy concept is applied, dealing with both quantity and quality aspects of the energy use. Final energy uses, such as, heating, cooling, DHW, cooking or electrical appliances require very different exergy levels at demand, however, high exergy sources (e.g. natural gas or electricity) can still be used at supply. Thus, the exergy efficiency indicator, (ψ_i) is applied, regarding to compare exergy levels between supply and demand [19]. It is expressed by Eq. (10), where, $Ex_{des,i}$ is the exergy desired (output) and $Ex_{req,i}$ is the exergy required (input) to perform a given task i.

$$\psi_i = \frac{Ex_{des,i}}{Ex_{req,i}} \quad (10)$$

The required exergy is directly related with the type or thermodynamic state of the supplied energy source. According to Kotas [19], exergy input associated to a given energy quantity could be calculated by the product between the quality factor of the source and the respective energy related. Thus, the exergy input is expressed as the product of quality factor by the primary energy input, given by Eq. (11).

$$Ex_{req,i} = F_{q,f} E_{f,i} + \sum_k F_{q,f,k} \frac{W_{el,k}}{\eta_{eg,k}} \quad (11)$$

where, $F_{q,f}$ is the quality factor of the fuel and $E_{f,i}$ is the fuel energy supplied for the task i. $F_{q,f,k}$ is the quality factor of the fuel source, k for the electricity production $W_{el,k}$. In this study, as natural gas is the major resource used both electricity generation, the quality factor $F_{q,f}$ = 1.04, was used [19].

On other side, the assessment of the desired exergy, $Ex_{des,i}$ is calculated by Eq. (12),

$$Ex_{des,i} = F_{q,i} E_{u,i} \quad (12)$$

where, $F_{q,i}$ is the quality factor for the desired task i and $E_{u,i}$ is the useful energy required to perform the task i. The assessment of $F_{q,i}$ is quite different from the quality factor of the source, $F_{q,f}$, since different exergy´s levels are involved for each task. Thus, in order to apply the exergy method it is important to split all the energy consumers according to their final use, defining a dead-state temperature and a required temperature for all thermal-based applications. For electric applications (excluding heating and cooling equipments), $F_{q,k}$ = 1 [34]. However, for thermal-based applications, such as space heating and cooling, DHW or cooking applications, $F_{q,i}$ is given by Eq. (13),

$$F_{q,i} = 1 - \frac{T_0}{T_i} \quad (13)$$

where T_0 is the dead state temperature and T_i is the required temperature to perform a given task i. The quality factors for the assessment of the desired exergy are shown in the next section.

3 The case study

3.1 Building description

The building under study is a four star hotel located in the city of Coimbra (Portugal), built in 1990. From top view, the building has a rectangular shape, with the major axis oriented north-south. The main glazing surfaces are east and west oriented. The building has a maximum capacity of 180 guests, distributed by one hundred and twenty rooms and thirteen suits, along of seven floors. The hotel has a useful (conditioned) area of 6531 m^2, from which about 3443 m^2 are reserved for parking and 596 m^2 for other non-useful areas. The energy systems installed in the hotel include a main central system constituted by a natural gas boiler for heating and domestic hot water (DHW) and a chiller for cooling requirements. Additionally, some individual air conditioning (AC) units were installed to work as auxiliaries of the main central system. Air handling units and extraction ventilators are installed in the roof, ensuring the air quality requirements.

3.2 The energy audit

The energy audit is the first procedure recommended by the Portuguese certification system [5] for the assessment of annual primary energy consumption of non-residential building, allowing the breakdown by demand end-users. The information about the building structure, construction materials, architectural drawings and installed systems was provided by the hotel's maintenance staff. It was possible to collect bills for natural gas and electricity – the main energy suppliers of the hotel – for the last three years. The list of the main analysed documents includes:

- the natural gas bills through the years 2007–2009;
- the electricity bills through the years 2007–2009;
- list of installed equipments in the hotel;
- technical catalogues of installed equipments;
- equipments’ maintenance reports;
- building constructions’ materials;
- architectural drawings;
- schedule profiles for the main energy consumers.

3.3 Energy end-users

The energy audit aimed to assess the specific energy consumption of the building and the division by its end-users' consumers. The related natural gas bills were divided into two independent sub-sectors: "hotel-building" and "hotel-kitchen". In the "hotel-building" sector, natural gas is used for DHW production and air space heating, while in the "hotel-kitchen" it is used for cooking tasks. Electricity is used for space heating/cooling systems, ventilation, water pumping, lighting and building equipments. As a transformed energy product, the overall power plant and electric grid efficiency were taken into account. Fig. 1 shows a scheme with the considered breakdown by energy end-user.

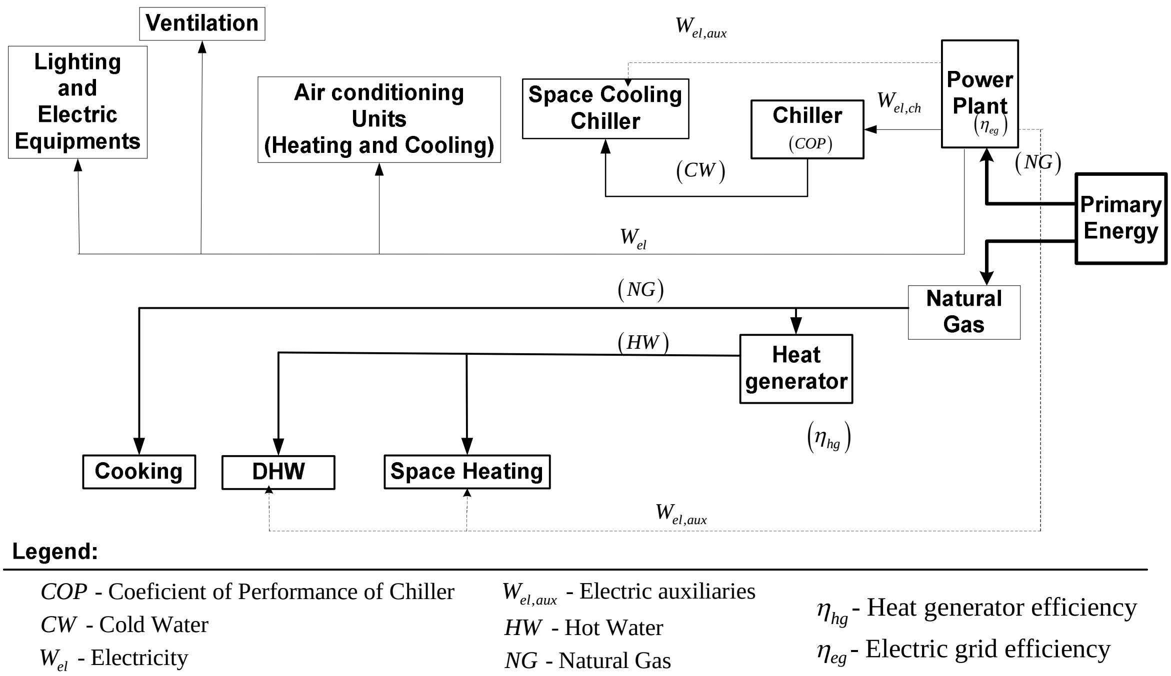


Figure 1: Scheme of the energy end-users of the hotel.

4 Discussion and results

4.1 Natural gas demand by end-users

The natural gas is mainly used for space heating, DHW and cooking tasks. From the analysis of the natural gas bills for the years 2007 to 2009, it resulted in an annual energy consumption of 706 080 kWh, where 632 990 kWh (90 %) are associated to space heating and DHW and 73 090 kWh (10 %) with cooking. The partition of the natural gas consumption between space heating/DHW applications was estimated based on monthly bills analysis and number of clients. Non-heating requirements were assumed from June to October, so for that period a natural gas consumption of 5.69 kWh per client was used. The results for the monthly natural gas consumption, allocated by space heating, DHW and cooking, are shown in Figure 2, and the annual results shown in Table 1.

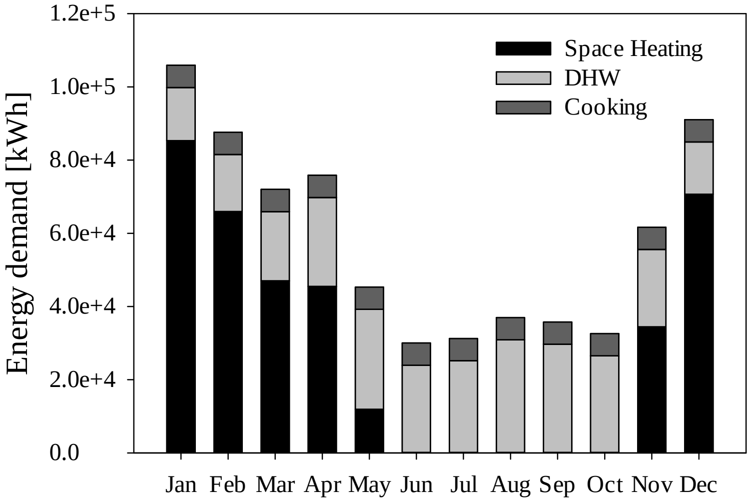


Figure 2: Natural gas energy demand for space heating, DHW and cooking applications.

Table 1: Annual natural gas allocated by energy end-user.

	Natural gas	**Space heating**	**DHW**	**Cooking**
Energy (kWh)	706 080	360 804	272 186	73 090
Allocation	100 %	51 %	39 %	10 %

4.2 Electricity demand by end-users

The electricity's versatility makes its allocation by end-users very difficult. In the current study, electricity is used for a huge variety of end-users, such as: space heating/cooling, hot/cold water pumping, ventilation, lighting, computers and other electric equipment. The hotel's annual electricity demand, derived from electricity bills analysis for the years 2007 to 2009 amounts to 656 093 kWh. The energy audit conducted aimed to divide the electricity demand of the hotel by its end-users. Figure 3 shows the monthly electricity consumption by end-user results, derived from the conducted audit. Furthermore, a more detailed audit was also conducted in the machinery area, for HVAC and DHW electricity distribution. In Table 2 are shown the allocation for the electricity in the machinery area for heating/cooling/DHW auxiliaries and ventilation tasks is shown.

For the analysis, the energy end-users were divided in six main groups, according to the type of energy end-user: space heating and cooling, ventilation, DHW, cooking and electric equipments (including lighting). The division of the annual energy consumption for natural gas and/or electricity and associated primary energy for the six energy end-users assumed is shown Figure 4. It demonstrates that the hotel's electric equipments are the major primary energy consumers; followed by space heating and cooling applications.

Figure 3: Monthly energy demand for the main electricity end-users.

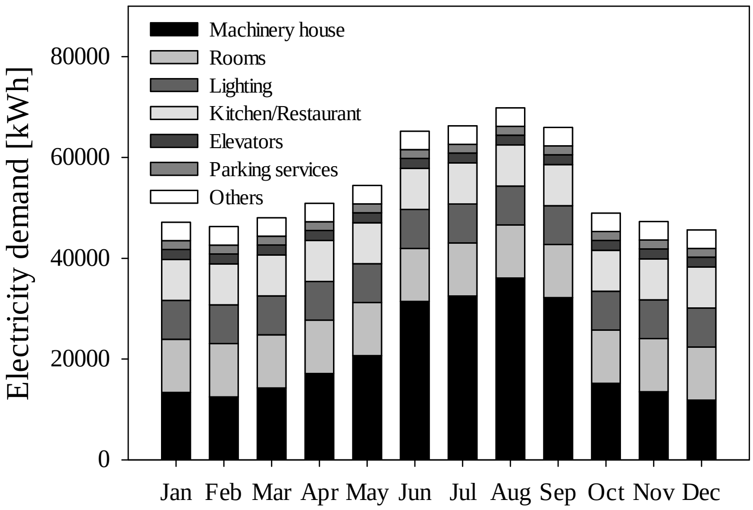


Figure 4: Primary energy, natural gas and electricity annual demand, allocated by end-users.

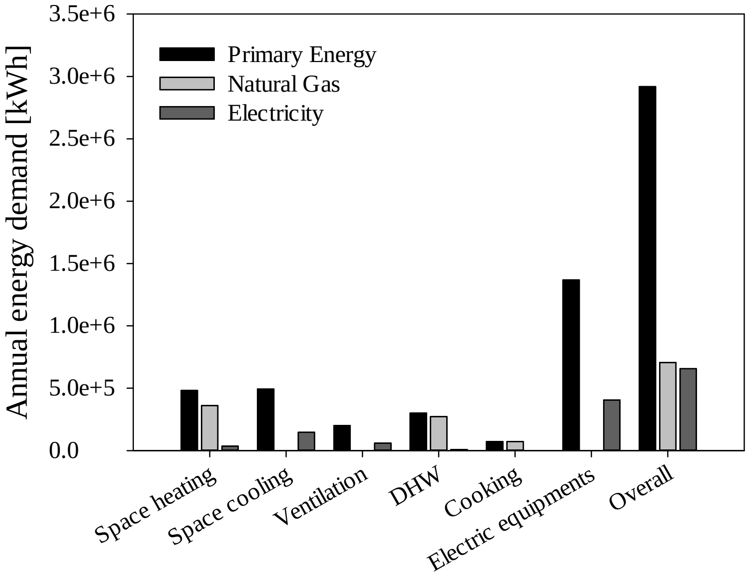


Table 2: Annual electricity allocation for the energy end-users of the technical area.

HVAC Systems	Allocation [%]	Electricity [kWh/year]
Chillers	35 %	88221
Cold water pumping	8 %	19298
AC (Cooling mode)	15 %	38813
Hot water pumping	4 %	9273
AC (Heating mode)	11 %	26972
Room convectors	1 %	3509
Ventilation (Extraction)	5 %	12281
Ventilation (outside air or "new")	18 %	43860
DHW pumping	3 %	8400
Overall	**100 %**	**250628**

As referred, for an exergy analysis, a reference dead-state temperature should be defined. In the study, as only monthly consumption was estimated, the dead-state temperature assumed was the average value of temperature verified for each month, so the quality factors change every month. For the calculation of the monthly consumption (input and useful), it was assumed that the seasonal variation, verified for the natural gas and electricity bills, is exclusively related with the air space conditioning (heating and cooling) process. The results of the monthly energy demand for the heating and cooling tasks are shown in Figure 5. The assessment of the useful energy at building's envelope was conducted based on previously formulation, using estimated efficiencies for the energy systems installed. Based on measurements derived from audit [32], the boiler (heat generator) thermal efficiency was estimated as 80 %, a *COP*=4.5 for the chiller and an average *COP*=2.5 for the individual AC units. The hot/cold water distribution and emission losses were estimated as 10 %. The useful energy for heating and cooling were also verified by dynamic simulation, where a model of the building was built and simulated using actual data provide by the maintenance staff of the hotel and the descriptive project of the building hotel.

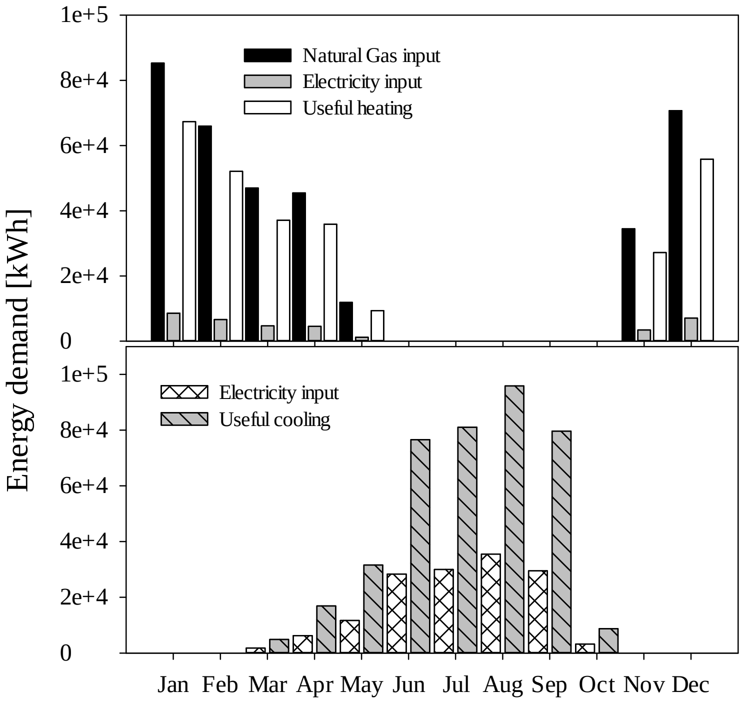


Figure 5: Monthly distribution for heating and cooling tasks, expressed as natural, electricity inputs and useful thermal at demand side.

4.3 Energy and exergy based indicators

Using the results derived from section 4.1 and 4.2 and assuming an overall efficiency for the electric grid of 30 %, value applied by [4], the *PER* and exergy efficiency indicators are presented. In Table 3 the results for natural gas, electricity and related primary energy input, the useful energy at demand side and *PER* indicator for the tasks: heating, cooling, ventilation, DHW, cooking and hotel electric equipments (lighting, elevators, personal computers and others) are presented. From the results, derived an overall *PER* of 0.49, which means that only 49 % of primary energy input is effectively used for the considered hotel's tasks. According to the results, electricity powered equipments (except the AC units and chillers) are identified as those with lower *PER* values (0.30), due to low overall electric grid efficiency used. Special attention should be given to space heating and cooling, provided by AC units (*PER*=0.59). The higher *PER* value obtained is associated to the chiller, since it has a high *COP* value. For a purely energy perspective, in Figure 6 the *EP* indicator and the *PER* for each energy end-user is shown. For the first, a floor area of 6531 m^2 was assumed. The hotel's electric equipments have the highest share of primary energy demand and the lowest associated *PER*, so they constitute the bigger end-user contributor for the decrease of the overall *PER* value of the hotel (all users). However, as it is highly influenced by the overall efficiency of the electric grid of the nation, the improvement of the overall *PER* of the building should be made by local production of electricity (e.g. Combined Heat and Power) or increase of renewable energy sources share, such as: wind, solar or hydro.

Table 3: Estimated annual energy values for heating, cooling, ventilation, DHW, cooking and hotel´s equipments and respective *PER* indicators.

Task	Primary energy [kWh/year]	Natural Gas [kWh/year]	Electricity [kWh/year]	Useful Energy [kWh]	*PER*
Heating (boiler)	360 804	360 804	n.a.	230 915	0.64
Heating (auxiliaries)	31 270	n. a.	9273	9 273	0.30
Heating (AC Units)	90 953	n.a.	26 972	53 944	0.59
Cooling (Chiller)	297 491	n.a.	88 221	317 595	1.07
Cooling (auxiliaries)	65 076	n.a.	19 298	19 298	0.30
Cooling (AC Units)	130 883	n.a.	38 813	77 626	0.59
Ventilation (quality air requirements)	201 144	n.a.	59 649	59 649	0.30
DHW	272 186	272 186	n.a.	174 199	0.64
DHW (auxiliaries)	28 327	n.a.	8 400	8 521	0.30
Cooking	73 090	73 090	n.a.	73 090	1.00
Hotel Equipments	1 367 276	n.a.	405 466	405 466	0.30
Overall	**2 918 500**	**706 080**	**656 093**	**1 429 577**	**0.49**

The assessment of the exergy level required of each task includes the assessment of a quality factor, which involves the definition of a reference state (or dead state). In this study, the monthly average outdoor temperatures were used for the dead-state air temperature for heating, cooling and cooking application and derived from the weather data available for Coimbra, Portugal [35]. For the DHW, as a water heating based user, a constant water dead state temperature of 10 ºC was assumed. The monthly dead state temperature, required temperature and correspondent quality factors for each task are shown in Table 4.

Table 4: Quality factors, dead-state temperatures and required temperatures for the thermal based tasks.

	Dead state (air), T_0 [ºC]	**Space heating (T_H = 20 ºC)**	**Space cooling (T_C =25 ºC)**	**Cooking (T_{CK} = 150ºC)**	**DHW (T_{HW} = 60 ºC; $T_{0,w}$ = 10 ºC)**
Jan	8.7	0.04	-	0.33	0.15
Feb	9.0	0.04	-	0.33	0.15
Mar	10.2	0.03	(-0.05)	0.33	0.15
Apr	12.8	0.02	(-0.04)	0.32	0.15
May	14.9	0.02	(-0.04)	0.32	0.15
Jun	17.9	-	(-0.02)	0.31	0.15
Jul	20.5	-	(-0.02)	0.31	0.15
Aug	20.1	-	(-0.02)	0.31	0.15
Sep	18.7	-	(-0.02)	0.31	0.15
Oct	15.3	-	(-0.03)	0.32	0.15
Nov	11.2	0.03	(-0.05)	0.33	0.15
Dec	9.1	0.04	-	0.33	0.15

The quality factor increases with the difference between the reference and the desired temperature for a given task. According to the obtained values, cooking and DHW tasks have higher quality factor values than space air conditioning tasks. The negative values presented in the space cooling column indicate that the monthly outdoor reference temperature is lower than the indoor desired temperature, which gives that T_0/T_i in Eq. (13) becomes lower than unit. It indicates that using average monthly values, a potential of the outdoor environment exists to perform the cooling tasks. For electric powered equipments (except for heating and cooling applications), the quality factor of the electric work is equal to the unit [34]. The exergy analysis results, expressed as specific annual exergy demand and the exergy efficiency for each end-user, are shown in Figure 7. Significant differences are shown between *PER* (Figure 6) and the exergy efficiency values. If the electricity powered equipments are associated to the lowest values of *PER*, the associated exergy efficiency assumes the highest values when compared with other tasks. Low exergy efficiency values indicate the use of high exergy sources to perform lower exergy tasks. The presented results show that space and heating application, contrarily to *PER* indication, wrongly apply the resource used as input. In this case, as these tasks have low exergy requirements, the use of high exergy source, such as natural gas, leads to low exergy efficiencies despite high *PER* values.

Figure 6: Annual primary energy demand and *PER* for hotel´s end-uses energy consumers.

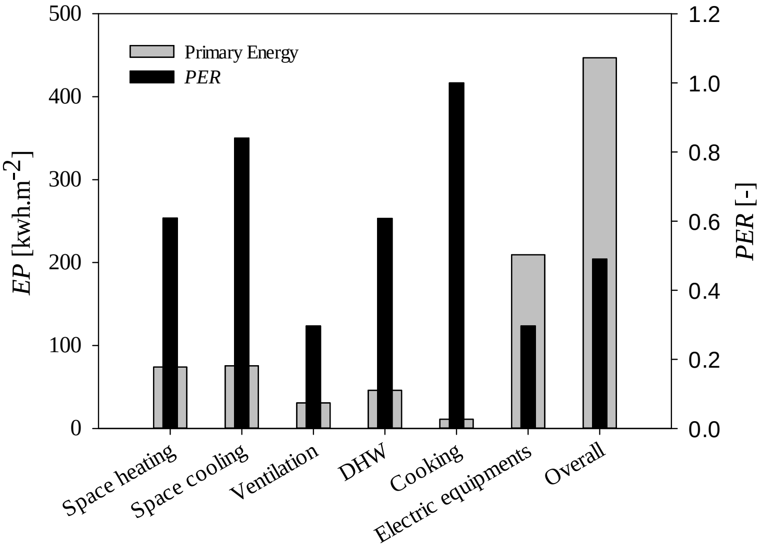
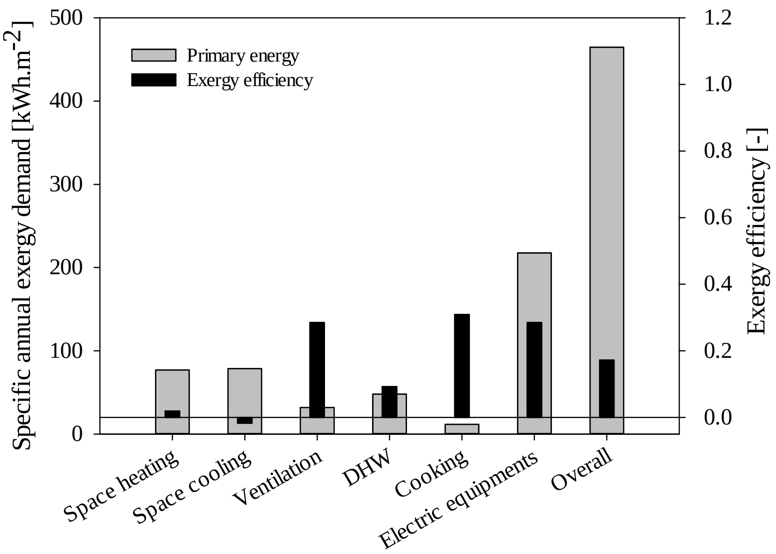


Figure 7: Annual primary energy demand, expressed as exergy values and exergy efficiency for Hotel´s end-uses energy consumers.



The "map" of the building, including information about *PER*, exergy efficiency and relative information about primary energy consumption for each task, are shown in Figure 8. The main differences between *PER* and exergy efficiency could be easily identify as well as the bigger contributors' users for the primary energy consumption of the building. Thus, the electric equipments, including lighting, ventilation and other electric devices are the main contributors to the primary energy consumption of the hotel. This is also related with its low associated *PER* value. On the other hand, space heating and cooling users reveal higher *PER* values than electric power equipments, despite low associated primary energy values. From an exergy analysis, results revealed that the electrical powered equipments are the most efficient together with the cooking application, and those associated to air conditioning systems present lowest exergy efficiencies.

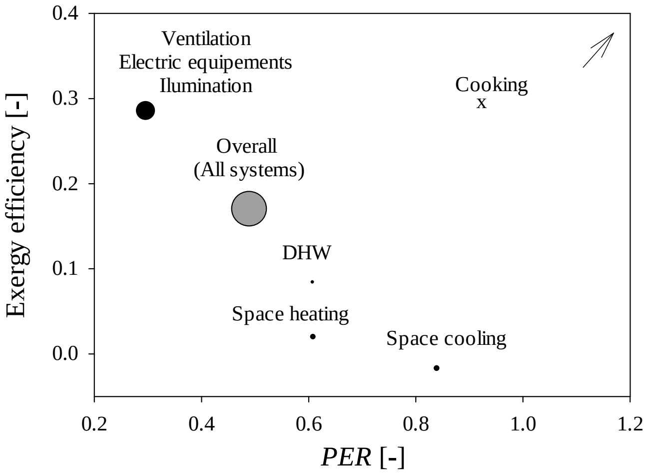


Figure 8: Exergy efficiency vs. *PER* diagram for Hotel´s end-uses energy consumers.

5 Conclusions

In this study, results derived from an energy audit conducted during an energy labelling process of a hotel building, located in Coimbra (Portugal) were used to evaluate energy and exergy performance of the building and its energy users for heating, cooling, DHW, ventilation and other hotel's electric equipments. The *EP* indicator, *PER* and exergy efficiency were evaluated as 446 kWh m^{-2} year, 49 % and 17 %, respectively. The "map" of the building, including relative information on primary energy, *PER* and exergy efficiency for the building and its energy end-users, revealed to be a useful tool for comparison between buildings and services. Furthermore, concerning the lack of exergy aspects into legislative frameworks on EPB, the study conducted could give important contributions for a possible integration of new exergy based performance indicators in new EPBD versions. As a future work, some sensitivity analysis using different energy efficiency values for the energy systems and different integrations of renewables should be taken into account to study the effect on energy and exergy performance of the building. Moreover, the approach followed could be implemented for different buildings and locations and used for comparative analysis studies.

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RESEARCH PAPER III

Energy-exergy benchmarks for energy performance assessment of buildings

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Energy-exergy benchmarks for energy performance assessment of buildings

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Abstract

Building sector is currently the largest world energy consumer, exceeding industry and transportation sectors. Traditionally, the energy assessment of buildings uses numerical indicators, based on primary energy use or related CO_2 emissions. However, these indicators are typically defined based on quantitative energy aspects, neglecting another important thermodynamic parameter related with energy quality, commonly known as exergy. In this study, primary energy and exergy based indicators are compared and their significance discussed for future inclusion on energy benchmark performance of buildings. As case-study, the primary energy and exergy performance of a student housing building located in Coimbra, Portugal was properly assessed. The annual primary consumption and exergy efficiency were evaluated as 353 kWh m^{-2} and 27 %, respectively. The contribution of each end use for the building inefficiencies is also evaluated through the indicator Exergy Destruction Ratio, indicating that space heating is the most inefficient end use of the building, followed by hot water and electric equipments. Additionally, a set of alternative supply options were proposed, and their related performances were evaluated from both energy and exergy perspectives. Significant differences were found between both approaches, concluding that despite some options may be assumed as efficient from a primary energy perspective, they may are associated to low exergy performances. The use exergy and primary energy based indicators revealed to be a more detail approach for energy performance description of buildings, expecting their integration in future energy building codes frameworks.

Keywords: Primary energy demand; Exergy analysis; Primary energy ratio; Exergy efficiency; Exergy efficiency defect.

Nomenclature

E_D	Total energy demand (kWh.m^{-2})
E_P	Primary energy (kWh.m^{-2}) or (kgoe)
Ex_D	Total exergy demand (kWh.m^{-2})
Ex_S	Total exergy supply (kWh.m^{-2})
$Ex_{s,k}$	Energy supply related to end use k (kWh.m^{-2})
$Ex_{d,k}$	Energy demand related to end use k (kWh.m^{-2})
F_p^e	Primary energy factor for electricity (-) or (kgoe.kWh^{-1})
F_p^f	Primary energy factor for fossil fuels (-)
$F_{q,eg}^f$	Quality factor of fossil fuels in use by the electric grid (-)
$F_{q,eg}^r$	Quality factor of renewable fuels in use by the electric grid (-)
$F_{q,hs}^f$	Quality factor of fossil fuels in use by the heating system (-)
$F_{q,hs}^r$	Quality factor of renewable fuels in use by the heating system (-)
T_0	Dead state temperature (K)
T_{rq}	Required temperature (K)
T_s	Supply temperature (K)
T_r	Return temperature (K)
$H2P$	Heat-to-power ratio (-)
Q_d	Thermal-energy demand (kWh.m^{-2})
W_e	Electric appliances demand (kWh.m^{-2})
I	Irreversibility (kWh.m^{-2})
PER	Primary energy ratio (-)
EDR	Exergy Destruction Ratio (-)

Greek symbols

ψ_{ove}	Overall exergy efficiency (-)
φ_e	Fraction of electricity produced from renewables (-)
φ_h	Thermal fraction produced by renewables (-)
η_{hs}^f	Efficiency of heating system powered by fossil fuels (-)
η_{eg}^f	Efficiency of electric system powered by fossil fuels (-)
η_{hs}^r	Efficiency of heating system powered by renewable sources (-)
η_{eg}^r	Efficiency of electric grid powered by renewable sources (-)

Subscripts

k	End use or task
j	Electric end use

Acronyms

ECBCS	Energy Conservation in Buildings and Community Systems
EPBD	Energy Performance of Buildings Directive
HVAC	Heating, Ventilation and Air Conditioning
RCCTE	“Regulation of the Buildings Thermal Behaviour Characteristics” (in Portuguese)
RSECE	“Regulation of the Energy Systems in Buildings” (in Portuguese)

1 Introduction

In the European Union, buildings are responsible for 40 % of energy consumption and 36 % of CO_2 emissions (Eurostat 2010). The current growth in population, growing of buildings' services and comfort levels, together with the increase of time spent inside buildings, assure that the upward trend in energy demand of buildings will continue in the future (Pérez-Lombard et al. 2008). Energy efficiency in buildings is a crucial objective for energy policy at a regional, national and international level. Within the European Union, the recast Directive 2010/31/EU aims to reinforce the improvement of the energy performance of buildings, which among other measures, recommends the adoption of a common general methodology and the use of a numerical indicator for energy performance assessment and comparison between buildings (European Commission 2010). This indicator shall be estimated based on actual annual energy consumption data, regarding to satisfy the different energy end uses of the building (e.g. space heating and cooling, domestic hot water, lighting, ventilation and electric appliances). The annual energy demand of buildings should then be converted into primary energy or CO_2 emissions values, using properly conversion factors applied independently to each energy carrier. These factors may be based on national or regional annual weighted averages or specific values for on-site production.

In Portugal, there are two main regulatory documents that establish rules and procedures for the assessment of energy performance of buildings: the Portuguese Decree-Law nº 80/2006 (RCCTE 2006) that is mostly concerned on thermal requirements of building envelopes and procedures for energy assessment of residential buildings; and the Portuguese Decree- Law nº. 79/2006 (RSECE 2006) establishes the rules for design, installation, maintenance and auditing of HVAC and other energy systems in buildings. Both documents propose an energy performance indicator based on primary energy use, using primary energy factors defined accordingly to the type of energy source or carrier (e.g. gas, oil or electricity).

Some authors have been studying the implementation of the European Directive on Energy Performance of Buildings (EPBD) in the different EU member states. Dascalaki et al. (2012) revised the EPBD transposition in Greece that was enacted into national law in 2008, and Ballarini et al. (2009) applied the EPBD method to conduct an energy assessment of residential buildings in Turin (Italy), where the heating and cooling energy use is expressed by a numerical indicator based on annual primary energy per square meter of conditioned area. Similar studies were undertaken for Ireland (Gallachóir et al. 2007), Portugal (Ferreira and Domingos 2011), Spain (González et al. 2011) and Greece (Dascalaki 2011). From the previous studies reviewed, energy indicators are exclusively based on energy conservation principle, giving especial attention to high energy consumption processes or low efficient systems. All the important aspects related with energy quality (or exergy) were neglected, lacking information about the energy quality degradation through its use in buildings. An important review study conducted by Pérez-Lombard et al. (2012) analysed and discussed some efficiency fundamental topics, avoiding unfounded judgements and misleading statements. The authors addressed the problem of measuring energy efficiency both in qualitative and quantitative terms, and discussed two key topics: the links between energy efficiency and energy savings, and the border between energy efficiency improvement and renewable sources promotion.

Concerning buildings, their main energy end uses include: space heating (SH) or cooling (SC), domestic hot water (DHW), food preparation (FP) or electric appliances (EA), which from a thermodynamic point of view have very different exergy requirements. The exergy of an energy form or a substance is the measure of its usefulness quality or potential to cause change, defined as the maximum work that can be produced by a system, flow of matter or energy when it comes to equilibrium with a specific reference or dead state (Rosen and Dincer 1997; Dincer and Rosen 2007). Unlike energy, exergy is only conserved during ideal processes and destroyed (unrecovered) due to irreversibilities in real processes (Moran and Shapiro 2008; Bejan 2006).

The exergy method has been applied in many fields: industrial sector (Madlool et al 2012; Al-Ghandoor et al. 2012 and Laurijssen et al. 2013); geothermal district heating systems (Ozgener et al. 2007; Oktay and Dincer 2009 and Ozgener and Ozgener 2009); or for a global scale to societies (Chen et al. 2011; Koroneos 2011). In buildings, the exergy method has been applied with different objectives: Gonçalves et al. (2012) compare energy and exergy indicators for each energy end use of a hotel building, using actual data derived from an energy audit; Yucer and Hepbasli (2011) performed a thermodynamic analysis of an educational building using exergy analysis method and found as exergetic efficiencies for boiler and the fan coil, 13.4 % and 37.6 %, respectively; and Yildiz and Güngör (2011) applied the energy and exergy method for the assessment of the entire space heating process of buildings, using a pre-design analysis tool, developed by Schmidt (2003) and also widely applied at ECBCS-IEA Annex 37 (IEA 2003). Significant contributions for the topic exergy analysis of buildings were done by the international research work ECBCS-IEA Annex 37 (IEA 2003) and Annex 49 (IEA 2010). Within ECBCS-IEA Annex 37, the authors define low exergy systems as “heating or cooling systems that allow the use of low valued energy as the energy source” with focus on space heating applications. On the other hand, ECBCS-IEA Annex 49 defines low exergy systems as “systems that are able to provide acceptable thermal comfort with minimum exergy destruction”, aiming to find the optimal match between quality (i.e. exergy) levels of supply and demand for any use or appliance within buildings. Furthermore, Schmidt (2009) summarises the international co-operative work ECBCS-IEA Annex 49 and Torio et al. (2009) conducted a critical review of the exergy analysis of renewable energy-based climatisation systems for buildings, finding among other conclusions, that exergy analysis should always come in parallel with the energy analysis, and that a common agreement on the methodologies for the exergy analysis of renewable energy-based climatisation systems is mandatory for any proposal dealing with the application of exergy indicators in a normative framework. In the research studies (Sakulpipatsin et al 2010; Gonçalves et al. 2011 and Balta et al. 2008), the exergy topic was applied highlighting its relevance for design and assessment of buildings and their HVAC systems.

Most of the papers devoted to energy assessment of buildings are mainly concerned on the reduction of their primary energy demand, which may be done by increasing insulation levels or increasing the air tightness of the building envelope. The exergy analysis can be used to optimise the performance of energy systems both on a component or system levels and some authors suggest that it should be performed always in parallel with the energy analysis. However, energy and exergy analyses lead to different or even opposite conclusions and it is not always explained how authors would combine the different indications derived from the two approaches. Concerning renewable sources, they are not necessarily low exergy sources (Torio et al. 2009) and some of them should be considered as high exergy sources (e.g. biomass is comparable to fossil fuels), while others are low exergy sources, when a physical boundary is adopted (e.g. solar thermal). It is still an open question whether it is more important to save primary energy or to save primary exergy, which means using renewable and non-renewables sources in the most efficient way. All these issues may represent a limit to the widespread of the exergy analysis and to the comprehension of its relevance. In this study, an overall methodology is presented combining energy and exergy analyses in renewable energy-based systems. It aims to apply a set of energy and exergy based indicators and discuss their use for different energy supply strategies, including the use of fossil and renewable sources. As a case study, a student housing building located in Coimbra (Portugal) was considered. A simple energy audit was conducted regarding to assess the monthly energy consumption profiles and the related break-down by energy end uses. The study comprises a whole energy and exergy analyses, following an approach from demand to supply side, including inputs from fossil and renewable sources. The overall primary-fossil energy consumption, primary energy ratio (*PER*) and exergy efficiency (ψ) were used as indicators. Additionally, the parameter proposed by Bejan et al. (1996), designated by Exergy Destruction Ratio (*EDR*) was assessed, regarding to find the main contribution of each end use for the building overall inefficiencies. A set of parametric analyses were conducted by changing parameters, such as: systems efficiency, heat demand or different integration of renewables into both thermal and electrical systems.

2 The energy and exergy method

2.1 Primary energy factors

The methodology followed by EPBD proposes the use of energy performance indicators based on primary energy use or CO_2 emissions. The quantification of suitable conversion factors is not an easy task, especially for electricity and thermal networks, since it takes into account several parameters, such as, the mix of energy sources within certain geographical boundaries (international, national, regional or local). Furthermore, the interaction between buildings and energy grids for every country or regional area has different challenges to face regarding their energy infrastructure, different climate and building traditions (Utlu and Hepbasli 2007).

EPBD establishes that every country has to define primary energy or carbon emission conversion factors for the different energy carriers, establishing requirements on energy efficiency or prioritizing certain supply technologies. There are not “right” conversion factors in absolute terms. Rather, different conversion factors are possible, depending on the scope and the assumptions of the analysis. It leads to the fact that ‘strategic factors’ weighting factors may be adopted in order to find a compromise agreement (Utlu and Hepbasli 2007). They may be used to include considerations not directly connected with the conversion of primary sources into energy carriers or to promote or discourage the adoption of certain technologies and energy carriers. As example, biomass and biofuels would have a very low conversion factor, making them an attractive solution, however, the availability of biomass is not infinite and it needs to be used also for other non-energy purposes, such as, food production. Therefore, in regions with low local availability, it may be desirable to increase the conversion factor in order to reduce the attractiveness of biomass relatively to other solutions (e.g. solar thermal systems) (Utlu and Hepbasli 2007).

In Portugal, the current legislation on energy performance of buildings, RCCTE (2006) proposes an energy efficiency indicator expressed in primary energy demand per square meter, applying as primary energy factors the following quantities: 0.290 kilogram(s) of oil equivalent (kgoe) per kWh of electricity, and 0.086 kgoe per kWh of solid, liquid or gas fuels. Conventionally, one kgoe is equivalent to the approximate amount of energy that can be extracted from one kilogram of crude oil, assigned a net caloric value of 41 868 $kJ.kg^{-1}$ or 11.63 kWh. Using the same units for the conversion factors (kWh), these factors are equivalent to 1 $kWh_p\ kWh^{-1}$ for solid, liquid or gas fuels and 3.372 $kWh_p\ kWh^{-1}$ for electricity, where the subscript “p” indicates a primary energy quantity. The value for electricity indicates a global efficiency (thermal to electrical conversion at the power plant, plus grid losses) of 30 %, or a requirement of 3.372 kWh of primary-fossil energy to supply 1 kWh of electrical energy at the end-user. However, this value is not updated and does not correspond to the actual Portuguese electric grid performance, because it does not consider the use of the recent installed renewables power plants for electricity production, leading to the reduction of primary-fossil resources demand, and thus to a different conversion factor. Furthermore, these parameters are only concerned with a pure energy quantitative perspective, neglecting important energy quality aspects. The proposed methodology includes primary energy and quality energy aspects and follows an approach from the demand to supply side, where ‘demand’ corresponds to energy or exergy requirements at end uses (e.g. heating (SH), domestic hot water (DHW), food preparation (FP), electric appliances (EA), .etc) and ‘supply’ corresponds to the energy or exergy supplied derived from renewables or fossil energy resources.

In Fig. 1, the main energy sources, energy flows, end uses and the boundary condition adopted by this study are represented, where the main sub-systems and flows applied by the case-study building and additional scenarios proposed are highlighted.

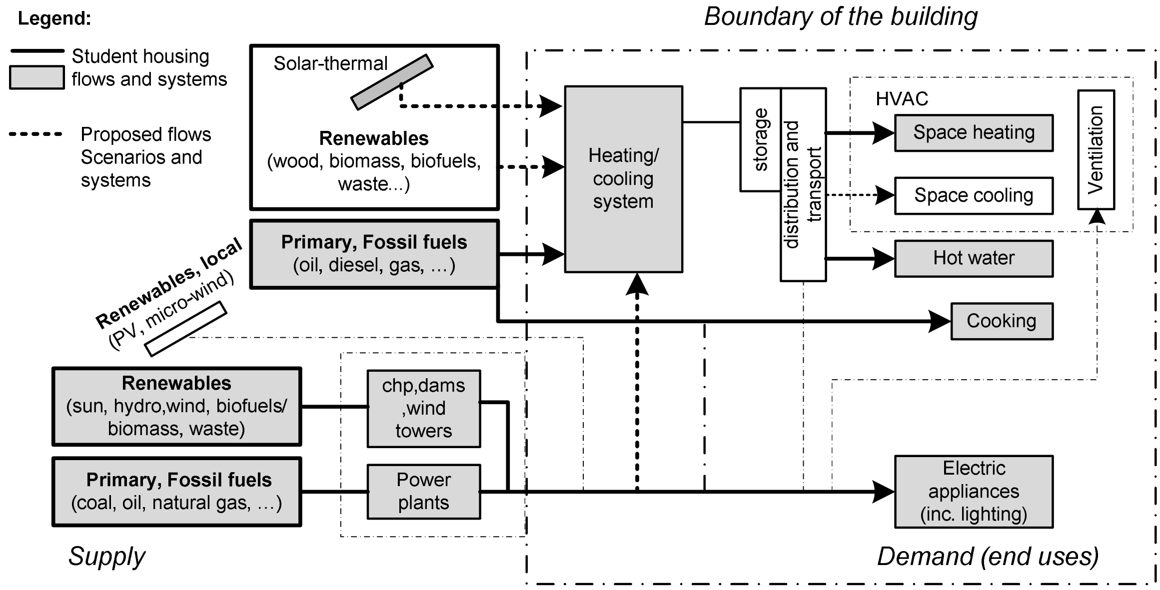


Fig.1 Generic scheme of the building energy systems and related energy flows

2.2 Energy and exergy at end uses

The total exergy demand of buildings is generically given by the sum of the exergy associated to thermal energy demand (e.g. SH, SC, DHW, FP) and electricity required for the electric based end-uses (e.g. ventilation, lighting and electric appliances). A simplified method to calculate the exergy demand related to thermal end uses was developed by Schmidt (2003). In this approach, the exergy thermal demand can be calculated simply by multiplying the energy demand with the quality factor of heat (or cold) at given required temperature (e.g. for space heating/cooling applications, the required temperature is usually considered to be the temperature of the indoor air). The exergy associated to electricity demand is equivalent to the energy quantity. Therefore, the total energy and exergy requirements at demand side of the building, including thermal and electric end uses is generically given by Eq. (1) and Eq. (2), respectively (IEA 2010).

$$E_D = \sum_k Q_{d,k} + \sum_j W_{e,j} \tag{1}$$

$$Ex_D = \sum_k Q_{d,k} \underbrace{\left(1 - \frac{T_0}{T_{rq,k}}\right)}_{F_{q,k}} + \sum_j W_{e,j} \tag{2}$$

where, $Q_{h,k}$ is the thermal energy demand related to end use k; T_0 and $T_{rq,k}$ are the dead state temperature and required temperature for the task k, respectively, and W_e is the electricity demand of the building. $F_{q,k}$ is usually called the quality factor (IEA 2010), related to thermal end use k. The exergy demand of thermal end uses only takes into account the thermal component of the energy demand, no chemical or pressure components are included; which is reasonable as long as no (de)humidification is present (IEA 2010). Furthermore, the method implies that all the energy is supplied at a given T_{rq} . This is the required temperature at which the energy can be supplied or removed from the zone ($T_{rq} \geq T_{room}$ in case of heating or $T_{rq} \leq T_{room}$ for cooling).

The assessment of thermal and electric requirements, Q_h and W_e, respectively may be given by two different approaches: for new buildings, they are estimated using methods defined based on legislative frameworks on energy performance of buildings; for existing buildings, the thermal and electric demand are usually estimated by an energy audit following an approach from supply to demand side, accounting for the inefficiencies through the supply energy network.

2.3 Primary-fossil energy demand

The sources that may be used to meet the energy requirements of the building are divided into fossil (non-renewable) and renewables, as shown in Fig. 1. These sources can be directly used by energy building systems or converted into electricity for further utilization in electric based applications. In this study, from a purely energy analysis perspective, only primary-fossil energy resources were accounted, following the same rule of the major regulatory frameworks on energy performance of buildings. Therefore, the most efficient buildings are those that make low use of primary fossil energy resources (that means using as much as possible renewable sources). In this section, the formulations for assessing the primary-fossil energy demand are presented. “Primary-fossil” or simply “primary” means the energy contained in fossil fuels, such as, natural gas, coal, fuel oil or diesel. The energy assessment of fuels is commonly given between the mass flow rate and the Lower Heating Value. Despite some of these energy sources require additional primary energy to be processed, those were not accounted in this study.

Taking into account the assumptions previously described, and knowing the thermal and electric energy demand of the building end uses, the total primary energy is given by Eq. (3). This formula was based on IEA (2010) and re-arranged for this study.

$$E_P = \sum_k F_{p,k}^f \frac{Q_{h,k}}{\eta_{hs,k}^f}\left(1-\varphi_{h,k}\right) + F_p^e \sum_j W_{e,j} \tag{3}$$

where, $F^{f}_{p,k}$ is the primary energy factor associated to the fossil source used to fulfil the thermal end use *k*, F^{e}_{p} is the primary energy factor of electricity, $\eta^{f}_{hs,k}$ is the efficiency of the energy conversion system powered by fossil sources and related to the end use *k*, $\varphi_{h,k}$ is the fraction of heat delivered derived from renewables, which is given by the ratio of heat derived from renewables to the total heat produced by the heating system . When electricity is used as energy carrier for the thermal end uses, $F^{f}_{p,k} = F^{e}_{p}$, where the primary energy factor for electricity is given by

$$F^{e}_{p} = \frac{1-\varphi_e}{\eta^{f}_{eg}} \tag{4}$$

where η^{f}_{eg} is the overall efficiency of the power plants installed, including energy losses in the distribution, and φ_e is the ratio of electricity derived from renewables to the total electricity produced.

2.4 Total exergy input

The assessment of the exergy input includes both fossil and renewable energy sources, aiming to find the most efficient use of these sources according to the different building exergy requirements. From an exergy viewpoint, high performance buildings are those that have a high match between exergy supply and demand, measured by the indicator “exergy efficiency” (further defined).

Considering the building of Fig. 1, the thermal and electric energy building end uses can be fulfilled by fossil and renewable sources, therefore the total exergy supplied to the building is generically given by Eq. (5). This formula was based IEA (2010) and re-arranged for this study.

$$Ex_S = \sum_k Q_{h,k}\left(\frac{1-\varphi_{h,k}}{\eta^{f}_{hs,k}}F^{f}_{q,hs,k} + \frac{\varphi_{h,k}}{\eta^{r}_{hs,k}}F^{r}_{q,hs,k}\right) + W_e\left(\frac{1-\varphi_e}{\eta^{f}_{eg}}F^{f}_{q,eg} + \frac{\varphi_e}{\eta^{r}_{eg}}F^{r}_{q,eg}\right) \tag{5}$$

where, $F^{f}_{q,k}$ and $F^{r}_{q,k}$ are quality factors associated to fossil fuels and renewable sources, respectively, $\eta^{f}_{hs,k}$ and $\eta^{r}_{hs,k}$ are the efficiency of the heating system associated to thermal use *k*, powered by fossil (or derived) and renewables, respectively. η^{f}_{eg} and η^{r}_{eg} are the efficiency of the electric grid, powered by fossil and renewable sources, respectively. $F^{f}_{q,eg}$

and $F^{r}_{q,eg}$ are quality factors associated to fossil fuels and renewable sources used by the electric grid, respectively. When a given thermal end used k is powered by electricity, $F^{f}_{q,hs,k} = \left(\frac{1-\varphi_e}{\eta^{f}_{eg}} F^{f}_{q,eg} + \frac{\varphi_e}{\eta^{r}_{eg}} F^{r}_{q,eg} \right)$, which represents the weighted quality factor for the electricity and may be produce from fossil and renewable sources.

For the particular use of direct low-temperature renewable sources (e.g. solar thermal system), the quality factor, $F^{r}_{q,hs}$ is calculated by Eq. (6), where, T_s and T_r are the supply and return temperature, respectively.

$$F^{r}_{q,hs} = 1 - \frac{T_0}{T_s - T_r} \ln\left(\frac{T_s}{T_r}\right) \tag{6}$$

2.5 Key Performance indicators

In this sub-section, two main indicators are defined regarding to assess the energy and exergy performance of the building. The Primary Energy Ratio (*PER*) aims to evaluate the primary-fossil energy use efficiency and the exergy efficiency measures the exergy performance of the buildings (including fossil and renewable inputs). Additionally, regarding to quantify the contribution of each end use for the overall inefficiencies of the building, the indicator *EDR* is also further defined.

2.5.1 Primary Energy Ratio

Primary Energy Ratio (*PER*) is defined as the ratio between useful energy (at building end uses) and total primary-fossil energy supplied, as given by Eq. (7) (IEA 2010).

$$PER = \frac{E_D}{E_P} \tag{7}$$

where, E_D is the overall energy demand building end uses, and E_P is the total primary-fossil energy demand of the building, defined by the Eq. (3).

2.5.2 Exergy efficiency

The exergy efficiency is an indicator able to measure the exergy performance of the building using whole-building energy and exergy data at supply and demand. It is always lower than unit and depends on the occurrence of the irreversibility degree at building energy conversion processes, being particularly suitable for assessing the thermodynamic perfection degree of the building (Moran and Shapiro 2008; Dincer and Rosen 2007). In this study, the exergy efficiency is given as the ratio between the exergy demand at the building end uses and overall exergy requirements of the building, as given by Eq. (8) (IEA 2010).

$$\psi_{ove} = \frac{Ex_D}{Ex_S} \tag{8}$$

where, Ex_S is the total exergy supplied, associated to energy inputs from renewables and fossil fuels, defined by Eq. (5), and Ex_D is the exergy associated to energy demand at end uses, given by Eq (2).

2.5.3 Exergy Destruction Ratio

Considering that the maximum exergy efficiency has a theoretical value of 100 %, the difference between the actual and theoretical exergy efficiency may give an indication about the exergy improvement potential of the building. Nevertheless, this indicator alone cannot provide any information about the contribution of each end use for the overall inefficiencies which occurred at the building. In this study, the concept of Exergy Destruction Ratio (*EDR*) defined by Bejan et al. (1996) was applied to identify and rank building energy end use by thermodynamic inefficiencies. *EDR* is defined by the ratio between the irreversibility associated to each end use, I_k and the total exergy inputs Ex_S, as defined by Eq. (9).

$$EDR_k = \frac{I_k}{Ex_S} \tag{9}$$

The irreversibility associated to a given building end use, *k*, is given by Eq.(10), where $Ex_{s,k}$ and $Ex_{d,k}$ are the exergy supplied and exergy demand, respectively, both associated to the end use *k*.

$$I_k = Ex_{s,k} - Ex_{d,k} \tag{10}$$

Furthermore, the sum of *EDR* of each *k* end use is related with the overall exergy efficiency of the building, ψ_{ove}, as given by the Eq. (11).

$$\sum_k EDR_k = 1 - \psi_{ove} \tag{11}$$

3 An illustrative example

As case-study, a student housing building located at Campus II of the University of Coimbra (Portugal), with a total floor conditioned area of about 1807 m^2 was examined. The building has four floors and from top-view has a rectangular shape, with the main facade south-orientated. Each floor is composed by eighteen double rooms (with bathroom), one kitchen, a living and study room. At the ground floor the technical rooms, laundry/clothes preparation and study rooms are located.

The building has a maximum capacity of 144 students and operates 24 hours per day, eleven months per year. In August, the building is closed and does not operate due to the students' holiday break, so this period was not included into the analysis. The building is equipped with a centralized heating system, constituted by a natural gas boiler, two storage tanks and a hydraulic distribution/emission system able to satisfy the requirements for space heating and domestic hot water requirements of the building. Natural gas is also used in the kitchen for food preparation. No HVAC systems are installed for space cooling needs. The electricity is used for lighting, appliances and other electric equipments, and it is supplied by the national Portuguese electric grid, which is supply with fossil and renewable sources. Four main energy end uses were included into the analysis: space heating, domestic hot water, food preparation and electrical appliances (lighting, elevators, computers, others).

3.1 Portuguese electric grid efficiency

The Portuguese electric grid accounts for a great number of energy sources for the electricity production, including both fossil and a high share of renewable sources. Using information from IEA (2012) for Portugal, the mix of sources used for electricity production is shown in Fig. 2.

In this study, fossil sources include coal, oil and natural gas, while renewables sources account for biofuels and waste and earth resources, which includes hydro, wind, solar PV and geothermal. Furthermore, to estimate efficiencies by type of source, the ratio of energy inputs to electricity produced from each source was accounted. Having these assumptions in mind, and using the symbols presented in Section 2, the Portuguese electric grid performance, including losses in distribution, presents the following parameters: $\eta_{eg}^{f} = 0.40$; $\eta_{eg}^{r} = 0.77$; $\varphi_r = 0.38$.

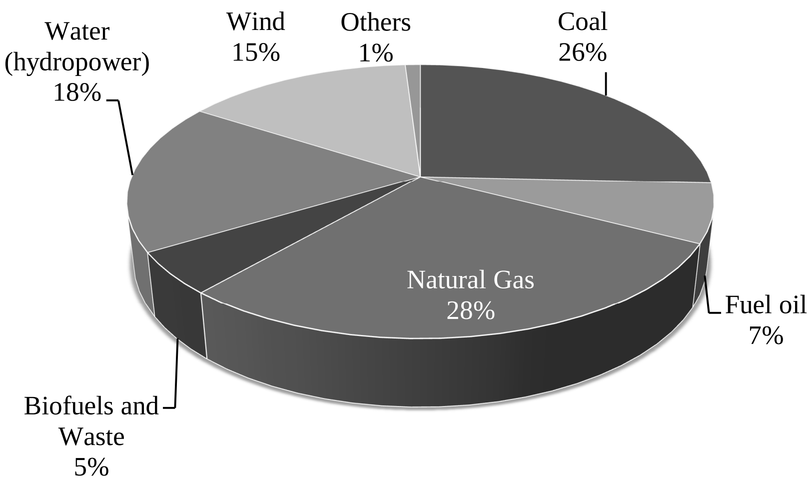


Fig. 2: Mix by sources used by the Portuguese electric system in 2009.

3.2 The reference environment and quality factors

The exergy analysis requires the knowledge of the monthly energy consumption and respective quality factor of the sources used, as well as, information about the minimum exergy requirement associated to each building end use. The exergy demand requires the knowledge of the dead-state and required temperature, defined for each building thermal-based end use. In this study, the dead state was defined using the outside monthly mean air temperature and required temperature for space heating, domestic hot water and food preparation were established as 20 ºC, 60 ºC and 120 ºC, respectively. The value of 20 ºC for space heating requirements is usually the minimum temperature required to achieve indoor comfort environments, and 60 ºC is the typical value defined for the hot water requirements in buildings. These two temperatures are in accordance with the related values presented at the studies (IEA 2010; Schmidt 2009). The required temperature defined for food preparation (120 ºC) may be discussed due to huge number of food preparation methods used (e.g. baking, roasting, frying, grilling, barbecuing, smoking, boiling, steaming and braising). The value of 120 ºC as required temperature for food preparation was defined based on Utlu and Hepbasli (2007). The monthly quality factor values defined for each building end use are presented in Table 1. For the electric powered equipment, the quality factor assumes the value of the unit.

At supply side, natural gas was used by the heating system and directly for food preparation. The quality factor associated to renewables for the heating system (e.g. hot water derived from solar-thermal) was calculated based on Eq. (6), assuming a supply temperature of 60 ºC and a return temperature of 40 ºC (IEA 2010). The quality factor associated to fossil sources for the electric system was calculated based on weighted quality factors of coal (1.03), natural gas (0.92) and oil (0.99) – the main fossil sources used by the Portuguese electrical system (Utlu and Hepbasli 2007). Finally, the quality factor associated to electric grid renewables was estimated based on the weighted quality factors of two main sources: earth sources (wind, hydro, etc), assumed as having a quality factor equal to unit; and biofuels and waste (burned fuels) that the quality factor was assumed as the same of the quality factor of wood (1.03) (Utlu and Hepbasli 2007). The quality factors at supply side applied in this study are presented in Table 2.

Table 1: Monthly air dead-state temperatures and related quality factors for the end uses: space heating (SH), domestic hot water (DHW) and food preparation (FP)

Month	T_0	$F_{q,SH}$	$F_{q,DHW}$	$F_{q,FP}$
Jan	282.35	0.04	0.15	0.33
Feb	282.95	0.03	0.15	0.33
Mar	283.95	0.03	0.15	0.33
Apr	286.25	0.02	0.14	0.32
May	288.85	0.01	0.13	0.32
Jun	291.75	0.00	0.12	0.31
Jul	294.25	0.00	0.12	0.30
Aug	294.25	0.00	0.12	0.30
Sep	292.75	0.00	0.12	0.31
Oct	289.45	0.01	0.13	0.32
Nov	284.95	0.03	0.14	0.33
Dec	282.45	0.04	0.15	0.33

Table 2: Main quality factors of the sources evaluated at supply side

Source	**Symbol**	**Value**	**Reference**
Natural gas	$F_{q,k}^{f}$	0.92	(IEA 2010)
Solar thermal	$F_{q,k}^{r}$	0.15	(IEA 2010)
Fossil fuels (electric grid)	$F_{q,eg}^{f}$	0.98 (weighted)	(Utlu and Hepbasli 2007)
Renewables (electric grid)	$F_{q,eg}^{r}$	0.97 (weighted)	(Utlu and Hepbasli 2007)

4 Results and discussion

The results presented in this section are based on an actual whole building energy data derived from natural gas and electricity bills reported to the year 2009. Additional information based on occupancy patterns, efficiency of the systems installed and other information provided by the technical staff were used for estimating the monthly energy breakdown by end use. The results are presented in Fig. 3, showing the energy demand for the different end uses of the building. Electric appliances, food preparation and domestic hot water have approximately a constant energy demand over the year, while, space heating demands show the expected seasonality. In this section, the energy and exergy performance of the building are presented for each month, using the current energy supply system. Additionally, *EDR* was applied to evaluate the contribution of each end use for the overall building inefficiencies. Keeping the same building energy requirements, a set of different alternative supply scenarios were proposed and their annual primary energy and exergy performance were assessed. At the end, the primary energy demand was compared with the reference primary energy value, established for this category of buildings in Portugal.

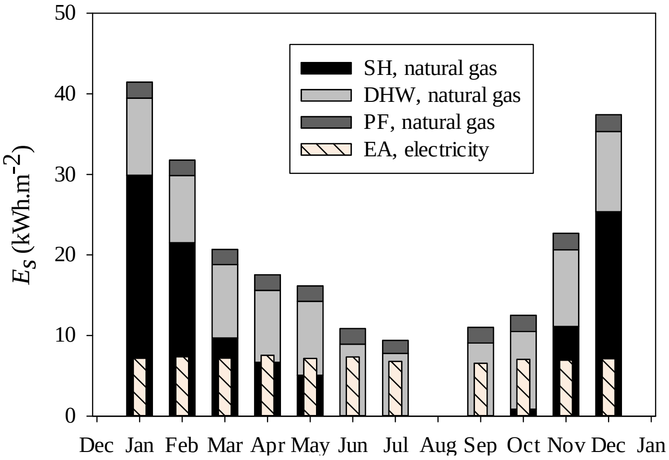


Fig. 3: Energy supply by energy source or carrier, considering the current energy supply scenario of the student housing building

4.1 Primary energy requirements

In the current energy supply scenario of the building, the heating system is constituted by a natural gas boiler, with a thermal efficiency of about 90 %, and do not include inputs from renewable. The electricity to fulfil the electric requirements is provided by Portuguese electric grid whose the related performance is presented in Section 3.2. The monthly primary energy demand and the ratio between heat demand and electricity (*H2P*) are presented in Fig. 4, showing how these two important parameters

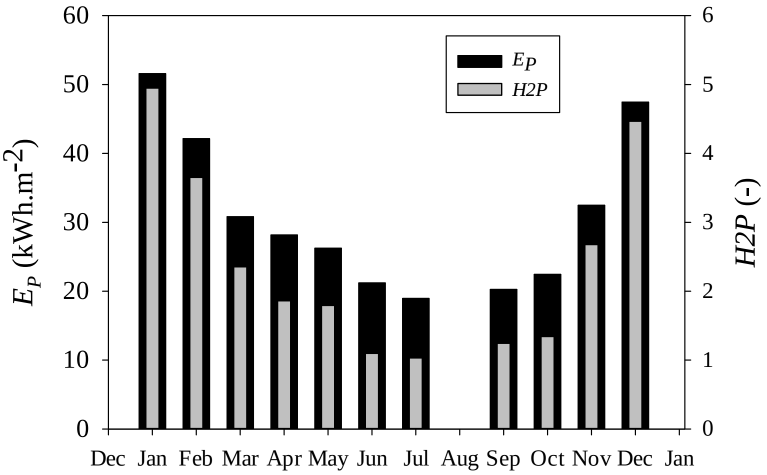


Fig. 4: Primary energy and heat to power ratio of the student housing building for the current energy supply scenario.

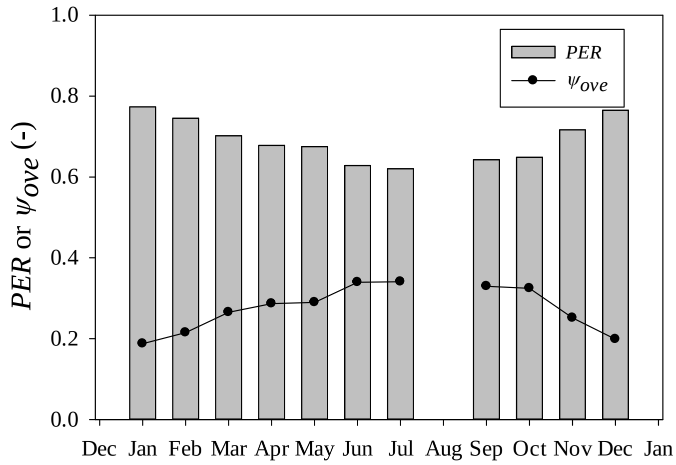
change over the year. Due to the increase of space heating requirements in the winter, high primary energy values (and *H2P*) are obtained in the winter season. With an exclusively primary energy approach, the results show that high potential for reducing the primary energy demand of the building occurs in the cold season (winter), indicating that more efficient heating systems should be installed or renewables can be supplied for thermal production.

4.2 Energy and exergy performance

The primary energy demand provides information about absolute energy quantities; however, it does not provide information about the efficiency of conversion itself. Using as energy efficiencies for the boiler and electric grid, 90 % and 40 %, respectively, it is possible to conclude that thermal based end uses are individually more efficient than electric ones. However, since the exergy levels of the building end uses are too different only an exclusive energy approach could lead to not thermodynamic true results.

In Fig. 5, the indicators *PER* (based on primary energy use) and exergy efficiency are presented for the current building energy supply scenario. The results show significant differences between primary energy and exergy efficiency perspectives: high *PER* values are obtained in the winter season, while the higher exergy efficiency is obtained in the summer. Despite the fact that the high energy efficiency (or *PER*) of the building occurs in the winter season, the low-exergy requirements associated to space heating tasks, together with the use of high exergy sources (e.g. natural gas) as supply sources, leads to low-exergy efficiencies in this period. On the other hand, when the space heating requirements are reduced or the ratio *H2P* decreases, the overall exergy of the building increases, and its maximum value occurs when the thermal needs are lower.

Fig. 5: Monthly evolution of *PER* and exergy efficiency of the student housing building for the current energy supply scenario.



From an exergy point of view, the results show that a higher potential for improving the exergy performance of the building occurs in the winter season, which could be accomplished by replacing high exergy sources (e.g. natural gas) by low-quality ones, such as, hot water from solar thermal or waste source nearby. Using low-temperature sources from renewables, the exergy performance of the building increases, while reduce the related primary energy demand is reduced.

4.3 Building inefficiency

The previous results showed that the annual primary energy of the building is 353 kWh m^{-2} and its annual exergy efficiency is about 27 %. For benchmark purposes, the legislation on energy performance of buildings recommends that the primary energy demand of the building should be compared with a given reference value, defined according to similar well-design buildings, taking into account the climate and suitable materials and construction techniques.

Concerning exergy, the maximum (ideal) building performance is achieved when exergy efficiency is equal to the unit (100 %). Thus, since the students' housing has annual exergy efficiency of about 27 %, the related building potential improvement is about 73 %, which represents a quantification of the building inefficiencies. Therefore, after quantifying the related thermodynamic inefficiencies, another question may arise: "Which is the contribution of each end use for the overall building inefficiencies?" This important question could be answered by the indicator *EDR* that was defined by Eq. (11). This important indicator was assessed for the four main end uses of the building, assuming the current building supply scenario.

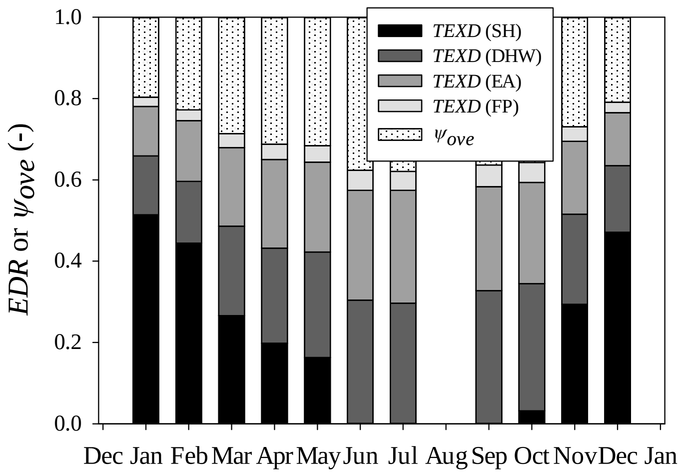


Fig. 6: Exergy efficiency and *EDR* related to the end uses of the student housing building

The results presented in Fig. 6 show that for winter season the main contributors of building inefficiencies are the space heating, followed by hot water and electric appliances.

On the other hand, in the summer season, the most inefficient end uses are associated to domestic hot water and electricity production. Space heating and hot water are clearly the most inefficient end uses of the building; nevertheless their main associated energy conversion system (natural gas boiler) has high thermal energy efficiency. *EDR* was found as a significant indicator that is able to identify and quantify the building inefficiencies contributors, pointing at the right directions for its performance improvement.

4.4 Primary energy vs. exergy efficiency

In the previous section, the monthly primary energy and exergy efficiency of the building were shown, and the contribution of each end use for the building inefficiencies was identified. In this section, a set of different energy supply scenarios are evaluated using primary energy and exergy efficiency indicators. The following parameters change for each scenario: share of renewables for electrical and heating system, heating system efficiency/technology and space heating demand. Fifteen scenarios, divided into four main groups (A-D), each one associated to a different parameter were proposed and evaluated. The proposed scenarios and related parameters are presented in Table 3.

Table 3: Proposed scenarios for the energy and exergy performance assessment

Scenario	Parameter	Value	Description
A-I	φ_e	0.00	- Integration of renewables in the electric system from 0 to 0.6.
A-II		0.20	
A-III		0.40	
A-IV		0.60	
B-I	η_{hs}^{f}	0.80	- Fuelled based heating system.
B-II		0.92	
B-III		0.98	- Electric heating.
B-IV		2.50	- Heating based on heat pump.
C-I	φ_h	0.10	- Integration of renewables in the heating system.
C-II		0.20	
C-III		0.50	
D-I	Q_h	-20 %	- Space heating demand decrease.
D-II		-40 %	
D-III		+50 %	- Space heating demand increase.
D-IV		+100 %	

The results related to each scenario, expressed as primary energy and exergy efficiency are presented in Fig. 7. The scenarios A-I to A-IV, parametric analyses with different integration of renewables into the electric system were examined. The results show that the integration of renewables in the electric grid leads to a reduction of primary energy demand of the building and an increase of exergy efficiency. These results occur because the energy efficiency related to renewables is higher than the fossil sub-system, 77 % and 40 %, respectively, as reported in Section 3.1.

The effects of applying different heating efficiencies or technologies are evaluated in Scenarios B-I to B-IV. As shown in Fig. 7, from B-I to B-II, the increase of the energy efficiency of fuel based heating systems conducts to a reduction of primary energy and an increase of exergy efficiency. When the fuel based heating system (B-II) is replaced by an electric one, even with approximately the same efficiency (B-III), the performance of the electric grid is included, leading to an increase of primary energy and a huge decrease of exergy efficiency. Replacing it by a heat pump *COP* 2.5 (Scenario B-IV), the exergy efficiency increases and the primary energy demand decreases. Among all, this scenario has the lower primary energy demand and the second best exergy efficiency performance.

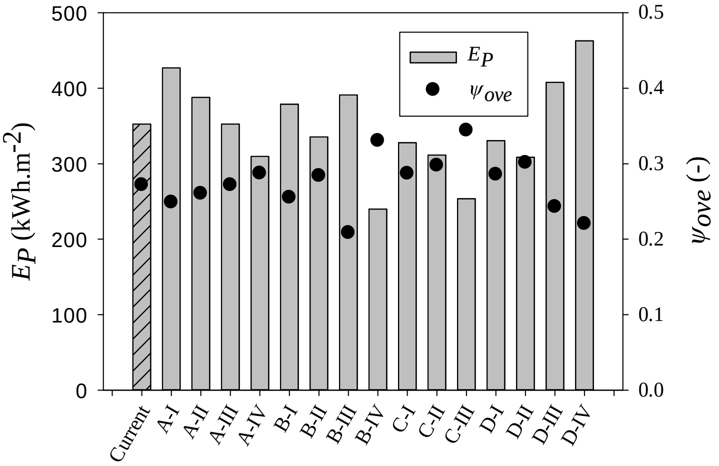


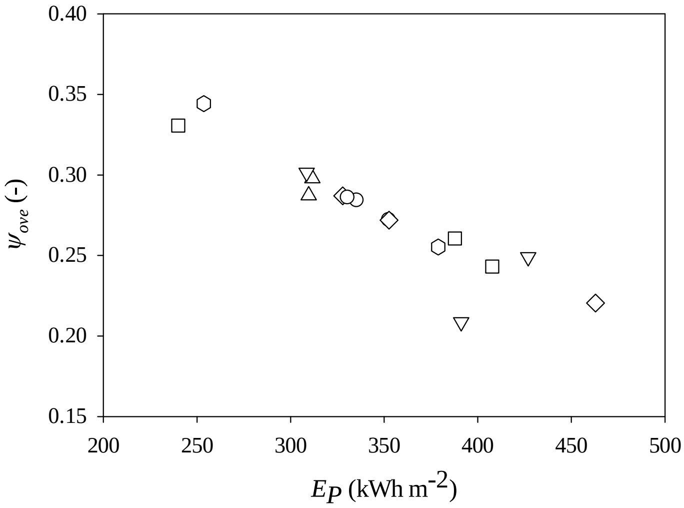
Fig. 7: Primary energy and exergy performance for the scenarios proposed in Table 3.

The scenarios C-I to C-III regard to evaluate the integration effect of renewables (from low-temperature sources: thermal solar system) into the heating system. According to the physical boundary defined in Fig.1, inputs from solar-thermal systems are assumed as thermal-based products, and in this study were evaluated as supply temperature, T_s = 60 ºC and return temperature, T_r = 40 ºC. Therefore, the replacement of high exergy inputs, such as natural gas, by low-exergy renewable ones (e.g. solar thermal sources), conducts to a decrease of the primary energy demand and an increase of exergy efficiency of the building.

Finally, scenarios D-I to D-IV aim to assess the sensitivity of the primary energy and exergy efficiency indicators by changing the space heating demand of the building. The results indicate that decreasing the space heating requirements of the building, the primary energy reduces, while the exergy efficiency improves. The contrary is verified when the space heating requirements of the building increase. Moreover, this parameter is highly influenced by the insulation of the building, so improvements on the building insulation lead to a decrease of the building space heating demand, contributing positively for the reduction of primary energy demand and increase on the exergy efficiency. These results also prove the results found out by *EDR* that attributes the most inefficient end use of the building to space heating requirements. So, any reduction of the space heating demand, leads to improvements on overall exergy efficiency, as shown by D-I to D-IV results.

For a general view of all options, the relationship between exergy efficiency and primary energy is shown in Fig. 8. The results show a decreasing tendency of the exergy efficiency, while the primary energy of the building increases. However, this tendency is not a rule, so it can be changed for other proposed scenarios not included in this study. It may be particularly useful to compare options with similar primary energy, but that could present different exergy performances. Furthermore, the results show that even for low-primary energy demand scenarios, their related exergy efficiency is far from the best ideal exergy scenario $(\psi_{ove} = 1)$.

Fig. 8: Relationship between primary energy and exergy efficiency for the scenarios proposed.



4.5 Energy-exergy benchmarks

Concerning the building benchmark, the primary energy demand is commonly compared with a given ‘reference’ value, calculated based on well-designed high efficient buildings. For student housing buildings, the Portuguese law, RSECE (2006) defines the reference value of 220 kWh m^{-2} for the annual primary energy consumption. The previous results indicate that the primary energy demand is higher than the reference value for most of energy supply scenarios analysed. Exception is made for B-IV and C-III that have relatively close values, indicating them as high efficient supply strategies. From an exclusive energy approach, high performance buildings are those that have an actual primary energy demand closer or lower than the reference. However, even for the most efficient energy scenario (B-IV, E_p=240 kWh m^{-2}), the related exergy efficiency is about 33 %, clearly lower than the ideal scenario. The use of a single primary energy reference value for assessing the energy performance of buildings revealed to be insufficient, so the exergy efficiency may be an useful complementary indicator for buildings benchmark.

The energy and exergy performance results are ranked by primary energy, as presented in Table 4. Both columns have different tones, depending how far each option is from their respective value. Relatively to the reference value, the low-primary energy demand scenario has a deviation of 9 %, while the related exergy efficiency has a deviation about 67 %, showing a good solution from an energy point of view, but a weaker solution from an exergy perspective.

Scenario	E_P (kWh.m^{-2})	ψ (-)
Reference	**220**	**1.00**
B-IV	240	0.33
C-III	254	0.34
D-II	309	0.30
A-IV	310	0.29
C-II	312	0.30
C-I	328	0.29
D-I	331	0.29
B-II	335	0.28
Student housing	**353**	**0.27**
A-III	353	0.27
B-I	379	0.26
A-II	388	0.26
B-III	391	0.21
D-III	408	0.24
A-I	427	0.25
D-IV	463	0.22

Table 4: Proposed scenarios ranked by primary energy use and related exergy efficiency.

As proposal for further building benchmark policy, it would be useful the definition of two characters (or numbers): one representing the primary energy performance and other indicating its related exergy efficiency. By this procedure, buildings may by characterized by quantity and quality aspects, giving information about their primary energy use, together with exergy match between exergy supply and demand.

5 Conclusions

In this study, a methodology for energy-exergy performance assessment of buildings was proposed. As a case-study, actual energy data derived from a simple energy audit of a student housing building was analysed from both energy and exergy perspectives. The monthly primary energy performance and exergy efficiency were evaluated, showing significant differences from both approaches. The annual primary energy is 353 kWh m^{-2}, while exergy efficiency is about 27 %. Furthermore, the indicator, *EDR* shows that space heating and domestic hot water are the most inefficient end uses of the building in the winter season, while in the summer season, electric appliances and hot water contribute with the same magnitude for the building inefficiencies. Additionally, comparing the supply options proposed, significant differences were found between primary energy and exergy perspectives. The most efficient primary energy option has a primary energy demand of 240 kWh m^{-2}, which is a close value to the reference efficient building value (220 kWh m^{-2}), but its related exergy efficiency is only of 33 %, showing a great exergy potential for improvement. Therefore, it shows that a single primary energy analysis is insufficient for a complete characterization of the energy performance of buildings and an additional parameter, such as exergy, should be included.

As a final conclusion, authors expect that the methodology reported here would be useful for demonstrating the exergy approach as one of the tools to investigate the most rational use of energy sources within the built environment, and may be a good basis for future implementation of the exergy concept in regulatory frameworks for performance.

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RESEARCH PAPER IV

Comparative energy and exergy performance assessments of a microcogenerator unit in different electricity mix scenarios

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Join author statement

As this PhD thesis contains articles made in collaboration with other researches, a join author statement about the contribution of PhD student and each co-authors for the article is recommended.

Title of the article	Comparative energy and exergy performance assessments of a microcogenerator unit in different electricity mix scenarios
Authors	Pedro Gonçalves, Giovanni Angrisani, Carlo Roselli, Adélio Rodrigues Gaspar, Manuel Gameiro da Silva

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Course	PhD on Sustainable Energy Systems (Doutoramento em Sistemas Sustentáveis de Energia)	

Description the contribution of each author to the above-mentioned article

	Design of research	Development of the method	Literature review	Data collection	Discussion of results	Reporting	Principal authorship
Pedro Gonçalves	X	X	X	X	X	X	X
Giovanni Angrisani		X		X	X	X	
Carlo Roselli			X		X	X	
Adélio Rodrigues Gaspar	X				X	X	
Manuel Gameiro da Silva	X				X	X	

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Comparative energy and exergy performance assessments of a microcogenerator unit in different electricity mix scenarios

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Abstract

The Directive 2004/8/EC on the promotion of cogeneration proposes a comparative indicator based on primary energy savings, neglecting some important thermodynamic aspects, such as exergy. This study aims to compare and discuss the usefulness of a set of complementary indicators for performance assessments of cogeneration systems, concerning thermodynamic principles based on first and second law (the exergy approach). As case study, a 6 kW electric output micro-combined heat and power unit was experimentally tested and a model of the unit was developed in TRNSYS. Considering as reference a set of different heat and electricity scenarios, including the actual electric mixes of Portugal and Italy, the indicators Primary Energy Savings (*PES*) and Primary and Total Irreversibilities Savings (*PIS* and *TIS*), as well as, energy and exergy renewability ratios were assessed and discussed. The results show that the use of MCHP has higher advantages for the Italian electric grid, than an equivalent scenario considering the Portuguese electric network as reference. As result, for a particular scenario analysed, *PES* and *PIS* have 3 % and 6 % for Portugal, and 10 % and 18 % for Italy, respectively. Furthermore, for one particular scenario evaluated, the indicators energetic and exergetic renewability ratios have 23 % and 14 %, respectively for the Portuguese electric grid, and 19 % and 10 % for the Italian electric system.

Keywords: Micro-Combined Heat and Power; Exergy analysis; Primary Energy Savings, Relative Irreversibilities Savings.

Nomenclature

EnRR	Energy Renewability ratio [-]
$\dot{E}_p$	Primary-fossil energy rate [kW]
$\dot{E}_r$	Primary-renewable energy rate [kW]
ExRR	Exergy Renewability ratio [-]
F_f	Exergy to LHV (Lower Heating Value) of the fuel (fossil) supplied [-]
F_h	Exergy to energy ratio of the heat delivered [-]
F_r	Exergy to LHV (Lower Heating Value) of the fuel (renewable) supplied [-]
HP	Heat-to-Power (electricity) ratio [-]
$\dot{I}_p$	Primary-fossil irreversibility rate [kW]
$\dot{I}_t$	Total irreversibility rate [kW]
LHV	Lower Heating Value [kJ/kg]
PER	Primary-fossil Energy Ratio [-]
PES	Primary-fossil Energy Savings [-]
PES^*_{ED}	Primary Energy Savings (EU Directive on cogeneration (2004)) [-]
PExR	Primary-fossil Exergy Ratio [-]
PIS	Primary-fossil Irreversibilities Savings [-]
PLR	Part-Load Ratio [-]
$\dot{Q}_h$	Thermal energy rate delivery [kW]
T_0	Reference (dead state) temperature [K]
T_r	Return temperature [K]
T_s	Supply temperature [K]
TIS	Total Irreversibilities Savings [-]
$\dot{W}_e$	Electricity rate delivered [kW]

Greek symbols

φ_{eg}	Fraction of renewables for the electric grid [-]
φ_{hs}	Fraction of renewables for the heating system [-]
$\eta_{h,chp}$	Thermal efficiency of the cogeneration unit [-]
$\eta_{e,chp}$	Electric efficiency of the cogeneration unit [-]
η_{hs}	Thermal efficiency of the reference heating system [-]
η_{eg}	Electric efficiency of the reference electric grid [-]

Subscripts

chp	Combined heat and power system
ref	Reference (separate heating system + electric grid)
eg	Electric grid
f	Fossil energy sources

hs	Heating system
r	Renewable energy sources
Acronyms	
CHP	Combined Heat and Power
EF	Sub-system of the electric grid powered by fossil sources
ER	Sub-system of the electric grid powered by renewable sources
HF	Sub-system of the heating system powered by fossil sources
HR	Sub-system of the heating system powered by renewable sources
MCHP	Micro-Combined Heat and Power
FS	Fossil sources
FS	Renewable sources

1 Introduction

Micro-combined heat and power (MCHP) systems have been investigated as an emerging technology with high potential for the residential and services sectors. If designed and operated correctly, the combined production of electrical and heat from a single fuel source could reduce the primary energy consumption and the associated greenhouse gas emissions, with respect to a traditional system based on separate production of electric and thermal energies. Its decentralised nature has also the potential to reduce peak demands on central power generation plants and reduce transmission and distribution losses on electrical grid. With respect to maximum electric power output, different definitions of micro or small size cogeneration are available in technical and scientific literature: the European Directive 2004/8/EC [1] on the promotion of cogeneration sets this value as 50 kW_{el}; De Paepe et al. [2] studied residential applications of MCHP systems (<5 kW_{el}) for detached single family households; and Dentice et al. [3] refer to residential and light commercial applications to characterize MCHP and Domestic CHP system, considering as maximum power output 15 kWel. The value of 15 kWel was adopted in this work as the reference size for the definition of micro-cogeneration, although there is no agreed size limit for the definition of micro-cogeneration.

Analyses of performance data from several MCHP units, coupled with an extensive model development and testing work were conducted within the International Energy Agency (IEA) Annex 42 [4-7]. Most of the developed models follow a pragmatic "grey box" approach, with a structure that partially reflects the physical process and partially relates to empirical relations. This approach was also applied by Rosato et al. [8] that calibrated and validated the performance of a 6 kWel MCHP unit. Kelly et al. [9] developed an approach to model a domestic microcogenerator systems in building simulation tools and Angrisani et al. [10] studied the Energy, Economic and Environmental implications (3-E analysis) of using these complex small scale trigeneration energy conversion systems, starting with the results of an intensive theoretical and experimental research activity. Based on experimental tests, Bush [11] calibrated and validated a model of a 4 kW MCHP system in TRNSYS [12]. Dorer et al. [13] identified parameters that influence the performance of MCHP system, using several building types and MCHP systems in terms of energy and emissions, comparing them with traditional condensing gas boiler and heat pump technologies. Possidente et al. [14] performed experimental tests on three different MCHP prototypes for a wide range of operating conditions, and Roselli et al. [15] reported the energy, economic and environmental implications of the use of small scale cogeneration systems, by an experimental research activity performed by the authors and other researchers.

The previously reviewed studies are exclusively based on First Law of Thermodynamics that states that all forms of energy are conserved in every device and cannot be destroyed or consumed [16]. From an engineering perspective, besides to quantitative aspects, energy should also be classified in terms of quality energy aspects, using also the Second Law of Thermodynamics. An important thermodynamic concept that deals with both First and Second Law of Thermodynamics is Exergy (or Availability), which defines the maximum useful work that can be extracted from an energy state or flow, relatively to a given reference state. This concept may be applied to compare energy states or flows according to their quantity and quality aspects [16-18]. The exergy method has been applied to some engineering applications, e.g., geothermal district heating systems [19-21], solar energy systems [22-24], desiccant cooling systems [25-27] or buildings [28-30]. Concerning exergy analysis of Combined Heat and Power (CHP) systems, Ertesvåg [31] conducted an exergy comparison of indices for combined heat and power systems, Abusoglu et al. [32] performed a thermodynamic analysis based on the first and second laws for an existing diesel engine cogeneration system and Gonçalves et al. [33] made a comparative study between a MCHP and a reference system, using current demand data for a student housing building, located in Coimbra (Portugal). Kanoglu et al. [33] assessed various building cogeneration plants through energy and exergy efficiencies, and in Ref. [35] the authors conducted an extensive overview of various energy-exergy based efficiencies used in power cycles, where the results of some illustrative examples are presented using combined energy and exergy diagrams. Also, Rosen et al. [36] conducted an efficiency analysis, accounting for both energy and exergy concerns to design a cogeneration-based district energy system. The results showed that complex array of energy forms involving cogeneration energy systems are difficult to compare without applying the exergy analysis method. Other studies based on exergy analysis of cogeneration systems are presented in the studies [37-40].

The European Directive 2004/8/CE [1] is a legal instrument that aims to increase the energy efficiency and improve security of supply, by creating a framework to promote and develop high efficient cogeneration systems. The document establishes rules and procedures to assess and compare CHP systems with separated heat and electricity supply scenarios. The main parameter applied by the directive is the Primary Energy Savings (*PES*), assessing the relative primary energy savings of a cogeneration plant relatively to a given reference system. The current Directive has been studied by some authors that have found some of the most relevant limitations. Frangopoulos [41] explained the main restrictions on the calculation of the power to heat ratio and proposed a new method for the calculation of the power to heat ratio and the primary energy savings of cogeneration system. Furthermore, Moreira et al. [42] discussed how the legal framework of the Portuguese energy market might be modified to accommodate the cogeneration Directive 2004/8/EC [1]. The authors found that changes on the framework of small and micro-CHP systems could induce strong improvements on electric grid connection limitations, inducing a strong growth in the number of installed systems.

From the previous studies, the following topics were reviewed: experimental methods for performance assessment of CHP/MCHP units; energy and exergy indicators for evaluation of cogeneration devices; and main methods and issues found in the current Directive 2004/8/EC [1]. Based on the main limitations found in these studies, this study aims to propose a set of complementary indicators to conventional one (*PES*), regarding to compare cogeneration and separate heat and electricity production systems (reference), applying principles based on both first and second law fundamentals. They are formulated based on two perspectives: one concerning levels of primary-fossil energy demand, and another based on thermodynamic concept of “irreversibility”, which accounts for differences in exergy levels between demand and supply. This approach involves also a separate treatment for fossil and renewable energy sources for the reference system. As case study, a micro-combined heat and power unit (6 kW) was experimentally tested at three different operating temperature levels, and a TRNSYS model of the unit was developed for the comparative studies performed. A set of parametric analyses were conducted, including different supply scenarios for heat and electricity separate production, including the actual electric grid mixes of Portugal and Italy. The indicators proposed were compared and discussed, highlighting their main advantages and limitations for each particular scenario examined.

2 Analytical framework

2.1 The European Directive on cogeneration

The European Directive 2004/8/CE [1] uses the indicator Primary Energy Savings $\left(PES^{*}_{ED}\right)$ to compare the relative primary (fossil) energy demand difference between a cogeneration and a reference system, based on separate heat and electricity production. The related formulation is given by Eq. (1) [1].

$$PES^{*}_{ED} = 1 - \frac{1}{\frac{\eta_{h,chp}}{\eta_{hs}} + \frac{\eta_{e,chp}}{\eta_{eg}}} \tag{1}$$

where, $\eta_{h,chp}$ and $\eta_{e,chp}$ are respectively the thermal and electric efficiency of the CHP unit, evaluated for the actual operating performance (or manufacture data). η_{hs} and η_{eg} are the efficiencies of the heating and electric system, respectively, evaluated using a reference framework or actual data (reference scenarios). Directive states that each cogeneration unit should be compared with the best available and economically justified technology for reference heating and electric systems rather than average power installed. The document follows the same fuel principle (both reference and CHP systems using same type or category of fuels are compared) and applies harmonized efficiency reference values for separate production of electricity and heat, as defined by the Commission Decision of 21 December 2006 [43]. This equation is valid for cogeneration units, defined in Annex I of the directive as type b) d) e) f) g) and h), with efficiency higher than 75 %; or type a) and c) 80 %. For lower efficiencies, an expression referred to assess the amount of the electricity that can be considered as cogenerated is applied.

Despite thermodynamically different, Eq. (1) applies to electricity and heat delivered the same weight or energy “quality value”. A well-known technique to distinguish energy quantities, according to their quality value, is the exergy analysis, which is the basis concept applied in the current paper for definition of a set of new alternative indicators for comparative assessment of combined and separate systems.

In Figure 1, a schematic layout of CHP and reference systems with all energy flows involved in this study is presented. The reference system may be powered by fossil and renewable sources. The reference electric system includes electricity produced in conventional power plants (sub-system EF), using primary-fossil sources (FS), and/or electricity produced at the sub-system (ER), using renewable energy sources (RS). In the same way, heat could be derived from RS (e.g. solar thermal, district heating, wood, biofuels or biomass) converted at the sub-system HR; or produced at sub-system HF, using FS (e.g. natural gas boiler, diesel or fuel oil).

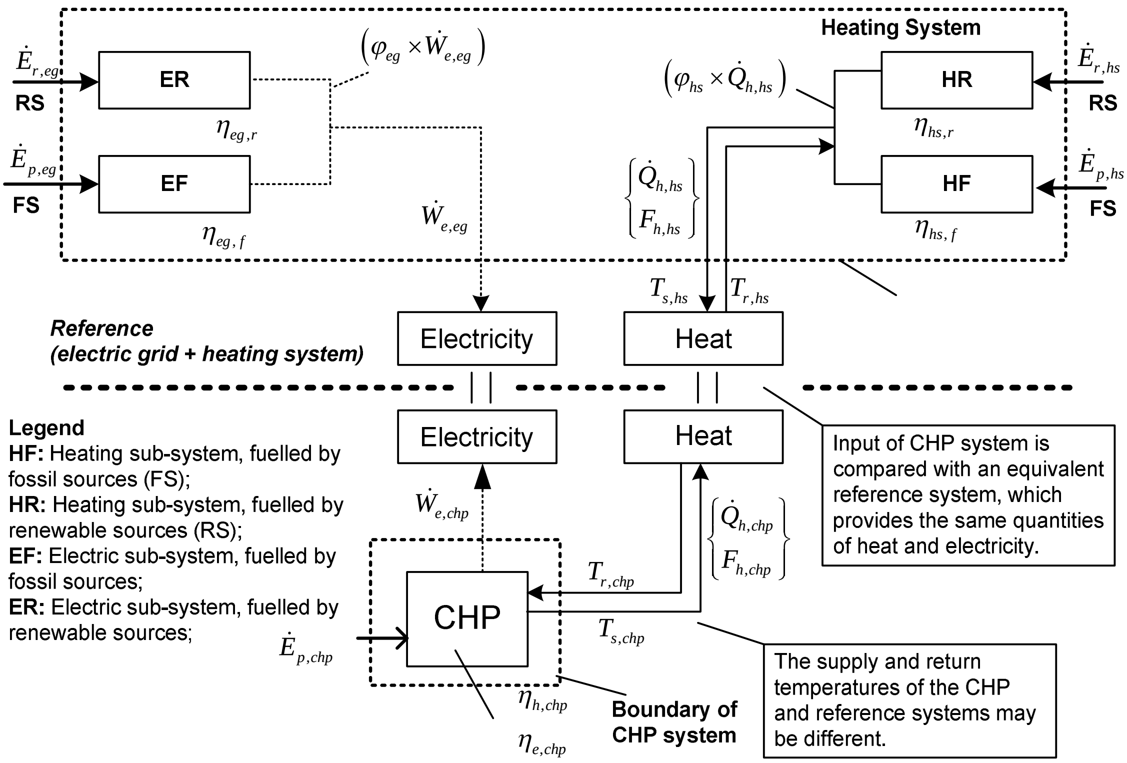


Figure 1: Schematic layout of all energy flows and temperatures involved in the energy and exergy analysis.

2.2 Energy performance assessments

2.2.1 CHP Unit

The energy performance indicator of a generic CHP plant is usually expressed by its energy efficiency. In this study, it is expressed by the parameter Primary Energy Ratio,

PER_{chp}, which is defined as the ratio of the useful (electric and thermal) energy rate delivered to the primary-fossil energy rate input, as expressed by Eq. (2).

$$PER_{chp} = \eta_{e,chp} + \eta_{h,chp} \quad (2)$$

where, $\eta_{e,chp}$ and $\eta_{h,chp}$ are the electric and thermal efficiency of the CHP plant, which are given by Eq. (3) and (4), respectively.

$$\eta_{e,chp} = \frac{\dot{W}_{e,chp}}{\dot{E}_{p,chp}} \quad (3)$$

$$\eta_{h,chp} = \frac{\dot{Q}_{h,chp}}{\dot{E}_{p,chp}} \quad (4)$$

where, $\dot{W}_{e,chp}$ is the delivered rate of electrical energy, $\dot{Q}_{h,chp}$ is the heat rate delivered and $\dot{E}_{p,chp}$ is the energy rate related to primary fossil sources. In this study, thermal energy delivery is assumed as single phase (liquid water), incompressible substance and with constant specific heat. Furthermore, in this study, the CHP system only considers primary-fossil energy inputs.

2.2.2 Reference system

The reference system is constituted by two main sub-systems: electric grid (ER + EF) and heating system (HR + HF) that could be fuelled by fossil sources, FS and/or renewable sources, RS. The indicator for assessing the primary energy performance of the reference system is described as Primary-fossil Energy Ratio, PER_{ref}, defined by the ratio between the sum of electricity and heat delivered to the sum of primary-fossil energy inputs to the heating system and electric grid, as expressed by the Eq. (5).

$$PER_{ref} = \frac{\dot{Q}_{h,hs} + \dot{W}_{e,eg}}{\dot{E}_{p,hs} + \dot{E}_{p,eg}} \quad (5)$$

where, $\dot{Q}_{h,hs}$ and $\dot{W}_{e,eg}$ is the thermal energy and electricity delivered, respectively; and $\dot{E}_{p,hs}$ and $\dot{E}_{p,eg}$ are the primary energy supplied for heating system and electric grid, respectively. Rearranging the equation, PER_{ref} can also be written by the Eq. (6), where, φ_{eg} and φ_{hs} are the fractions of renewables for electricity and heat production, respectively. They are defined as the ratio of electricity (or heat) produced from renewables to total electricity (or heat) derived from electric grid (or heating system). $\eta_{eg,f}$ and $\eta_{hs,f}$ are the energy efficiency of the EF and HF sub-systems, respectively. The primary energy performances between reference and CHP systems can be directly compared ($PER_{chp}; PER_{ref}$), finding which of the system provides a better utilization of primary energy resources.

$$PER_{ref} = \frac{1 + \left(\dfrac{\dot{Q}_{h,hs}}{\dot{W}_{e,eg}}\right)}{\left(\dfrac{1-\varphi_{eg}}{\eta_{eg,f}}\right) + \left(\dfrac{1-\varphi_{hs}}{\eta_{hs,f}}\right)\left(\dfrac{\dot{Q}_{h,hs}}{\dot{W}_{e,eg}}\right)} \tag{6}$$

2.3 Performance assessments based on exergy analysis

2.3.1 CHP Unit

Following the previous approach for primary energy, the exergy based efficiency of a CHP plant is defined by the ratio of exergy delivered (electricity and heat) to total exergy supplied. Thus, for devices exclusively powered by FS, the Primary-fossil Exergy Ratio (*PExR*) of a given CHP unit is given by,

$$PExR_{chp} = \frac{\dot{W}_{e,chp} + F_{h,chp}\dot{Q}_{h,chp}}{F_{f,chp}\dot{E}_{p,chp}} \tag{7}$$

where, $\dot{W}_{e,chp}$ is the electricity rate delivered, $\dot{Q}_{h,chp}$ is the heat rate delivered and $\dot{E}_{p,chp}$ is the primary-fossil energy rate. $F_{f,chp}$ is the exergy to LHV ratio of the fuel for the CHP and $F_{h,chp}$ is the exergy to energy ratio of the delivered thermal energy, which could be defined by Eq. (8),

$$F_{h,chp} = 1 - \frac{T_0}{\left(T_{s,chp} - T_{r,chp}\right)} \ln\left(\frac{T_{s,chp}}{T_{r,chp}}\right) \tag{8}$$

where, $T_{s,chp}$ and $T_{r,chp}$ are the supply and return temperatures of CHP, respectively, and T_0 is the dead-state temperature.

2.3.2 Reference System

Similarly to Section 2.2.2, the primary-exergy performance of the reference system, $PExR_{ref}$, is generically given by Eq. (9).

$$PExR_{ref} = \frac{\dot{W}_{e,eg} + F_{h,hs}\dot{Q}_{h,hs}}{F_{f,eg}\dot{E}_{p,eg} + F_{f,hs}\dot{E}_{p,hs}} \tag{9}$$

Rearranging the equation for highlighting some important quantities, $PExR_{ref}$ can also be given by Eq. (10).

$$PExR_{ref} = \frac{1 + F_{h,hs}\left(\frac{\dot{Q}_{h,hs}}{\dot{W}_{e,eg}}\right)}{F_{f,eg}\left(\frac{1-\varphi_{eg}}{\eta_{eg,f}}\right) + F_{f,hs}\left(\frac{1-\varphi_{hs}}{\eta_{hs,f}}\right)\left(\frac{\dot{Q}_{h,hs}}{\dot{W}_{e,eg}}\right)} \tag{10}$$

where, $F_{f,eg}$ and $F_{f,hs}$ are the exergy to LHV ratio of the fossil fuel for the electric grid and heating system, respectively. $F_{h,hs}$ is also given by an equation similar to Eq. (8), although the symbols $T_{s,chp}$ and $T_{r,chp}$ are replaced by the supply and return temperatures delivered by the heating system. $PExR_{ref}$ could be compared with $PExR_{chp}$, aiming to evaluate the exergy performance of both system, when only fossil sources are used by the reference system.

2.3.3 Parameters for renewable performance assessments

In the literature, there are some thermodynamic parameters used for performance assessment of energy systems, which include inputs from both fossil and renewable sources. In this section, the parameters energetic renewability ratio and exergetic renewability ratio proposed by Coskun et al. [44] are introduced. The energetic renewability ratio $(EnRR)$ is defined as the ratio of useful renewable energy obtained from a system to the total energy input, including both renewable and fossil sources. On the other hand, the exergetic renewability ratio $(ExRR)$ is defined as the ratio of useful renewable exergy delivered by a system to the total exergy input, considering also both renewable and fossil sources. Using the symbols of Figure 1, *EnRR* and *ExRR* are formulated by Eq. (11) and Eq. (12), respectively.

$$EnRR_{ref} = \frac{\varphi_{eg}\dot{W}_{e,eg} + \varphi_{hs}\dot{Q}_{h,hs}}{\dot{E}_{p,eg} + \dot{E}_{r,eg} + \dot{E}_{p,hs} + \dot{E}_{r,hs}} \tag{11}$$

$$ExRR_{ref} = \frac{\varphi_{eg}\dot{W}_{e,eg} + \varphi_{hs}F_{h,r}\dot{Q}_{h,hs}}{F_{f,eg}\dot{E}_{p,eg} + F_{r,eg}\dot{E}_{r,eg} + F_{f,hs}\dot{E}_{p,hs} + F_{r,hs}\dot{E}_{r,hs}} \tag{12}$$

The symbol $F_{h,r}$ is the exergy to energy ratio of the heat delivered by the sub-system HR, and its value can also be calculated using Eq. 8, applying the supply and return temperatures of the heat delivered by the sub-system HR. $\dot{E}_{p,eg}$ and $\dot{E}_{r,eg}$ are the primary-fossil and renewable energy supplied to the sub-systems EF and ER, respectively. $\dot{E}_{p,hs}$ and $\dot{E}_{r,hs}$ are the primary-fossil and renewable energy supplied to the sub-systems HF and HR, respectively. If the heating is fuelled by renewable thermal sources (e.g. hot water from solar-thermal or wastes), $F_{r,hs}$ is also similar to Eq. (8), where $T_{s,chp}$ and $T_{r,chp}$ are replaced by the supply and return temperatures to the sub-system HR.

2.4 Comparative assessments between CHP and reference systems

The indicators defined in Section 2.3 aim to assess individually the energy and exergy performances of CHP or reference systems, identifying which of them has highest energy or exergy performance. However, they do not quantify the differences between cogeneration and separate heat and electricity production, which may be evaluated by the indicator primary energy savings (*PES*) or paying respect to the second law, comparing the irreversibilities differences between cogeneration and separate production, using the indicators *PIS* or *TIS*. The formulations of these indicators are defined in the following sub-sections.

2.4.1 Primary-fossil Energy Savings

The formulation of Primary Energy Savings, applied by the European Directive on cogeneration [1] was presented in Section 2.1. In the directive, the cogeneration is compared with a reference system, where the efficiencies are based on harmonized values using the same type of fuel than CHP. In the current study, the same concept is also applied, although the cogeneration system is assumed as exclusively fuelled by primary-fossil energy sources and the reference system may be fuelled by both fossil and renewable sources. Similarly to Eq. 1, this new formulation for *PES* also assumes the following conditions:

$$\begin{cases} \dot{Q}_{h,chp} = \dot{Q}_{h,hs} \\ \dot{W}_{e,chp} = \dot{W}_{e,eg} \end{cases} \tag{13}$$

where, $\dot{Q}_{h,chp}$ and $\dot{Q}_{h,ref}$ are the heat rate delivered by CHP and reference system, respectively; and $\dot{W}_{e,chp}$ and $\dot{W}_{e,eg}$ are the electricity rate output of CHP and reference system, respectively. *PES* is then given by Eq. (14).

$$PES = 1 - \frac{1}{\eta_{e,chp}\left(\frac{1-\varphi_{eg}}{\eta_{eg,f}}\right) + \eta_{h,chp}\left(\frac{1-\varphi_{hs}}{\eta_{hs,f}}\right)} \tag{14}$$

2.4.2 Primary-fossil and Total Irreversibilities Savings

Based on the previous analysis for *PES*, the following indicators measure the "irreversibilities savings" between CHP and reference were proposed. The concept of irreversibility is extensively used in exergy analysis and it is related with fraction of exergy input that is destroyed (not recovered) in energy conversion process. The indicators Primary-fossil Irreversibilities Savings (*PIS*) and Total Irreversibilities Savings (*TIS*) were proposed. *PIS* assumes only primary-fossil energy inputs in the reference system; while *TIS* includes both fossil and renewable energy inputs. These indicators are similar to *RAI* proposed by Ertesvåg [31], however these indicators differ by the term used to make the parameter dimensionless: *RAI* uses the exergy input, while *PIS* and *TIS* use irreversibility rate associated to the reference system. The authors decided here to use the irreversibility of the reference system, following the same approach of *PES*, which dimensionless by the parameter that is being compared. Furthermore, through this approach, the maximum theoretical value of the indicator is equal to 1, which occurs when the cogeneration system has no irreversibilities associated. *PIS* is then defined by Eq. (15) or Eq. (18).

$$PIS = 1 - \frac{\dot{I}_{chp}}{\dot{I}_{p,ref}} \tag{15}$$

where, $\dot{I}_{chp}$ and $\dot{I}_{p,ref}$ are the primary-fossil irreversibilities rates that occur at the CHP and reference system, respectively. $\dot{I}_{chp}$ and $\dot{I}_{p,ref}$ are given by Eq. (16) and (17), respectively. Detailing Eqs. (15) to (17), *PIS* is given by Eq. (18).

$$\dot{I}_{chp} = F_{f,chp}\dot{E}_{p,chp} - \dot{W}_{e,chp} - F_{h,chp}\dot{Q}_{h,chp} \tag{16}$$

$$\dot{I}_{p,ref} = F_{f,eg}\dot{E}_{p,eg} + F_{f,hs}\dot{E}_{p,hs} - \dot{W}_{e,eg} - F_{h,hs}\dot{Q}_{h,hs} \tag{17}$$

$$PIS = 1 - \frac{\dfrac{F_{f,chp}}{\eta_{e,chp}} - 1 - F_{h,chp}HP}{F_{f,eg}\left(\dfrac{1-\varphi_{eg}}{\eta_{eg,f}}\right) + F_{f,hs}\left(\dfrac{1-\varphi_{hs}}{\eta_{hs,f}}\right)HP - 1 - F_{h,hs}HP} \quad (18)$$

In the Eq. (18), *HP* is the ratio of heat to electricity delivered, which is assumed as the same for the CHP or reference system: $HP = \left(\dot{Q}_{h,chp} / \dot{W}_{e,chp}\right) = \left(\dot{Q}_{h,hs} / \dot{W}_{e,eg}\right)$. This equation only includes as inputs primary-fossil energy sources. For particular situations, in which two or more reference systems are under comparison (including the same EF and HF, but different HR and ER sub-systems), *PES* or *PIS* may not be sufficient to compare cogeneration and separate reference systems. Therefore, the indicator *TIS* is proposed for assessing the total irreversibilities savings, considering inputs from both fossil and renewable sources. *TIS* is defined by Eq. (19), where $\dot{I}_{t,ref}$ is defined by Eq. (20). Developing Eqs. (19) and (20) the final formulation for *TIS* is expressed by Eq. (21).

$$TIS = 1 - \frac{\dot{I}_{p,chp}}{\dot{I}_{t,ref}} \quad (19)$$

$$\dot{I}_{t,ref} = F_{f,eg}\dot{E}_{p,eg} + F_{f,hs}\dot{E}_{p,hs} + F_{r,eg}\dot{E}_{r,eg} + F_{r,hs}\dot{E}_{r,hs} - \dot{W}_{e,eg} - F_{h,hs}\dot{Q}_{h,hs} \quad (20)$$

$$TIS = 1 - \frac{\dfrac{F_{f,chp}}{\eta_{e,chp}} - 1 - F_{h,chp}HP}{F_{f,eg}\left(\dfrac{1-\varphi_{eg}}{\eta_{eg,f}}\right) + F_{r,eg}\left(\dfrac{\varphi_{eg}}{\eta_{eg,r}}\right) + F_{f,hs}\left(\dfrac{1-\varphi_{hs}}{\eta_{hs,f}}\right)HP + F_{r,hs}\left(\dfrac{\varphi_{hs}}{\eta_{hs,r}}\right)HP - 1 - F_{h,hs}HP} \quad (21)$$

3 Experimental and modelling procedures

In this study, MCHP unit was experimentally tested and its performance compared with a set of different separate heat and electricity production scenarios, including the actual electric grid mixes of Portugal and Italy and combining other options for heat production, including different share of renewables.

3.1 Description of the tested MCHP unit

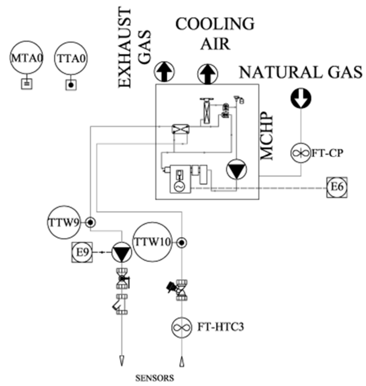
The tested MCHP unit is based on a water cooled internal combustion engine, with three cylinders and a displacement of 952 cm^3. The engine is connected to an electronically controlled 16 poles synchronous generator, with an inverter automatically synchronized in phase and frequency. The electrical output can vary from 0.3 to 6 kW according to the user's demand in electric following mode. The manufacturer refers a rated heat output rate of 11.7 kW, with a water flow rate of 33.5 l/min, considering 65 ºC and 60 ºC as supply and return temperature, respectively. The heat is recovered from exhaust gases and engine jacket, being afterwards transferred to an external water flow circuit in a plate heat exchanger. The manufacturer main technical data of the unit is presented in Table 1.

Table 1: Main technical data of the MCHP unit

Parameter (unit)	**Nominal value or range**
Electric power delivered (kW)	0.3 - 6.0
Rated thermal energy delivery (kW)	11.7
Rated natural gas power input (kW)	20.8
Water outlet temperature (ºC)	60-65
Engine displacement (cm^3)	952
Shaft speed range (RPM)	1600-1800
Rated electrical efficiency (%)	28.8
Rated thermal efficiency (%)	56.2
Overall efficiency (%)	85.0

3.2 Experimental procedures

The experimental assessment of the MCHP performance was conducted through a set of experimental tests performed in a test facility located at University of Sannio in Benevento (Italy). The MCHP unit is connected to a heating coil, where the supplied heat may be used to regenerate a silica-gel rotor in a desiccant air-conditioning system. More information about this installation can be found in Ref.s [45–50]. The main instrumentation data, measuring range, accuracy and locations in the test facility are represented in Figure 2. The data acquisition system supplied by the manufacturer was complemented with some others devices, including a graphical interface to display and record data, such as: supply and return water temperatures, natural gas and water mass flow rate, rate of thermal energy recovered, electrical power output and auxiliaries loads. The current performance of the unit was evaluated by measuring the parameters: electric power output, rate of thermal energy delivered and fuel energy input rate. The unit was tested at different Part-Load Ratio (*PLR*) and supply/return temperatures. *PLR* is obtained dividing electricity rate by the rated electric power of the unit (6 kW). Different supply/return temperatures were experimentally assessed, for different values of *PLR*. Each assessment point was evaluated on the basis of significant number of samples, obtained for thermal energy delivered steady state conditions. The tests were performed with an outdoor environmental temperature of 15 ºC, which was also assumed for the reference state in the exergy analysis.



NAME AND SYMBOL		MEASURED PARAMETER	MEASURING RANGE	ACCURACY
TTA0	TTA	AIR TEMPERATURE	-50 / +50 °C	± 0.9 °C
MTA0	MTA	AMBIENT RELATIVE HUMIDITY	0 - 99%	± 5%
FT-HTC3		VOLUMETRIC FLOW RATE	2 - 60 L/min	± 2% FS
FT-CP		MASS FLOW RATE	0 - 2.5 Nm3/h	± 0.2% FS
TTW9,10	TTW	WATER TEMPERATURE	-10 / +120 °C	± 1.4 °C
E6,9	E	ELECTRIC ENERGY METER		

Figure 2: Test facility layout of the MCHP unit located at University of Sannio (Italy).

3.3 Briefing about TRNSYS model

As referred, a computational tool was developed in software TRNSYS to perform the energy and exergy comparisons of CHP systems and separate production systems. Based on experimental assessments, a model of MCHP was implemented using Type 907/TESS, which is able to read the performance data of the engine from an external text file. This file contains information about efficiency (both mechanical and electrical) and heat transfer data, including the fraction of total thermal energy rate recovered by the after-cooler, oil cooler, exhaust gas heat exchanger, engine jacket and the thermal energy fraction dissipated to the environment. Additionally, Type 5 is used to model the internal heat recovery system of the MCHP unit, where two important input parameters were defined: the mass flow rate passing through the hot side and the overall heat transfer coefficient. Performance parameters related to the separate heat and electricity production systems (reference) were also included into the TRNSYS project, through the Equation Object.

3.4 Electricity mix scenarios

The electricity mixes of Portugal and Italy were used to compare the actual performance of the MCHP in real electric grid contexts. Based on data of the International Energy Agency (IEA) [51], primary energy inputs (fossil and renewables) and corresponding electricity produced were used to assess the overall efficiency by source. In Table 2 and 3 are presented the energy inputs and electricity associated to fossil and renewable sources, the related efficiencies of EF and ER sub-systems and fraction of renewables corresponding to the electric mixes of Portugal and Italy. Concerning renewables, this study is divided into: ‘biofuels and waste’ (including solid biofuels, liquid biofuels, industrial and municipal waste products), and ‘earth resources’, corresponding to hydro, wind, geothermal, solar, tide/wave/ocean energy sources. For “earth resources”, as inputs, (IEA) [51] assumed the electricity produced by each source. The fraction of renewables was obtained by the ratio of electricity derived from renewable sources to the total electricity produced.

Table 2: Electricity mix and production performance for Portugal in 2009.

	Fossil sources			Renewable sources	
Technology	**Coal and Peat**	**Fuel oil**	**Natural gas**	**Earth resources***	**Biofuels and waste****
Total Energy Input (GWh)	32 959	8 734	29 912	17 968	6 257
Electricity generated (GWh)	12 896	3 285	14 712	16 930	2 384
Losses in the electric grid (%)	7.55 %				
Overall efficiency, η_{eg}	40 %			74 %	
Fraction of renewables, φ_{eg}				38 %	

* Directly used as exist in Earth (e.g. hydro, wind, solar, geothermal, etc).
** Sources produced or derived from Human activity.

Table 3: MCHP performances obtained by the experimental tests, used for the text file of Type 907/TESS.

	Fossil sources			Renewable sources	
Technology	**Coal and Peat**	**Oil Products**	**Natural gas**	**Earth resources***	**Biofuels and waste****
Total Energy Input (GWh)	116 951	87 993	307 334	109 776	36 100
Electricity generated (GWh)	43 416	25 946	147 269	66 607	9 403
Losses in the electric grid (%)	6.95 %				
Overall efficiency, η_{eg}	39 %			48 %	
Fraction of renewables, φ_{eg}				26 %	

* Directly used as exist in Earth (e.g. hydro, wind, solar, geothermal, etc).
** Sources produced or derived from Human activity.

4 Results and discussion

4.1 Energy and exergy assessments of MCHP unit

The performance results derived from the experimental tests conducted to MCHP unit are expressed as electric, thermal and *PER* (or overall efficiency) in Figure 3. The performances were evaluated for three supply/return temperatures levels (averaged values), according to the experimental tests performed:

- **trial #1:** $T_{s,chp} = 65\,^{\circ}C$ and $T_{r,chp} = 60\,^{\circ}C$;

- **trial #2:** $T_{s,chp} = 59\,^{\circ}C$ and $T_{r,chp} = 54\,^{\circ}C$;

- **trial #3:** $T_{s,chp} = 72\,^{\circ}C$ and $T_{r,chp} = 67\,^{\circ}C$.

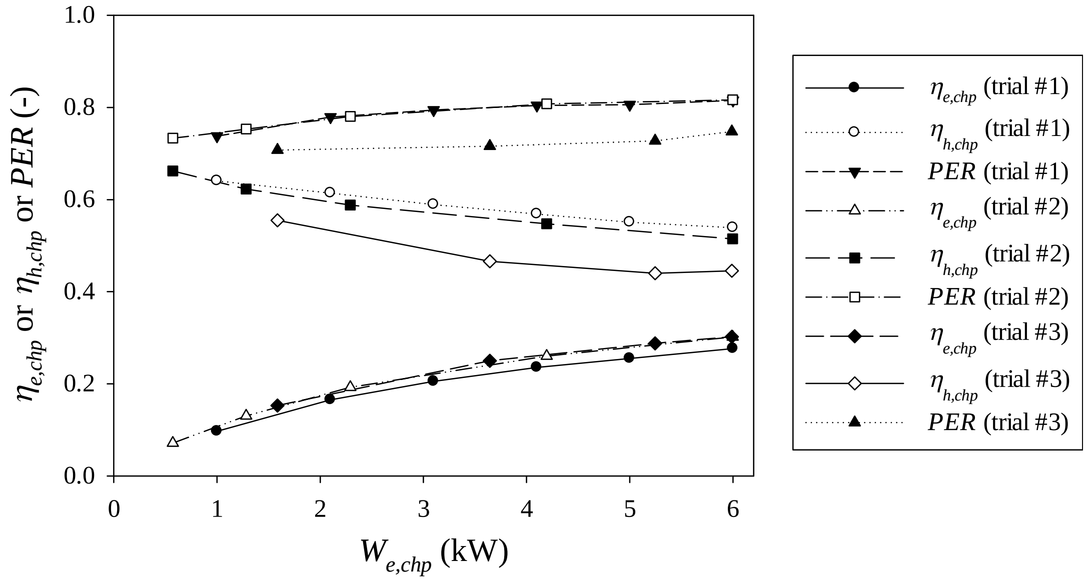


Figure 3: Experimental results of electric, thermal and overall (*PER*) energy performance of the MCHP unit.

The tests were conducted for temperatures in the internal circuit of the MCHP higher than 55 ºC, corresponding to normal operating conditions. The results indicate similar performances for trial #1 and #2, where the unit's performance is approximately constant within operating temperatures from 55 ºC to about 70 ºC. At about 70 ºC, as security control measure, the internal circuit of the unit is partially deviated to an external radiator, releasing part of heat generated into the surrounding environment. Therefore, the thermal efficiency and related *PER* drop for operating temperatures higher than 70 ºC, as also shown in the trial #3 curves in Figure 3. These results are then applied to set up the text file required by Type 907/TESS. In Table 4 is presented all the parameters needed to build the file, considering the performance results obtained by the trial #1.

Finally, regarding to compare the energy and exergy performances (*PER* and *PExR*) of the MCHP, in the Figure 4, they are represented for the various experimental tests conducted. Significant differences were found between *PER* and *PExR*, especially due to low exergy content of the heat delivered by the microcogenerator, although concerning only *PExR*, the differences are almost imperceptible for the various levels of temperatures, because the exergy associated to thermal is too low.

Table 4: MCHP performances obtained by the experimental tests, used for the text file of Type 907/TESS.

	Part-Load Ratio (*PLR*) [-]					
	0.17	**0.34**	**0.51**	**0.68**	**0.84**	**1.00**
Electrical rate [kW]; A	1.0	2.1	3.1	4.1	5.0	6.0
Primary-fossil energy rate [kW]; B	10.3	12.7	15.1	17.4	19.6	21.7
Total waste heat rate [kW]; C=B-A	9.3	10.7	12.0	13.4	14.5	15.7
Waste heat recovered rate [kW]; D	6.6	7.8	8.9	9.9	10.8	11.7
Electrical Efficiency [-]; E=A/B	0.10	0.16	0.20	0.23	0.26	0.28
Mechanical Efficiency [-]; F=A/0.95/B	0.10	0.17	0.21	0.25	0.27	0.29
Fraction waste heat recovery [-]; G=D/C	0.71	0.73	0.74	0.74	0.74	0.75
Fraction waste heat to environment [-]; H=1-G	0.29	0.27	0.26	0.26	0.26	0.25

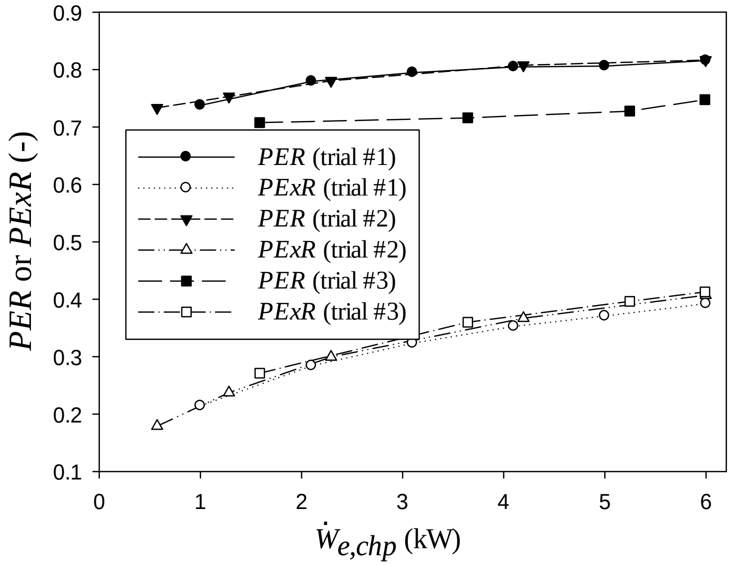
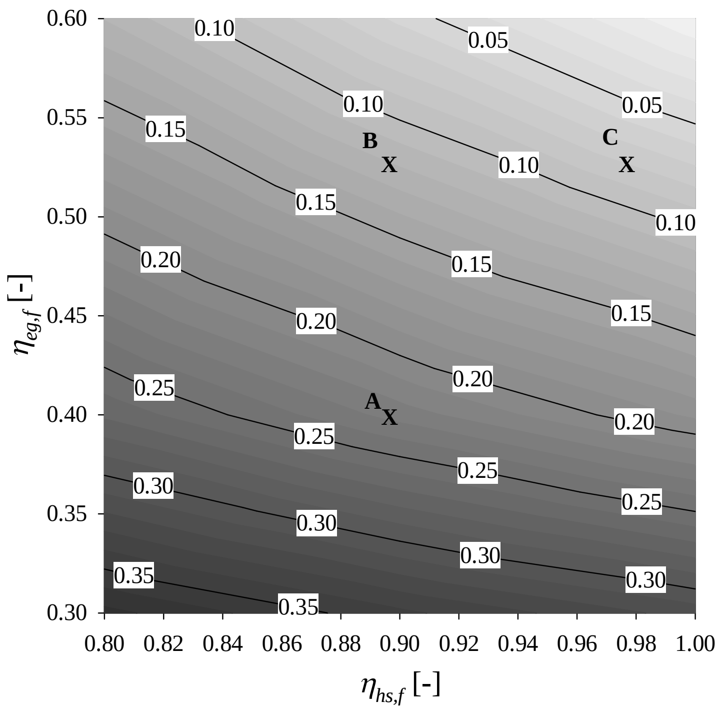


Figure 4: Energy and exergy performance assessments of MCHP for the experimental tests conducted.

4.2 Primary-fossil Energy Savings

PES iso-lines diagrams are useful tools allowing a quick assessment of the primary energy savings provided by MCHP for a huge number of electricity/heat efficiencies reference scenarios. In Figures 5 and 6, different efficiencies for electric and heating system and integration of renewables are compared with MCHP evaluated at *PLR*=1 (trial #1). Figure 5 is a *PES* iso-line diagram considering different efficiencies values for the power plant and heating system (assuming no renewables) – a similar approach followed by European Directive 2004/8/EC [1]. Negative values of *PES* indicate no advantages for the use of the cogeneration system. Using this chart, three points (A, B and C) were represented: Point A corresponds to a fossil-based power plant with an efficiency of 40 % (corresponding to the Portuguese electric grid power installed/subsystem EF in Figure 1) and a heating system with 90 % efficiency (reference efficiency for natural gas boiler in [43]); Point B corresponds to reference efficiency of 52.5 % for the electricity production (harmonized value for electricity production considering a CHP with natural gas as fuel and 2006-2011 as installation period, [43]) and the same heating efficiency than point A (90 %); and Point C keeps the same electric efficiency than B, but considers an improvement of heating efficiency to about 98 %, corresponding to a typical efficiency of a condensing boiler. The related *PES* for A, B and C are 23 %, 12 % and 8 %, respectively. As expected, improvements on efficiency in the electric grid and heating system remove advantages to the use of MCHP.

Figure 5: Iso-lines *PES* diagram as function of heating system efficiency (e.g. boiler) and electric grid efficiency (no renewables included).



The values of *PES* are even lower when renewables are included. Figure 6 presents *PES* iso-lines for a constant heating system efficiency of 90 %, and considers power plant (EF) efficiencies from 30 to 60 %, and a fraction of electricity produced from renewables (φ_{eg}) from 0 to 40 %. Two points are represented: Point A, with an efficiency of 52.5 % for electricity production [43] and φ_{eg} = 0; and Point B considering the same electric grid efficiency, but with 15 % of electricity produced from renewables (φ_{eg} = 0.15). For Point A, *PES* is about 12 %, while for Point B, *PES* decrease to about 5 %. The use of these diagrams clearly shows that improvements on efficiency or including renewables into electric system could effectively limit the use of cogeneration systems. Furthermore, since there are a huge number of scenarios in which *PES* has the same value; including the second law into analysis, different result may be obtained.

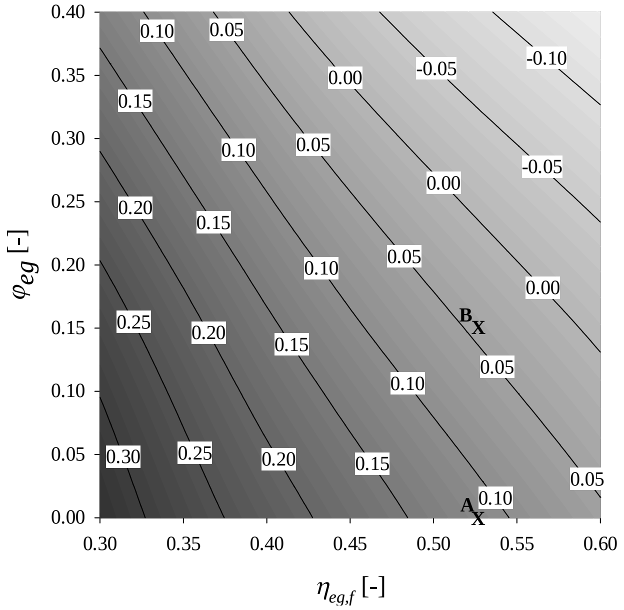
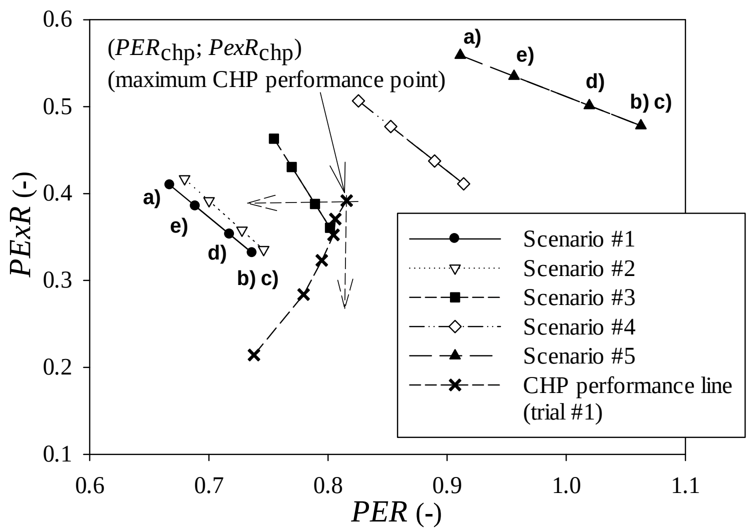


Figure 6: Iso-lines *PES* diagram as function of electric grid efficiencies and integration of renewables into electric grid (Heating system with 90% efficiency, and no thermal energy from renewables).

4.3 Energy and exergy assessments of reference system

Since there are a huge number of parameters involved in the energy-exergy performance of the reference system, in this section, different scenarios were proposed aiming to assess the sensitivity of *PER* and *PExR* with those parameters. The heat to electricity ratio of CHP (or reverse, power-to-heat ratio, as it is mentioned in European Directive [1]) is an important parameter that strongly affects the viability of the cogeneration. Particularly, this occurs because efficiencies of separate system related to electricity and heat production are very different, as can be seen in harmonized values of the efficiencies defined in Ref. [43].

Figure 7 compares the indicators *PER* and *PExR* by changing the following parameters: $\left(\dot{Q}_{h,hs}/\dot{W}_{e,eg}\right)$, $\eta_{eg,f}$, φ_{eg} and φ_{hs}. The values of $\left(\dot{Q}_{h,hs}/\dot{W}_{e,eg}\right)$ correspond to implicit values for production units types a) b) c) d) and e) of Annex II of the Directive on Cogeneration [1], where a) 1.05, b) and c) 2.22, d) 1.81 and e) 1.33. Six scenarios were proposed, where the efficiency of the heating system (HF) was kept constant (90 %) for all the scenarios, and the others parameters changed ($\eta_{eg,f}$, φ_{eg} and φ_{hs}) are presented the table below Figure 7. The results show that for high values of $\left(\dot{Q}_{h,hs}/\dot{W}_{e,eg}\right)$ *PER* increases (highest value at unit a), while *PExR* decreases (lowest value at unit type b and c). *PER* evolution is explained due to higher efficiency of the heating system (HF) when compared with electric grid (EF). On the other hand, the exergy content of the heat is much lower than the corresponding one for electricity, therefore *PExR* decreases with the increase of $\left(\dot{Q}_{h,hs}/\dot{W}_{e,eg}\right)$. Figure 7 also shows that *PER* and *PExR* increase when electricity produced from renewables increase (Scenarios #2 and #3), or when heat production derived from renewables increases (Scenarios #3 to #6). In these scenarios, the heat is derived from renewable thermal sources, assuming the typical supply/return temperatures of a solar thermal system. Therefore, the corresponding exergy to energy ratio is obtained by Eq. 8: $F_{r,hs}$=0.124, where T_s=60 ºC, T_r = 40 ºC, with T_0 = 283.15 K. In addition, Figure 7 also shows the related performance of MCHP, corresponding to trial #1. At maximum performance (*PLR*=1), the points located on the left of the vertical arrow show lower energy performances at reference system than for the microcogenerator and the points below horizontal the arrow indicate lower exergy performance for the reference system.



	$\eta_{eg,f}$	φ_{eg}	φ_{hs}
Scenario #1	0.525	0.00	0.00
Scenario #2	0.400	0.26	0.00
Scenario #3	0.400	0.38	0.00
Scenario #4	0.400	0.38	0.20
Scenario #5	0.400	0.38	0.40

Figure 7: Energy and exergy performance (*PER* and *PExR*) considering different reference systems.

4.4 Comparative analysis between combined and separated heat and electricity production

Through the direct comparison between performance indicators (*PER* or *PExR*) it is possible to identify the more efficient systems (combined or separate heat and electricity production), from energy or exergy viewpoints. However, the relative difference between equivalent MCHP and reference systems (evaluated as primary energy or irreversibility savings), considering the same heat and electricity production, may be obtained through indicators *PES*, *PIS* and *TIS*. These indicators are compared as discussed in this section. Additionally, the indicators *EnRR* and *ExRR* are also compared, regarding to evaluate energy and exergy performance using renewables for the separate heat and electricity production. Since there are a huge number of variables involved in each parameter, five distinct analyses were developed regarding to evaluate in detailed their importance for each particular scenario.

Analysis #1: Assessment of *PES* and *PIS* as a function of electricity delivered by the microcogenerator

In Figure 8, *PES* and *PIS* are presented for different MCHP electric outputs, corresponding MCHP performances obtained at trial #1. The reference assumes the same heat to electricity ratio of the MCHP at each electric load evaluated, considering also the following parameters: $\eta_{eg,f}$ = 52.5 %, $\eta_{hs,f}$ = 90 %. No renewable sources for heat and electricity production in reference system were considered. For the reference, $F_{h,hs} = 0.209$, corresponding to a supply and return temperature of 90 ºC and 70 ºC (typical temperature value of a boiler, according Ref. [52]. On other hand, MCHP has supply and return temperatures of 65 ºC and 60 ºC, respectively, corresponding to $F_{h,chp}$=0.156. These two quality factors values were calculated using the same reference dead-state temperature, as 283.15 K. The results show that both *PES* and *PIS* increase having their maximum values at full load of the MCHP. Due to the increase of microcogenerator performance with increase of electricity delivered rate, $\dot{W}_{e,eg}$, together with reduction of heat to electricity ratio (HP), *PES* and *PIS* increase. Moreover, *PIS* increases faster than *PES* with electric output, indicating that the ratio of irreversibility rate of CHP to reference $\dot{I}_{chp} / \dot{I}_{ref}$ decreases faster with $\dot{W}_{e,chp}$ than the equivalent ratio evaluated as primary energy.

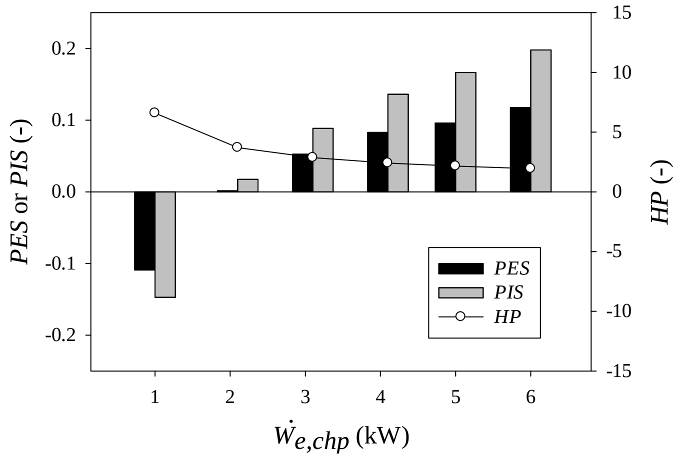


Figure 8: *PES* and *PIS* evaluated for different HP ratios and assuming the actual MCHP performance at each load.

Analysis #2: PES and PIS assessments for different MCHP operating temperatures

Depending on type of heating system, different supply/return temperatures pairs are possible. In Ref. [52] maximum temperatures are defined for different systems: oil boiler, natural gas boiler, air source or ground source heat pump, solar thermal collectors. For the same thermal load produced by different technologies, different exergy levels are derived, even for the same conversion efficiency. Concerning the microcogenerator tested, it has a limited range of supply/return water temperatures. The normal operating temperatures range from 55 ºC to 70 ºC in the internal circuit: for temperatures below 55 ºC in the internal circuit at the outlet of the plate heat exchanger (see Figure 2), so the unit has a control system for the warm-up period, avoiding that the entire internal flow rate crosses the plate heat exchanger. On the other hand, for temperatures higher than 70 ºC, the control system partially by-pass the fluid flow rate to the internal radiator, wasting heat to the surrounding environment. In Figure 9, *PIS* and *PES* are presented for the trial #1, #2 and #3 conducted at *PLR* = 1. The same parameters were assumed for the reference system as in the previous analysis #1. *PES* of trial #1 and #2 are approximately the same, as thermal and electrical performances of MCHP are very similar (see Fig. 3). Although, looking at irreversibilities, since the heat is released at different temperatures at trial #1 and #2, *PIS* assume different values. Due to lower supply/return temperatures at trial #2, the irreversibilities savings are higher for this tested condition, indicating a high irreversible MCHP system when compared with the equivalent reference. The reduction of the thermal efficiency leads to a reduction of both *PES* and *PIS*, therefore trial #3 is not comparable with the other two.

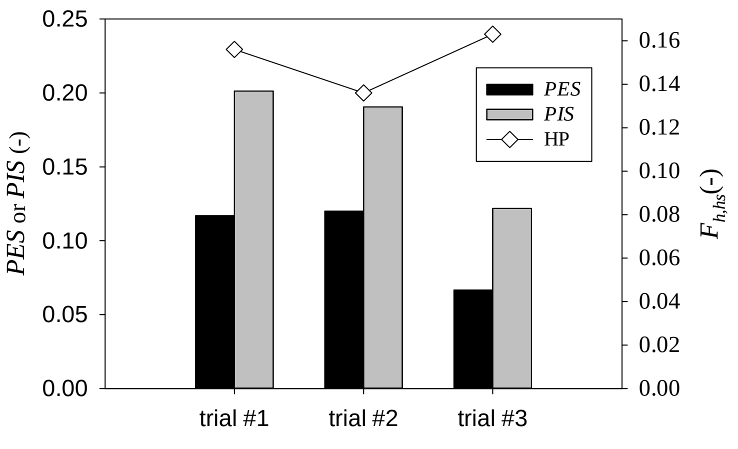


Figure 9: *PES* and *PIS* assuming the MCHP performance at *PLR*=1 for the three experimental trials and fixing the reference system for each comparison.

Analysis #3: PES and PIS assessments considering the heating system operating at different supply/return temperatures

Different heating technologies are able to provide heat within a distinct range of supply/return temperatures. As example, boilers could produce water or steam at very different temperature/pressure, keeping approximately the same values of efficiencies values, although with high differences concerning exergy performance. In Figure 10, *PES* and *PIS* are evaluated assuming the microcogenerator operating at *PLR* = 1 (of trial #1) and considering three supply/return temperatures for the reference heating system, with no efficiency variation. The different supply/return temperature pairs considered were: T-I) $T_{s,hs}$ =90 °C and $T_{r,hs}$ =80 ºC; T-II) $T_{s,hs}$ =80 °C and $T_{r,hs}$ =70 ºC; and T-III) $T_{s,hs}$ =70 °C and $T_{r,hs}$ =60 ºC (T_0 = 285.15 K). As most of energy parameters for both CHP and reference system were kept constant, *PES* is the same for all the scenarios evaluated. Concerning *PIS,* since different supply/return temperatures are considered, $F_{h,hs}$ changes leading to different relative irreversibilities between CHP and reference. From the results, lower delivered supply/return temperatures mean higher irreversibilities at the heating system (T-III); higher *PIS* values mean a more inefficient reference system and higher benefits for the cogeneration. As *PES* is constant for all these scenarios, these analyses demonstrate how *PIS* could be an add value parameter for comparing CHP and reference with heat delivered at different supply/return temperatures.

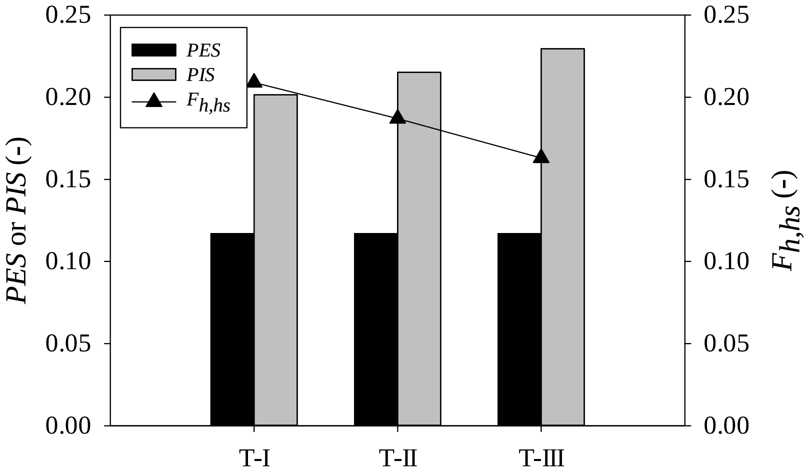


Figure 10: *PES* and *PIS* assessments considering the MCHP at PLR=1 (trial #1) and changing the supply/return temperatures of the reference system.

Analysis #4: Assessment of *PES, PIS, EnRR* and *ExRR* for different electric mix scenarios and share of renewables for heat production

Considering the MCHP unit operating at *PLR*=1, this analysis takes into account different combinations of electric grid and heating systems. Portuguese and Italian electric mixes are considered, as well as different share of renewables used for heat production. The results are presented in Figure 11, where the scenarios PT-I to PT-III are related to Portuguese electric grid performances, and IT-I to IT-III to the Italian electric grid, both corresponding to fractions of heat derived from renewables equal to 0, 0.30 and 0.60, respectively. For all the scenarios, it was assumed that thermal sources are directly derived from solar thermal, $F_{r,hs}$= 0.124 (considering T_s= 60 ºC, T_r = 40 ºC and T_0 =283.15 K). The results show higher *PES* values for Italian electric grid context than for the corresponding

Portuguese one. This is a consequence of the low fraction of electricity derived from renewables in Italy, increasing the demand for primary-fossil energy by the reference system and higher primary irreversibilities. Comparing the scenarios PT-I and IT-I, corresponding to 0 % of renewables in heating system ($\varphi_{hs} = 0$), *PES* has a value of about 3 % for the Portuguese electric grid as reference system, and about 10 %, when the Italian electric grid is considered. Concerning *PIS* at $\varphi_{hs} = 0$ (PT-I and IT-I), the irreversibilities saved by MCHP are evaluated as 6 % for the Portuguese electric grid, and about 18 %, for the Italian context. It indicates that the quality match between supply (from fossil origin) and demand is higher for the Portuguese electric grid than for Italy. Since the irreversibilities of the Portuguese electric grid are lower, the same MCHP system allows higher irreversibility reduction in the Italian context.

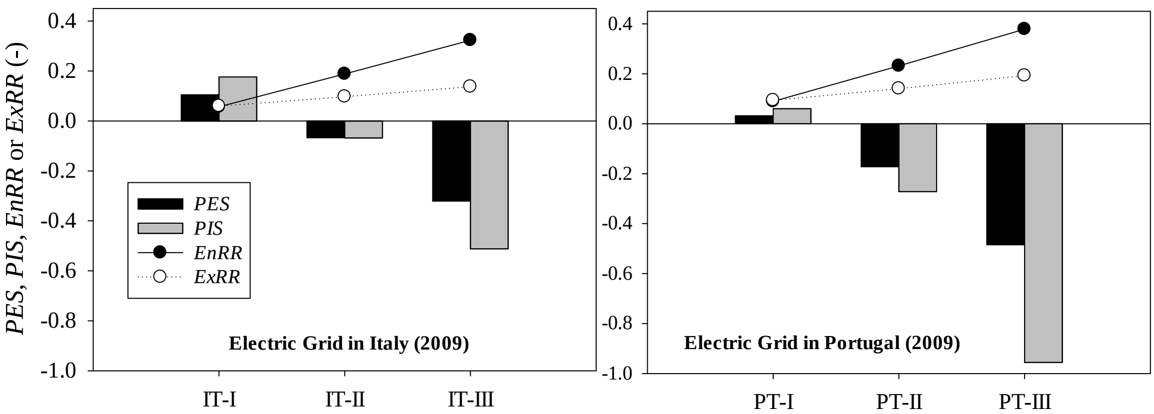


Figure 11: *PES*, *PIS*, *EnRR* and *ExRR* assessments assuming different fraction of heat delivered from renewables and considering the actual performance of electric grid of Portugal and Italy.

Additionally, since different fractions of heat and electricity are derived from renewable sources, the renewability ratios were also assessed. They aim to provide information about the use of renewables by the reference heating system and electric grid. The results indicate that for the same equivalent scenarios (e.g. PT-I and IT-I, PT-II and IT-II,…), the Portuguese electric grid has higher values of both *EnRR* and *ExRR* than the corresponding Italian context, due the higher share of renewables for electricity production in Portugal. Both *EnRR* and *ExRR* increase with increase of renewables for heat production by the reference system. *ExRR* is always lower than *EnRR* especially for high heat fractions of heat produced from renewables, indicating the heat produced as a low exergy product.

Analysis #5: The rule of *TIS* for assessing different renewable supply scenarios

The current analysis aims to demonstrate particular situations, in which *TIS* provides particular results not accomplished by *PES* or *PIS*. In the following analysis, *TIS* is evaluated for three similar reference scenarios, where the conversion efficiency of renewables (sub-system ER) changes. All scenarios consider that 20 % of heat and electricity are produced by renewable sources. Thermal input sources are considered for the HR, where $F_{r,hs} = 0.124$, evaluated using Eq. 8, where supply and return temperatures are assumed as 60 ºC and 40 ºC [52], respectively (T_0 = 283.15 K).

The results are presented in Figure 12, where the efficiency of electric grid/renewables sub-system ER $\left(\eta_{eg,r}\right)$ in scenarios S-I, S-II and S-III are 40 %, 60 % and 90 %, respectively. From the results, *PES* and *PIS* present the same values, because fossil based heating and electric systems, as well as the share of renewables, are the same for all scenarios. However, the quantity of renewables sources changes due to different efficiencies considered for ER sub-system. In the scenarios S-I to S-III, the increase of efficiency for the sub-system ER leads to a decrease of *TIS*, indicating an increase of exergy performance of the reference system relatively to MCHP, so the irreversibilities savings at S-III are lower when compared with S-I. Concerning the renewability ratios *EnRR* and *ExRR*, the results show a moderate increase of these two indicators when the efficiency of the electric grid/renewables sub-system ER is improved. Since *ExRR* < *EnRR*, it indicates the presence of low-exergy renewable sub-products (20 % of low temperature heat delivered at by reference system is derived from renewable sources).

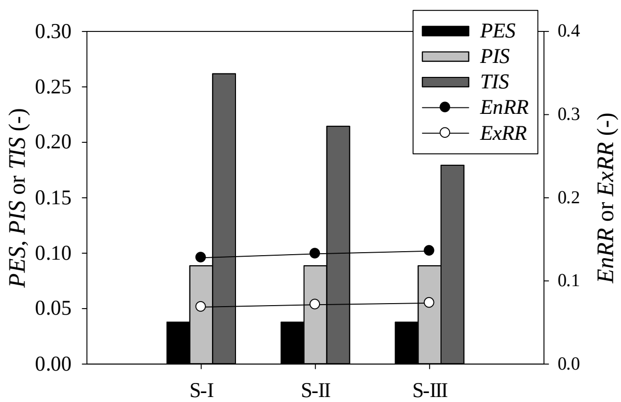


Figure 12: *PES*, *PIS*, *EnRR* and *ExRR* assessments applying different efficiencies for the ER sub-system.

5 Conclusions

In this study, the importance of the exergy analysis for cogeneration systems assessments is highlighted. The limitations of the European Directive 2004/8/EC were reported and some complementary indicators based on first and second law of thermodynamics were proposed. The main indicator used by the European Directive (*PES*) revealed to be insufficient to characterize and compare CHP systems and separate systems for heat and electricity production. *PIS* revealed to provide additional results to *PES*, especially when equivalent reference system are compared (same efficiencies and fuels inputs), but delivering heat at different temperatures. MCHP unit was compared with different heating supply options and the electric grids contexts of Portugal and Italy. Considering no renewables for heating system, *PES* and *PIS* have as results: 3 %, 6 % for Portugal, and 10 %, 18 % for Italy, respectively. Additionally, *TIS* revealed to be an useful indicator to compare similar fossil based reference scenarios (same conversion efficiencies at EF or HF, and fraction of heat and electricity produced from renewables), but different inputs in the sub-systems powered by renewables (ER, HR). Finally, the indicators energetic and exergetic renewability ratios were found as significant indicators, giving information about quantity and exergy content of heat and electricity produced from renewables by the reference system.

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RESEARCH PAPER V

Exergetic analysis of a desiccant cooling system: searching for performance improvement opportunities

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Exergetic analysis of a desiccant cooling system: searching for performance improvement opportunities

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Abstract

The current increase of the energy consumption of buildings requires new approaches to solve economic, environmental and regulatory issues. Exergy methods are thermodynamic tools searching for sources of inefficiencies in energy conversion systems that the current energy techniques may not identify. Desiccant cooling systems are equipments applied to dehumidifying and cooling air streams, which may provide reductions of primary energy demand relatively to conventional air-conditioning units. In this study, a detailed thermodynamic analysis of open-cycle desiccant cooling system is presented. It aims to assess the overall energy and exergy performance of the plant and identify its most inefficient sub-components, associated to higher sources of irreversibilities. The main limitations of the energy methods are highlighted and the opportunities given by exergy approach for improving the system performance are properly identified. As case-study, using a pre-calibrated TRNSYS model, the overall energy and exergy efficiency of the plant were found as 32.2 % and 11.8 %, respectively for a summer week in Mediterranean climate. The exergy efficiency defect identified the boiler (69.0 %) and the chiller (12.3 %) as the most inefficient components of the plant, so their replacement by high efficient systems is the most rational approach for improving its performance. As alternative heating system to the boiler, a set of different technologies and integration of renewables were proposed and evaluated applying the indicators: Primary Energy Ratio (*PER*) and exergy efficiency. The heating system fuelled by wood was found as having the best primary energy performance (*PER* = 109.6 %), although the related exergy efficiency is only 11.4 %. The highest exergy performance option corresponds to heat pump technology with *COP* = 4, having a *PER* of 50.6 % and exergy efficiency of

28.2 %. Additionally, the parametric analyses conducted for different operating conditions indicate that the overall irreversibility rate increases moderately for larger cooling effects and more significant for higher dehumidification rates.

Keywords: Desiccant cooling systems; Exergy efficiency; Exergy efficiency defect; Renewable energy sources.

Nomenclature

$\dot{C}_{\min}$	Minimum of the capacitance rate [kJ K^{-1} s^{-1}]
$c_{p,a}$	Specific heat at constant pressure of dry air [kJ kg^{-1} K^{-1}]
$c_{p,v}$	Specific heat at constant pressure of water vapour [kJ kg^{-1} K^{-1}]
COP	Coefficient of performance [-]
$\dot{E}_p$	Primary-fossil energy input rate [kW]
$\dot{E}_r$	Renewable energy input rate [kW]
ex	Specific exergy of moist air [kJ kg^{-1}]
$\dot{E}x$	Exergy rate [kW]
ex_{ch}	Specific chemical exergy of mixture [kJ kg^{-1}]
ex_{tm}	Specific thermo-mechanical exergy of mixture [kJ kg^{-1}]
ex_w	Specific exergy of water [kJ kg^{-1}]
F_{el}^{p}	Primary energy factor for electricity [-]
F_f^{ex}	Chemical exergy to Lower Heating Value (LHV) of the fuel [-]
F_r^{ex}	Quality factor associated to the renewable energy source used [-]
h	Specific enthalpy [kJ kg^{-1}]
h_f	Specific enthalpy of saturated-liquid (water) [kJ kg^{-1}]
h_{fg}	Enthalpy of vaporization for water [kJ kg^{-1}]
$\dot{I}$	Irreversibility rate [kW]
$\dot{I}_R$	Relative irreversibility [-]
$\dot{m}_{a,C}$	Mass air flow rate for air stream C [kg s^{-1}]
$\dot{m}_{a,P}$	Mass air flow rate for air stream P [kg s^{-1}]
$\dot{m}_{a,R}$	Mass air flow rate for air stream R [kg s^{-1}]
$\dot{m}_{cw}$	Mass flow rate of chilled water [kg s^{-1}]
$\dot{m}_{hw}$	Mass flow rate of hot water [kg s^{-1}]
$\dot{m}_w$	Water mass flow rate for the evaporative cooler [kg s^{-1}]
p	Pressure [kPa]
p_{sat}	Saturated pressure [kPa]
PER	Primary Energy Ratio [-]
$\dot{Q}_{reg}$	Heat rate required for air regeneration [kW]

R_a	Ideal gas constant of dry air [kJ kg^{-1} K^{-1}]
R_v	Ideal gas constant of water vapour [kJ kg^{-1} K^{-1}]
RIS	Relative irreversibilities savings [-]
s	Specific entropy [kJ kg^{-1} K^{-1}]
s_f	Specific entropy of saturated-liquid (water) [kJ kg^{-1}]
T	Temperature [ºC] or [K]
T_w	Wet-bulb temperature [K]
v_f	Specific volume of saturated-liquid (water) [m^3 kg^{-1}]
$\dot{W}_{el}$	Electricity input rate [kW]
y_i	Molar fraction of a substance *i* in the mixture [-]

Greek symbols

ε	Effectiveness [-]
δ	Exergy efficiency defect [-]
ϕ	Relative humidity [-]
φ_r	Fraction of heat produced from renewables [-]
η_{eg}	Averaged electric grid efficiency [-]
η_{hs}	Thermal efficiency of heating system [-]
μ_i	Chemical potential of the substance *i* [kJ kg^{-1}]
ψ	Exergy efficiency [-]
ω	Humidity ratio [kg kg^{-1}]

Subscripts

0	Restricted dead state
hs	Heating system.
in	Input or required
j	Assessment point
k	Component
out	Output or desired
ove	Overall
r	Return
ref	Reference scenario
s	Supply

Acronyms

DCS	Desiccant Cooling System
DW	Desiccant wheel

1 Introduction

The exergy analysis is a thermodynamic analysis technique based on second law of thermodynamic that provides an alternative way for assessing and comparing processes and systems more rationally and meaningfully. This well-known technique is defined as a measure of the potential work of different energy forms or states evaluated in a given reference environment [1-3]. The method may be applied to any thermodynamic system, and in particular for multi-component systems, it is able to identify and locate irreversibility sources, allowing to evaluate the contribution of each sub-system for the overall inefficiency of the plant [4].

Regarding to achieve comfort indoor environmental conditions, active energy systems are usually installed in buildings. Nevertheless, due to their high energy consumption, operating costs and/or some harmful effects on environment, these systems have been replaced by alternative ones, including hybrid systems that make use of renewable energy resources. Despite most of conventional systems are strongly implemented, most of their alternatives are still under research or development stages. The Desiccant Cooling Systems (DCS) are heat-driven systems, designed to provide cooled and dehumidified air to indoor environments, and have been moderately applied as alternative or complement to conventional compression/absorption cooling systems. These systems could have potentially economic, energy and environmental advantages with respect to traditional cooling devices, although the complexity of such systems may reduce their acceptance, especially in situations where there aren't on-site qualified operating professionals. Its operation is based on a rotary dehumidifier (the Desiccant Wheel, DW), where the air is dehumidified. It is made by a desiccant material, such as silica gel, activated alumina or lithium chloride salt, which is able to hold the moisture of the air. Although, it has to be regenerated through a warm air stream, usually heated by a gas fired boiler. Low-grade thermal energy (60-95 ºC) is sufficient for the regeneration, meaning that solar, geothermal or waste heat may be used. Previously dehumidified and after passing through an air-to-air heat exchange, the air stream can be cooled to the desired temperature, forcing it to cross a cooling coil (connected to a conventional chiller, for example). A DCS may avoid the air stream of overcooling and re-heating, as occurs in the conventional systems providing cooled and dehumidified air.

Several research works involving DCS have been conducted in the last years. Angrisani et al. [5–8] conducted a set of experimental-based studies on a small scale poly-generation system, constituted by a natural gas microcogenerator connected to a desiccant cooling system. The authors assessed all technical features of all the sub-components of a DCS system and successfully implemented and calibrated it into a model, developed in TRNSYS [9]. Parmar et al. [10] developed an artificial neural network model for predicting the dry bulb temperature and specific air humidity at the outlet of a desiccant wheel. La et al. [11] studied a modified regenerative evaporative cooling system coupled to a rotary desiccant cooling process, which can produce both dry air and chilled water simultaneously. The authors aimed to evaluate the feasibility and energy saving potential of this novel system. Combining chilled ceiling, displacement ventilation and desiccant dehumidification, Hao et al. [12] investigated the feasibility of this integrated system for finding the configuration that can realize desirable levels of indoor air quality, thermal comfort and energy savings in hot and humid climates.

From all the studies reviewed [5-12], they are based on an entirely energy conventional (or first law of thermodynamic) approach, do not revealing the actual thermodynamic performance of the systems under analysis, and do not answering to questions, such as: ‘How far each system is from ideal system?’; or ‘What is the most inefficient component of the plant?’; or even ‘How much each system contributes for the plant inefficiency?”. These and other questions, may be answered using exergy methods that have been applied as valuable tools for design, analysis or performance assessments of different type of systems: solar thermal systems [13,14], cogeneration systems [15,16], buildings and HVAC systems [17, 18], power and refrigeration cycles [19,20]; or even in large scale, such as societies or countries [21].

Using the second law analysis, Darwish et al. [20] investigated a liquid-phase separation novel refrigeration cycle, concluding that the highest inefficient component is the heating generator, contributing to the total exergy destruction of the plant in 42 %. Roux et al. [14] conducted a thermodynamic optimisation of a small scale solar thermal Brayton cycle, dividing inefficiency sources into two types of irreversibilities (internal and external), finding that the internal irreversibility rate is almost three times the external irreversibility rate. Wei et al. [22] presented an exergy analysis study of variable air volume (VAV) system for office buildings air-conditioning, and concluded that the largest improvement on exergy efficiency is obtained by changing the heating source from electricity to renewable energy sources (such solar or geothermal), closing that the use of mechanical cooling in cold climate should be more questioned. The benefits of exergy analysis combined with dynamic energy simulation tools were also claimed by Wei et al. [22], which suggested the integration of the exergy methods into building energy codes (such as, EnergyPlus [23] or TRNSYS [9]).

Specifically in the field of desiccant cooling systems, few studies on exergy analysis have been found in literature: Lavan et al. [24] assessed the overall second law performance for a desiccant air conditioning system, applying the concept of “feasible performance”. Additionally, Kanoglu et al. [25] developed a procedure for energy and exergy analysis of desiccant cooling systems. The authors found that desiccant wheel has the greatest percentage of exergy destruction followed by the heating system. These analyses allowed to quantify and identify the sites with the losses of exergy and therefore showing the direction to approach the ideal *COP*. And Hurdogan et al. [26] evaluated the energy-exergy performance a novel desiccant cooling system, using average measured parameters obtained from experimental results. The exergy efficiencies of all the systems components were determined in attempt to assess their individual performances and potential for improvement be found. In the field of liquid desiccant dehumidification systems, the studies [27-29] were also performed.

From the studies reviewed of desiccant cooling systems [24-26], the authors have applied exergy analysis to assess in detail the exergy to performance or finding irreversibility sources, although without considering other sources/technologies for the heating system (e.g. solar thermal, wood or heat pump systems) or evaluating the impact of replacing one of components on the exergy performance of other components or plant as a whole. In this study, the exergy method was implemented into a pre-calibrated DCS model, previously implemented in TRNSYS by Angrisani et al. [7,30]. The objective is to assess the overall energy and exergy performance of all components and DCS plant as whole and locate the most inefficient components, associated to higher sources of irreversibilities. As case-study, using weather data corresponding to the city of Naples (Italy), for the period from 1st to 7th August (9h00-18h00), the indicators primary energy ratio (*PER*), exergy efficiency, irreversibilities rate, exergy efficiency defect and relative irreversibility were assessed and discussed. Additionally, the *PER* and exergy efficiency were assessed and compared for a set of renewable energy scenarios and different heating technologies (e.g. solar thermal, wood fuelled heating systems and heat pumps). The main irreversibilities present in the DCS were evaluated as function of the operating conditions in the period, and at the end, an iso-line diagram was proposed for evaluating irreversibilities savings due to improvements on boiler efficiency or integration of renewables from solar thermal.

2 The exergy method applied to DCS

In DCS, moist air is exposed to several changes of temperature and humidity ratio, so special attention should be given to the exergy variations of moist air in each system component. The definition of the reference dead-state is also a very sensitive parameter in exergy analysis and should be carefully treated. According to Ref. [1], the specific exergy of a mixture air flow is constituted by a thermo-mechanical and chemical exergy component, generically described by Eq. (1).

$$ex = ex_{tm} + ex_{ch} \quad (1)$$

where ex_{tm} is the thermo-mechanical exergy and ex_{ch} is related to the chemical exergy term, which are related to the change from the actual state to a restricted or dead state. Neglecting kinetic and potential effects, the thermo-mechanical exergy and chemical exergy are given by Eq. (2) and (3), respectively [1].

$$ex_{tm} = \left(h - h_0\right) - T_0\left(s - s_0\right) \quad (2)$$

$$ex_{ch} = \sum_{i=1}^{n} y_i\left(\mu_i - \mu_{i,0}\right) \quad (3)$$

where, in Eq. (2), h is the specific enthalpy, s the specific entropy and T_0 is the dead state temperature. In Eq. (3), y_{i} and μ_i are the molar fraction of substance in the mixture and the chemical potential of the substance i, respectively, and the sub-script ‘0’ represents the restricted dead-state point.

2.1 Specific exergy of moist air and water

Assuming the outdoor air as an ideal gas mixture, constituted by dry air and water vapour, the exergy of moist air at a given point j, neglecting kinetic and potential effects, is given by Eq. (4) [1], where, $c_{p,a}$ and $c_{p,w}$ are the specific heat of dry air and water vapour at constant pressure, ω_j and ω_0 are the humidity ratio of moist air at point j and dead-state point, respectively, T_j and T_0 are the temperature at point j and dead-state, respectively. R_a is the ideal gas constant of dry air and p_j and p_0 are the pressure at point j and dead-state, respectively. Furthermore, the specific exergy of water at point *j* is described by Eq. (5) [1].

$$ex_j = \underbrace{\left(c_{p,a} + \omega c_{p,v}\right)\left[T_j - T_0 - T_0 \ln\left(\frac{T_j}{T_0}\right)\right]}_{thermal} + \underbrace{\left(1 + 1.608\omega_j\right) R_a T_0 \ln\left(\frac{p_j}{p_0}\right)}_{mechanical} + \underbrace{R_a T_0 \left[\left(1 + 1.608\omega_j\right)\ln\left(\frac{1+1.608\omega_0}{1+1.608\omega_j}\right) + 1.608\omega \ln\left(\frac{\omega_j}{\omega_0}\right)\right]}_{chemical} \quad (4)$$

$$ex_{w,j} = \underbrace{\left(h_{f,j} - h_{f,0}\right) - T_0\left(s_{f,j} - s_{f,0}\right)}_{thermal} + \underbrace{v_f\left(p_j - p_{sat}\right)}_{mechanical} - \underbrace{R_v T_0 \ln \phi_0}_{chemical} \quad (5)$$

where the symbols $h_{f,j}$ and $h_{f,0}$ are the specific enthalpy of saturated-liquid at a generic point *j* and at dead-state, respectively; $s_{f,j}$ and $s_{f,0}$ are the specific entropy of saturated-liquid at a generic point *j* and at dead-state, respectively. T_0 is the dead state temperature, v_f is the specific volume of liquid water, p_j and p_{sat} are the pressure at a generic point *j* and saturated pressure, respectively. R_v is the universal constant for the water vapour (ideal gas) and ϕ_0 is the relative humidity at dead state. For water flows in closed-cycle circuits, without any contact with air, the chemical term $R_v T_0 \ln \phi_0$ becomes zero, since it is assumed $\phi_0 = 1$ (saturated state). For applications with steam injector, where pure water enters or leaves the control volume (e.g. evaporative coolers), ϕ_0 is calculated for the air properties at dead-state point.

2.2 Exergy-based indicators

In engineering systems, non-dimensional energy ratios are usually applied to evaluate energy systems efficiencies (e.g. the thermal efficiency or coefficient of performance, *COP*). It gives information about “the ability to produce a desired effect with minimum use of energy or resource” [2]. However, the efficiency based on a purely an energy approach is ambiguous, and cannot accurately measure “the distance” to ideal (reversible) system. Therefore, the performance of a given energy system should be evaluated by means exergy or second law efficiency. A general definition of exergy efficiency for a given *k* component is given by Eq. (6).

$$\psi_k = \frac{\dot{E}x_{out,k}}{\dot{E}x_{in,k}} = 1 - \frac{\dot{I}_k}{\dot{E}x_{in,k}} \tag{6}$$

where, $\dot{E}x_{out,k}$ and $\dot{E}x_{in,k}$ are the exergy output and input rate to the component *k*, respectively, and $\dot{I}_k$ is the irreversibility rate generated at component *k*. The symbols $\dot{E}x_{out,k}$ and $\dot{E}x_{in,k}$ could not represent physical input/outputs rates, but desired or required effects. The ratio of exergy output to exergy input is always less than unit and its value depends on the degree of irreversibility of the process, which is a particular suitable criterion for the degree of thermodynamic perfection of a process [3].

A multi-component system like a DCS, where the control volume can be divided into a finite number of sub-systems, there are advantages to introduce the concepts "exergy efficiency defect" (δ) and relative irreversibility (I_R). Exergy efficiency defect is given by the ratio between exergy destruction rate at the *k*-th component to the total exergy input rate to the overall system, as given by Eq. (7) [3].

$$\delta_k = \frac{\dot{I}_k}{\sum \dot{E}x_{in,k}} \tag{7}$$

The relative irreversibility, $I_{R,k}$ is defined by the ratio of exergy destruction of the *k*-th component to the total irreversibility rate occurring in the system, as shown by Eq. (8).

$$I_{R,k} = \frac{\dot{I}_k}{\sum_k \dot{I}_k} \tag{8}$$

The sum of the exergy efficiency defect of the *k* components is expressed by Eq. (9), where ψ_{ove} is the overall efficiency of the system. It shows the direct causal relationship between component's irreversibility rate and their effect on overall efficiency of the system.

$$\sum_k \delta_k = 1 - \psi_{ove} \tag{9}$$

Finally, the comparison of irreversibilities levels between systems may be done through the indicator the Relative Irreversibilities Savings (*RIS*) [35], expressed by

$$RIS_k = 1 - \frac{\dot{I}_k}{\dot{I}_{k,ref}} \tag{10}$$

where $\dot{I}_k$ are the irreversibility rate for a given heating system under and $\dot{I}_{ref}$ is the irreversibility rate for the reference scenario.

3 Methodology

3.1 System description

The DCS system under study is an air handling unit located at the *Università degli Studi del Sannio*, Benevento (Italy), constituted by a desiccant wheel, an air-to-air heat exchanger, an evaporative cooler and heating and cooling coils. Natural gas boiler is used as heating system for the DW regeneration and the sensible cooling of the process air exiting the cross flow heat exchange is realized by a conventional chiller. The schematic of the system is shown in Figure 1, where three air flows (R, C and P) are represented:

- "*Stream R*" is used for the regeneration of the desiccant wheel (5-6) after its passage in the heating coil interacting with the boiler (1-5);
- "*Stream C*" is the auxiliary air flow used for the pre-cooling of the processed air (7-8) after its passage in the evaporative cooler (1-7);
- "*Stream P*" is the process air, dehumidified by the desiccant wheel (1-2), pre-cooled at the cross flow heat exchanger (2-3) and cooled at the cooling coil (3-4), which interacts with the chiller.

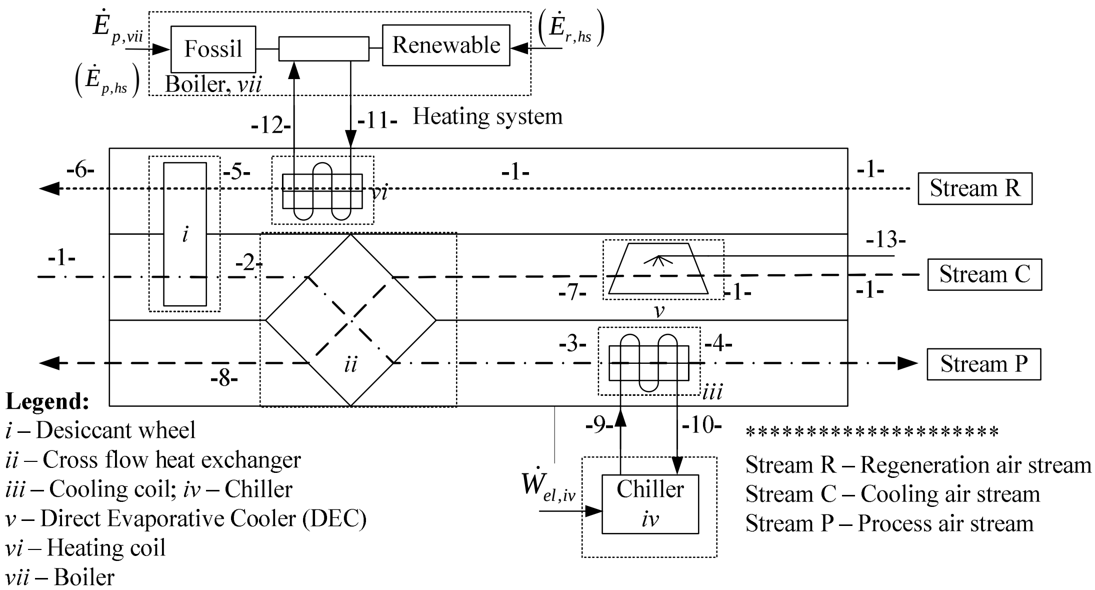


Figure 1: Schematic of the desiccant cooling system.

The assessment points (1-13) are presented in Figure 1, where point no. 1 represents the outdoors conditions. In Ref. [5–8], more detailed information about the experimental plant lay-out is available. The TRNSYS model of the DCS was calibrated and validated using experimental data by Angrisani et al. [7] and implemented in [31]. The main parameters used for each DCS component (Type in TRNSYS) are presented in Table 1.

Table 1: The main parameters of the TRNSYS types used for the components models under investigation.

Component	Type no.	Parameter	Value
i	1716	Dehumidifier F1 effectiveness [-]	0.207
		Dehumidifier F2 effectiveness [-]	0.717
		Set-point outlet air humidity ratio [kg/kg]	0.008
ii	91	Heat exchanger effectiveness [-]	0.446
iii	508	Coil bypass fraction [-]	0.177
iv	655	Rated capacity [kW]	8.45
		Rated *COP* [-]	2.93
v	506	Saturation efficiency [-]	0.551
vi	670	Effectiveness of heat exchanger [-]	0.842
vii	6	Maximum heating rate [kW]	26.7
		Efficiency of auxiliary heater [-]	0.902

3.2 Energy and exergy methods applied to DCS

In this study, for the energy and exergy analysis of the DCS system described in Figure 1, the following assumptions were taken into account:

a) Steady-state and one dimensional condition;

b) Negligible potential and kinetic energy effects;

c) No pressure losses across the components;

d) The auxiliaries' loads for the fans and pumps were neglect.

According to Figure 1, the system was divided in seven components (*i-vii*) and thirteen assessment points (1-13), where the specific energy and exergy were evaluated. In Eq. (11-17) [26], a set of equations describing mathematical formulations for energy and exergy based performances of the components *i-vii* are shown [25, 26].

Desiccant wheel, *i*:

$$\begin{cases} \varepsilon_i = \dfrac{\dot{m}_{a,P}\left(\omega_1-\omega_2\right)h_{fg}}{\dot{m}_{a,R}\left(h_5-h_1\right)} \\ \psi_i = \dfrac{\dot{m}_{a,P}\left(ex_2-ex_1\right)}{\dot{m}_{a,R}\left(ex_5-ex_6\right)} \end{cases} \quad (11)$$

Heat exchanger, *ii*:

$$\begin{cases} \varepsilon_{ii} = \dfrac{\dot{m}_{a,P} c_{p,a} \left(T_2 - T_3\right)}{\dot{C}_{\min} \left(T_2 - T_7\right)} \\ \psi_{ii} = \dfrac{\dot{m}_{a,C} \left(ex_8 - ex_7\right)}{\dot{m}_{a,P} \left(ex_2 - ex_3\right)} \end{cases} \tag{12}$$

Cooling coil, *iii*:

$$\begin{cases} \varepsilon_{iii} = \dfrac{\dot{m}_{a,P} c_{p,a} \left(T_3 - T_4\right)}{\dot{C}_{\min} \left(T_3 - T_9\right)} \\ \psi_{iii} = \dfrac{\dot{m}_{a,P} \left(ex_3 - ex_4\right)}{\dot{m}_{cw} \left(ex_9 - ex_{10}\right)} \end{cases} \tag{13}$$

Chiller, *iv*:

$$\begin{cases} COP_{iv} = \dfrac{\dot{m}_{cw} \left(h_9 - h_{10}\right)}{\dot{W}_{el,iv}} \\ \psi_{iv} = \dfrac{\dot{m}_{cw} \left(ex_9 - ex_{10}\right)}{\dot{W}_{el,iv}} \end{cases} \tag{14}$$

Evaporative cooler, *v*:

$$\begin{cases} \varepsilon_{v} = \dfrac{\left(T_1 - T_7\right)}{T_1 - T_{w,1}} \\ \psi_{v} = \dfrac{\dot{m}_{a,C} ex_7}{\dot{m}_{a,C} ex_1 + \dot{m}_{w,13} ex_{w,13}} \end{cases} \tag{15}$$

Heating coil, *vi*:

$$\begin{cases} \varepsilon_{vi} = \dfrac{\dot{m}_{a,P} c_{p,a} \left(T_5 - T_1\right)}{\dot{C}_{\min} \left(T_{11} - T_1\right)} \\ \psi_{vi} = \dfrac{\dot{m}_{a,R} \left(ex_5 - ex_1\right)}{\dot{m}_{hw} \left(ex_{11} - ex_{12}\right)} \end{cases} \tag{16}$$

Natural gas boiler, *vii*:

$$\begin{cases} \eta_{vii} = \dfrac{\dot{m}_{hw} \left(h_{11} - h_{12}\right)}{\dot{E}_{p,vii}} \\ \psi_{vii} = \dfrac{\dot{m}_{hw} \left(ex_{11} - ex_{12}\right)}{F^{ex}_{f,vii} \dot{E}_{p,vii}} \end{cases} \tag{17}$$

The symbol h_{fg} is the enthalpy of vaporization for water, ω is the humidity ratio, h is the specific enthalpy and *ex* is the specify exergy. $\dot{m}_{a,P}$, $\dot{m}_{a,R}$ $\dot{m}_{a,C}$ are the air mass flow rate for stream P, R and C, respectively. $\dot{m}_{hw}$ $\dot{m}_{cw}$ are the hot and cold water mass flow rate, respectively. $F^{ex}_{f,vii}$ is the chemical exergy to Lower Heating Value (LHV) (quality factor) of the fuel (natural gas), which in this study was assumed equal to 1.04, according to Ref. [3]. $\dot{E}_{p,vii}$ is the primary-fossil energy input (natural gas) and $\dot{W}_{el,iv}$ is the electric power input to the chiller (equivalent to exergy).

In the Eq. 11, the effectiveness related to the DW is defined as the ratio between the dehumidification performance of the wheel with respect to the regeneration heat input. In the Eq.s 12, 13 and 16, the effectiveness related to components *ii*, *iii*, and *vi*, respectively is given as the ratio of the amount of heat transfer to the maximum possible heat transfer, where $\dot{C}_{\min}$ is the minimum of the capacitance rate of cold and hot streams, given by the product of mass flow rate and specific heat related to each stream. *COP* is the coefficient of perform of the chiller and η is the thermal efficiency of the boiler.

The overall energy performance of the DCS is defined by Primary energy Ratio (*PER*), which is defined by the ratio of cooling capacity to the total primary-fossil energy inputs, as expressed in Eq. (18).

$$PER_{ove} = \frac{\dot{m}_{a,P}\left(h_1 - h_4\right)}{\underbrace{\dot{E}_{p,vii}}_{boiler} + \underbrace{F^{p}_{el}\,\dot{W}_{el,iv}}_{chiller}} \tag{18}$$

where, $\dot{E}_{p,vii}$ is the primary energy input to the boiler, given by the product of fuel mass flow rate to the Lower Heating Value of fuel. In this study, natural gas is assumed as primary energy source. For electricity, the conversion factor for primary-fossil energy, F^{p}_{el} is calculated based on the average electric grid efficiency. In this paper, $F^{p}_{el} = 2.17$, calculated for the efficiency of Italian electric grid, η_{eg} = 46.1 % [32].

3.3 Energy-exergy performances and integration of renewables

The heat required for DW regeneration could be provided from both renewables and fossil energy sources. Depending of required temperature levels, only some type of renewable sources could be used for the regeneration of the desiccant wheel, so renewables combined with fossil powered systems are commonly used. As example, solar thermal systems are usually combined with boilers or heat pump systems. On other side, combustion-based renewable systems, fuelled by wood, pellets or others biofuels may be used as stand-alone (single) heating system, once they could provide enough air temperature for DW regeneration.

When renewables are included, the demand for primary-fossil energy is reduced, leading to an increase of the energy performance of the system (*PER*). Thus, for a given fraction of heat delivered from renewables $\left(\varphi_r\right)$, the corresponding primary energy demand of a fuel-based heating system, $\dot{E}_{p,hs}$ is generically obtained by

$$\dot{E}_{p,hs} = \frac{\dot{Q}_{reg}}{\eta_{hs}}\left(1-\varphi_r\right) \tag{19}$$

where $\dot{Q}_{reg}$ is the heat required for the regeneration and η_{hs} is the overall thermal efficiency of heating system. For electric-based heating systems, the value given by Eq. (19) should be multiply by F_{el}^{p}, the primary conversion factor related to electricity.

Concerning the assessment of total exergy input when renewables are included into the heating system, the exergy input rate is formulated by

$$\dot{E}x_{hs} = F_{f,hs}^{ex}\dot{E}_{p,hs} + F_{r,hs}^{ex}\dot{E}_{r,hs} \tag{20}$$

where, $\dot{E}_{p,hs}$ and $\dot{E}_{r,hs}$ are fossil and renewable source energy inputs, respectively and $F_{f,hs}^{ex}$ and $F_{r,hs}^{ex}$ are the exergy to Low Heating Value (LHV) ratio of the fossil and renewable fuels, respectively. As regards renewables, if direct thermal sources are used (e.g. hot water from solar thermal), $F_{r,hs}^{ex}$ is commonly calculated by Eq. (21), where T_s and T_r are the supply and return temperature, respectively, and T_0 is the dead-state temperature [33].

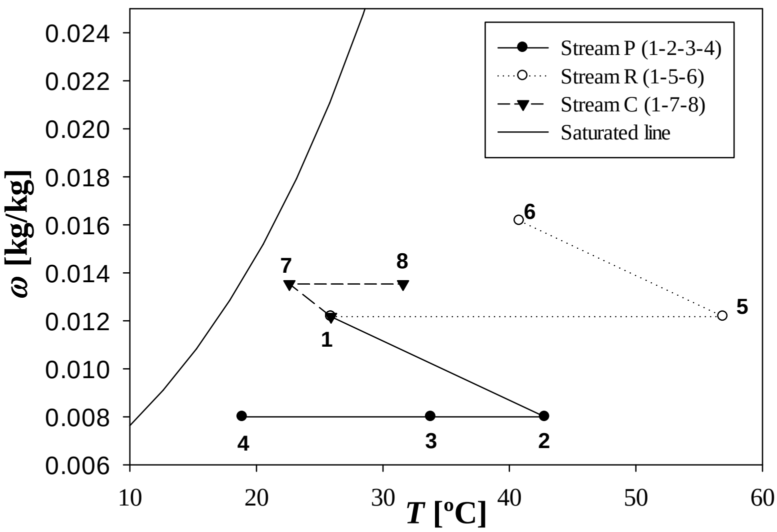
$$F_{r,hs}^{ex} = 1 - \frac{T_0}{\left(T_s - T_r\right)}\ln\left(\frac{T_s}{T_r}\right) \tag{21}$$

4 Results and discussion

In this section, the energy and exergy results derived from the simulations of the DCS model [30] are presented. Averaged values for temperature, humidity ratio, dry air/water mass flow rate and power inputs, calculated for the period from 1st to 7th August, from 9h00 to 18h00 and using climate data corresponding to the city of Naples (Italy), were used to perform the analyses. In this period, the outdoor temperature varies from 21 to 29 ºC and the humidity ratio from 0.008 to 0.017 kg of water/kg dry air.

The evolution of humidity ratio and dry bulb temperature for the air points (1-8) of the DCS is shown in Figure 2, where the saturated line corresponding to the moist air with humidity ratio 100 % is also represented. In air stream P (air points 1-2-3-4), water vapour is removed from the air by means of the desiccant wheel (1-2); two constant humidity ratio cooling processes then follows: one at cross flow heat-exchanger (2-3) and the other at cooling coil (3-4). In air stream C, water vapour is added by means of the evaporative cooler (1-7), a heating process (7-8) at heat exchanger then follows. Finally, as regards the regeneration air stream R, the air flow is heated in the heating coil (1-5), before crossing the desiccant wheel (5-6).

Figure 2: Evolution of the temperature and humidity ratio for the points of the stream P, C and R.



4.1 Dead-state point

An important issue in exergy analysis is the definition of the dead-state point, which describes conditions where the specific exergy is zero. In the literature on exergy analysis of DCS, there is no recommended value for the definition of the dead state condition, although this is a very important issue and should be carefully chosen. For this study, the median of outdoor temperature and humidity ratio that occurs in the period from 1st to 7th August (9h00 to 18h00) was chosen as dead-state, regarding to be the nearest point of the environmental conditions during the operation of the plant. Using the climate file corresponding to the city of Naples (Italy), the dead-state was found as $T_0 = 26.1\,^{\circ}\mathrm{C}$,

$\omega_0 = 0.0114$ kg water/kg dry air, $(\phi_0 = 53.5\,\%)$. The dead state pressure was assumed constant for all points assessed, $p_0 = 101\,325$ Pa, so the mechanical part of exergy in Eq. 4 is neglected in this study.

4.2 Energy and exergy properties

The evolution of the specific exergy of moist air at each point of Streams P, C and R is shown in Figure 3. Comparing the exergy variation of the three main air streams, stream R has the highest point's exergy variation, followed by stream P and C. Points in stream C are near environmental conditions or dead state point, therefore their specific exergy are near zero. Furthermore, the iso-line at ϕ_0 = 53.5 % is represented, having the lowest value (zero) at dead state conditions.

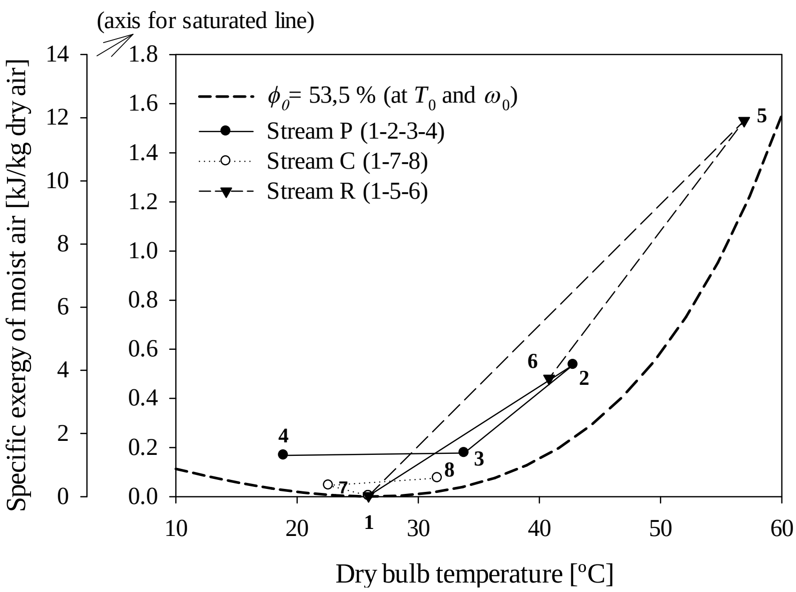


Figure 3: Evolution of the specific exergy with dry bulb temperature at each point of the stream P, C and R.

The numeric values of temperature, humidity ratio, enthalpy and specific exergy of the points (1-13) in DCS are presented in Table 2. The specific enthalpy of moist air and specific enthalpy/entropy of water, required by Eq. 5, were calculated by the software package Engineering Equation Solver (EES) [33]. Additionally, thermal and chemical exergy components (Eq. 4) of moist air points are also presented in Table 2, as well as the fraction related to thermal exergy (ratio of specific thermal exergy to total specific exergy). As expected, higher fractions of thermal exergy occur for high deviations of air temperatures relatively to dead state temperature (Points 2 and 5). For points particularly near to the dead state temperature (Points 1, 3, 4 and 7), the specific exergy of moist air is mostly equally divided in thermal and chemical exergy. As stated, since the pressure differences related to dead state were neglected, the mechanical component of exergy was ignored. Some special attention is given for specific exergy of the water points (9-12) and (13), which differs in one magnitude order. Thus, in the points (9-12) only thermo-mechanical aspects were assumed, because as points in a closed circuit, without air contact, a saturated atmosphere is assumed $\left(\phi_0 = 1\right)$, and $R_v T_0 \ln \phi_{0s} = 0$. Nevertheless, the water spray used for air humidification (13), both thermo-mechanical and chemical exergy of water should be taken into account, since $\phi_0 \neq 1$.

Table 2: Air and water properties used for exergy analysis.

Fluid [point]	*T* [ºC]	*ω* [kg/kg]	*h* [kJ/kg]	*m* [kg/s]	*ex* [kJ/kg]	$ex_{(th)}$ [kJ/kg]	$ex_{(ch)}$ [kJ/kg]	$ex_{(th)}/ex$ [%]
Air [0]	26.1	0.0114	55.4	-	0.000	0.000	0.000	0.0
Air [1]	25.9	0.0122	57.2	0.225	0.004	0.000	0.004	2 %
Air [2]	42.8	0.0080	63.5	0.225	0.536	0.459	0.077	85 %
Air [3]	33.8	0.0080	54.5	0.225	0.176	0.099	0.077	56 %
Air [4]	18.9	0.0080	39.3	0.225	0.167	0.090	0.077	53 %
Air [5]	56.9	0.0122	89.1	0.225	1.531	1.527	0.004	100 %
Air [6]	40.8	0.0162	82.8	0.225	0.483	0.362	0.121	75 %
Air [7]	22.6	0.0135	57.1	0.225	0.046	0.021	0.025	47 %
Air [8]	31.6	0.0135	66.4	0.225	0.076	0.051	0.025	68 %
Water [0]	26.1	-	109.4	-	0.000	-	-	-
Water [9]	13.9	-	58.4	0.404	1.070	-	-	-
Water [10]	16.0	-	67.2	0.404	0.729	-	-	-
Water [11]	62.7	-	262.5	0.165	8.661	-	-	-
Water [12]	52.3	-	219.0	0.165	4.534	-	-	-
Water [13] (spray)	22.6	-	94.8	0.001	82.630	-	-	-

4.3 Energy and Exergy Performances

The individual operation of each component allows to identify and quantify the sites with the exergy destruction (irreversibilities) occurs showing the direction to approach the best plant performance (or reversible *COP*). In this section, the energy- and exergy-based results for each individual component and plant as whole are presented. The parameter commonly applied to assess the energy-based performance of heat exchangers, desiccant wheel or evaporative cooler is the effectiveness. On other hand, for the boiler and chiller parameters, such thermal efficiency and *COP* are currently applied. Furthermore, these energy-based performances influence the exergy performances and the related irreversibilities rates. The differences between energy-based and exergy efficiencies of each DCS component are shown in Figure 4. The effectiveness of DW presents the lowest energy-based performance, while chiller and boiler have higher energy efficiencies, following by the heating and cooling coils, with values of 75 % and 84 %, respectively. The chiller has a *COP* estimated in the period of 2.37, while the boiler has a constant thermal efficiency of 90.2 %. The overall *PER* of the DCS has a value of 32.2 %, showing that there are potential for improving *PER*. Questions such as: “where” or “how” this improvement can be more rationally made are given further, using the exergy results.

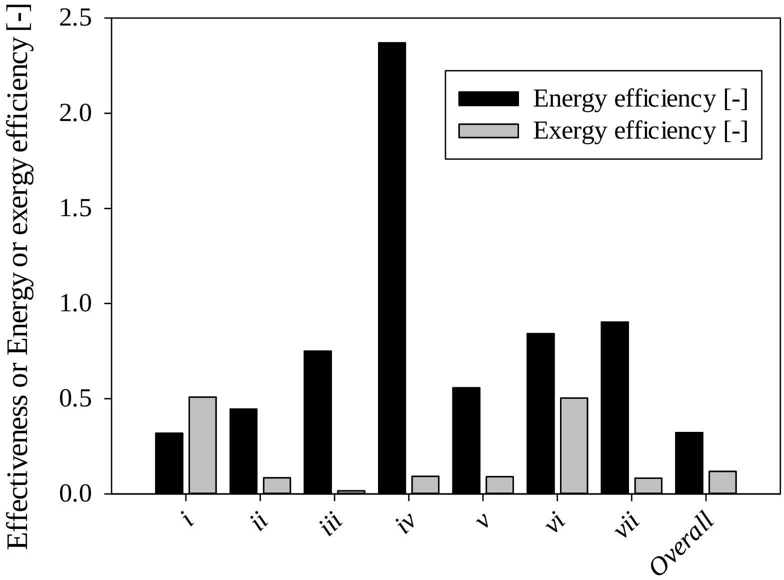


Figure 4: Energy and exergy based efficiencies of sub-components of DCS and overall system.

Energy efficiency deals only with energy quantities aspects, while exergy relates both quantity and quality aspects, indicating the actual “effort” required by each component to “produce” the “desired product”. Being exergy a non-conservative property, significant differences are found between energy and exergy-based efficiencies. Especially for components working near dead-state conditions (*ii*, *iii*, *iv* and *v*), the exergy efficiencies are extremely low. The exergy efficiency could give hints about the most inefficient component of the plant, although this indicator alone is not enough since each component has different exergy input rates. Concerning the chiller and the boiler that from an energy perspective appear to be the most efficient components of plant, from an exergy point of view, they have indeed very low efficiency values: 9.2 % and 8.2 %, respectively as shown in Table 3. The overall exergy performance of the DCS was estimated as 11.8 %, which indicates an even higher potential for improvement than from energy perspective.

Better than individual exergy efficiencies of components, exergy analysis techniques may also provide information about the highest contributors for plant inefficiencies, applying the concept of “relative irreversibility” and “exergy efficiency defect” [2-3]. The irreversibilities generated in each component of the plant are related with the exergy efficiency and the exergy input rates. The exergy input rate, irreversibility rate, exergy efficiency and relative irreversibility for each component are shown in Table 3.

Table 3: Exergy analysis results of the DCS, for dead state conditions: T_0 = 26.1 ºC, ω_0 = 0.0114 kg water/kg dry air and p_0 = 101.325 kPa.

Plant Component	Exergy input rate [kW]	Irreversibility rate [kW]	Exergy efficiency [%]	Relative Irreversibility [-]
i	0.236	0.116	50.8%	1.2%
ii	0.081	0.074	8.4%	0.8%
iii	0.138	0.135	1.6%	1.4%
iv	1.496	1.358	9.2%	13.9%
v	0.113	0.103	9.0%	1.1%
vi	0.683	0.339	50.4%	3.5%
vii	8.329	7.646	8.2%	78.2%
Overall	11.075	9.772	11.8%	100.0%

The results indicate the boiler (*vii*) as the component, where the highest irreversibility rate occurs (7.6 kW) followed by the chiller (1.4 kW), with a relative irreversibility of 78.2 % and 13.9 %, respectively. As the major part of the air state points are relatively near to the dead state conditions, the use of high exergy sources, such as electricity for the chiller and natural gas in the boiler, leading to high levels of irreversibilities in those components.

Concerning the most inefficient component in the plant (the boiler), the irreversibilities arise mainly due two energy conversion processes: the chemical exergy of the fuel (natural gas) when converted into thermal energy, usually evaluated at flame temperature (about 2200 K); and when the thermal energy is converted into low-temperature thermal sources (hot water). Therefore, the replacement of the boiler by a more exergy efficient technology, or that makes use of low-exergy thermal sources, may significantly contribute for the reduction of the irreversibility rates. Besides to relative irreversibility indicator, the concept of exergy efficiency defect [3] is applied to compare the irreversibility rate at a given component and the total exergy input to the plant. The results are shown in Figure 5 and indicates that the most inefficient component of the plant (higher exergy efficiency defect) is the boiler (69.0 %), followed by the chiller (12.3 %) and heating coil (3.1 %). The overall exergy efficiency defect is about 88.2 %, indicating a huge potential for improvement. For the rational improvement of the exergy performance of the system, the exergy analysis method indicates the boiler as the first component to be replaced, since has the highest value of exergy efficiency defect.

As previously stated, the reference state is a very important parameter for the exergy analysis. Since other alternatives for dead state could be used, the sensitivity of the overall exergy efficiency of the system with the reference (dead-state) temperature was examined. As results, the exergy efficiency varies from 14 % to about 8 % when the reference temperature increases from 19 ºC to 37 ºC (292 K to 310 K). They show that for higher outdoors (reference) temperature, the margin or potential for improving the system increases, meaning the actual exergy input rate “grow faster” than the theoretical useful exergy rate. Nevertheless, the reference humidity ratio was assumed constant (0.0114 kg/kg), therefore different results could arise if the variation of ω_0 was also taken into account.

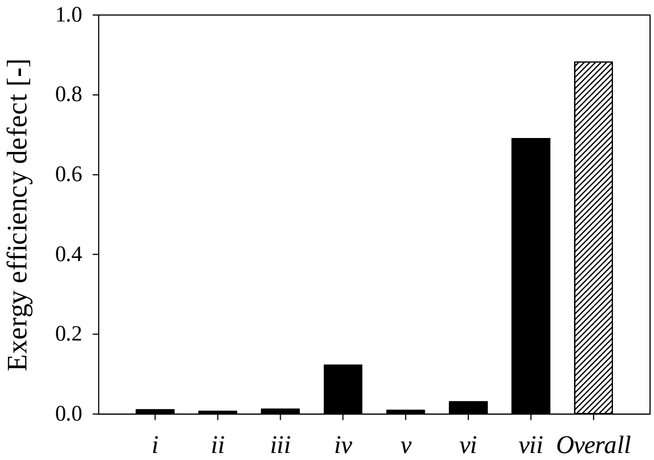


Figure 5: Exergy efficiency defect for the components (i-vii) of DCS.

4.4 Analysis of performance for different heating technologies and renewable energy sources

Alternative ways for improving the heating system exergy performance include its replacement by another technology that makes use more efficiently of primary-fossil energy resources (e.g. heat pump or cogeneration system) or use low-temperature (or low-exergy) sources, preferentially derived from renewable sources (e.g. solar thermal system or other thermal waste).

The current combustion heat generator (natural gas boiler) leads to very low-exergy performances due to high irreversibility levels that occur during the energy conversion process. Once the temperature levels required for the air regeneration are relatively moderate (less than 90 ºC), the use of low-temperature thermal renewable sources is a good alternative for the heating system. However, some renewable options cannot effectively lead to improvements on exergy efficiency, although conduct to reductions on primary fossil energy demand (e.g. heating systems fuelled by wood, biofuels/biomass). In this way, to compare different heating systems alternatives, primary energy and exergy performance indicators should be used. In this study, a set of different heating alternative systems technologies (including renewables) were proposed and the indicators *PER* and exergy efficiency were applied to compare them, keeping the cooling system as the same (i.e. chiller with an averaged *COP* 2.37). A brief description of the proposed scenarios and the main parameters used for each are presented in Table 4.

Furthermore, in Figure 6, a *PER* vs. exergy efficiency diagram is presented showing the differences between primary energy and exergy performance for each scenario considered. There are a couple of options that make lower use of primary-fossil energy sources, but that may not correspond to high exergy efficiency scenarios. The intensive use of renewables conducts to reductions on fossil energy sources (increasing of *PER*), although concerning exergy efficiency, the results show significant differences depending the type or quality of sources used. As an example, in Scenario D, heating requirements are totally provided by wood (considered a fully renewable source). This scenario presents the highest value of *PER*, however, it corresponds to the lowest exergy efficient option $(\psi = 11.4\,\%)$, because wood is a high exergy source and the combustion process is a highly irreversible process. On the other side, Scenario G (heat pump with *COP* 4 as heating system) presents the highest exergy efficiency (about 27 %), despite a moderate *PER* (50.6 %). The worst *PER* option is the Scenario E (a purely electric heating system) corresponds to a primary energy efficiency (*PER* = 95%). This is mostly related to the primary energy associated to the electricity production, leading to a low *PER* value.

Figure 6: PER vs. Exergy efficiency concerning different renewables and heating technologies scenarios.

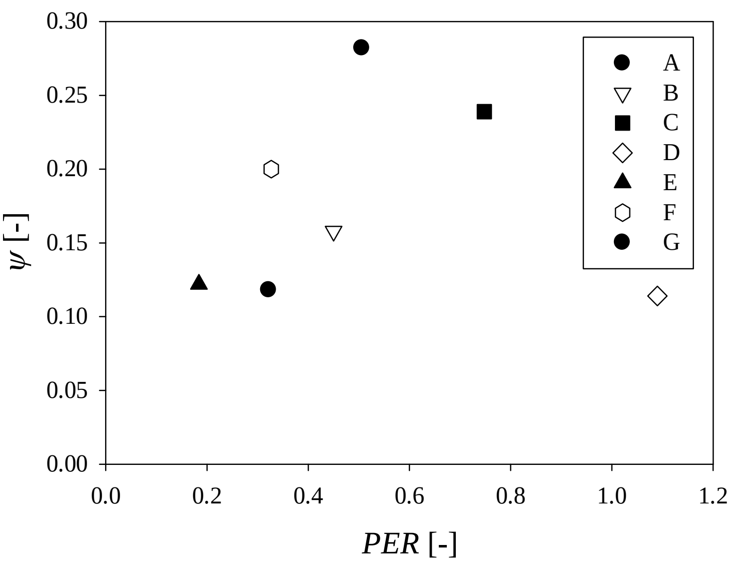


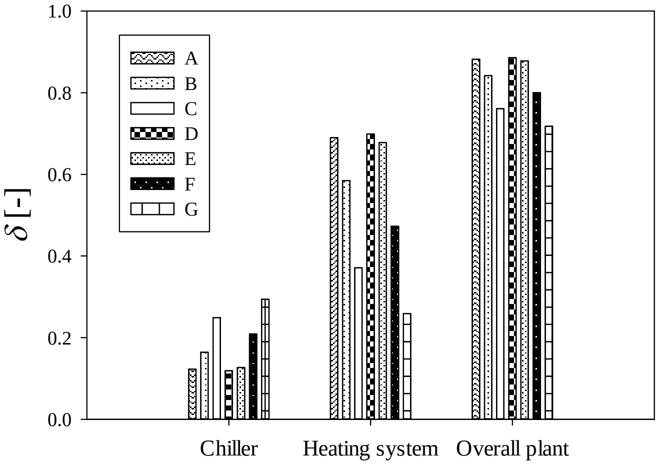
Table 4: Proposed scenarios and main parameters used for the exergy analysis of DCS, concerning renewables and others heating technologies.

Scenario #	Description
A	Natural gas boiler, with thermal efficiency 90 % (**original system**).
B	**Scenario A (60 %) + solar thermal system (40 %)**: the natural gas boiler provides 60 % of the heat requirements and the solar thermal system 40%. Solar thermal supply and return temperatures: T_s=60 ºC and T_r = 40 ºC, respectively. $\left(F_{r,hs}^{ex}=0.15\right)$ [32].
C	**Scenario A (20 %) + solar thermal system (80 %)**: the natural gas boiler provides 20 % of the heat requirements and the solar thermal system 20%. Solar thermal supply and return temperatures: T_s=60 ºC and T_r = 40 ºC, respectively. $\left(F_{r,hs}^{ex}=0.15\right)$ [32].
D	Heat requirements fully provided by a **wood-fuelled heating system**, with thermal efficiency of 86 %, based on efficiency based harmonized values [34]. Exergy to LHV of wood $\left(F_{r,hs}^{ex}=1.05\right)$ [32].
E	Heat requirements fully provided by an **electric heating system**, with an estimated thermal efficiency of 95 %.
F	Heat requirements fully provided by air source heat pump, assuming **COP = 2.**
G	Heat requirements fully provided by heat pump, assuming **COP = 4.**

Additionally, the exergy efficiency associated to this option presents also a low value, indicating the electric resistance as an inadequate technology converting electricity (high exergy) into thermal energy (low-exergy) for air regeneration. These analyses is show that the exclusive use of *PER* is not sufficient to describe the overall performance of DCS, and the exergy efficiency indicator reveals to be a good complementary indicator providing additional information about the rational use of energy sources.

Considering these scenarios, Figure 7 shows the variations of the parameter "exergy efficiency defect" occurring in the two most inefficient components of the plant (the chiller and the heating system) and the overall plant. The results clearly show the high exergy efficient options as C and G, which corresponds to scenarios with low exergy efficiency defect values (76.1 % and 71.8 %, respectively). They correspond to the best exergy performances, due to irreversibilities reductions obtained at the heating system. In these results, exergy efficiency defect is demonstrated as an important parameter that helps to identify the most inefficient component of the plant at each scenario. As example, in the scenario A, the heating system (natural gas boiler) was responsible for 69 % of exergy efficiency defect and chiller for 12.3 %. The heating system was found as the most inefficient system, so its replacement by a more efficient technology could contribute for improvements on overall performance of the plant. Additionally, for the most exergy efficient option (G), the exergy efficiency defect is 25.9 % for the heating system (heat pump) and 29.4 % for the chiller, showing in this case the chiller as a higher contributor for the inefficiencies than the heating system.

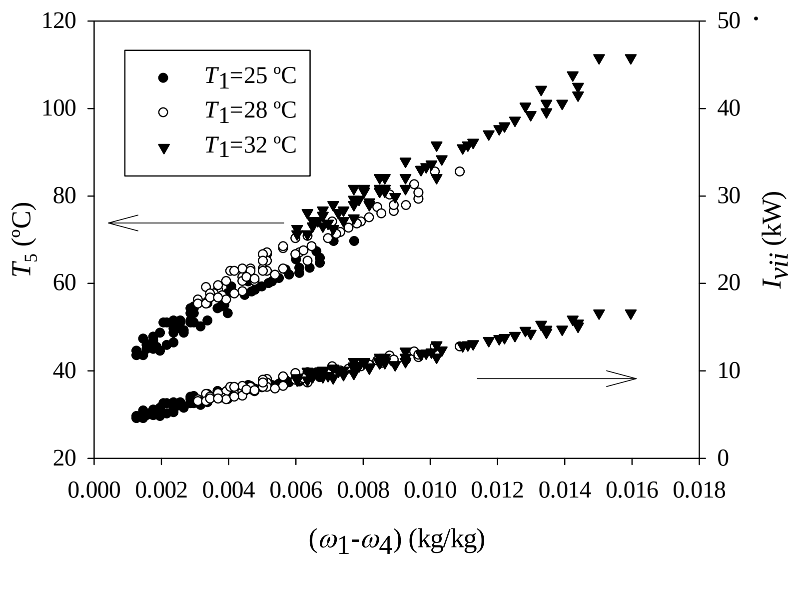
Figure 7: Exergy efficiency defect for the proposed heating systems and their impact on chiller (primary based) and overall plant.



4.5 Operating conditions and irreversibilities savings

For the desiccant wheel regeneration, depending of the outdoors conditions (temperature and humidity ratio), well-defined air temperatures and heat loads are required. For the period of analysis, and choosing as desired output conditions, $T_4 = 18\,$ºC and $\omega_4 = 0.008\,$kg/kg, some parametric analysis were conducted for three inlet temperatures levels (T_1 = 25 ºC, 28 ºC and 32 ºC) and assuming the humidity ratio occur in the period. In Figure 8, the temperature requirements for air regeneration at point (5), and the corresponding irreversibility rate at the boiler are shown. The results show that the temperature required for air regeneration (T_5) and irreversibility rate of the boiler increase

Figure 8: Regeneration temperature and irreversibility rate at boiler (Scenario A, B and C).



for higher humidity ratio and temperature differences between points 1 and 4.

Concerning the same period of analysis, in Figure 9 surfaces corresponding to the irreversibility rate occurring in scenarios A, B and C are represented as function of inlet temperature and humidity ratio, (T_1, ω_1) pairs verified in the period of analysis. For simplicity, no other scenarios were taken into account. The output desired conditions were kept constant at $T_4 = 18^o C$ and $\omega_4 = 0.008$ kg/kg.

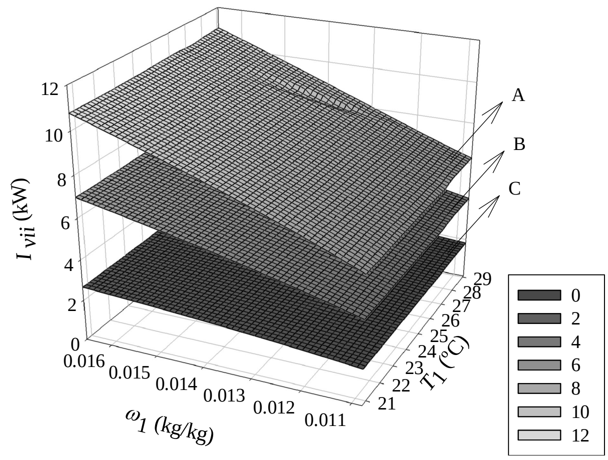


Figure 9: Irreversibility rate at heating system (vii), as function of inlet temperate and humidity ratio for Scenarios A, B and C.

Similarly, the results show that irreversibility rate rises for increasing values of T_1 and ω_1. Comparing the scenarios A, B and C, the lowest irreversibility rate is obtained when high share of (solar thermal system) are used for the heating system. In this example, the quality factor associated to low-temperature solar thermal sources is $F_{r,hs}^{ex} = 0.15$, calculated based on supply and return temperatures of 60 ºC and 40 ºC, respectively [32].

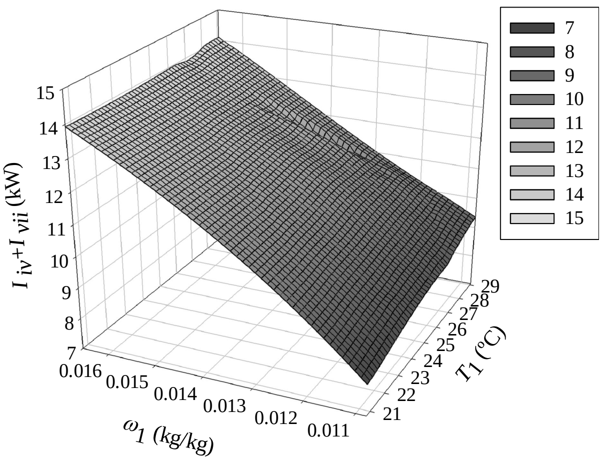


Figure 10: Sum of the irreversibility rate at boiler (vii) and chiller (iv), as function of inlet temperate and humidity ratio.

For these temperature levels, solar thermal systems alone could not be enough for DW regeneration, especially for high temperature requirements. Therefore these systems have to be integrated with other technological systems able to deliver heat at adequate temperature levels for the regeneration process. In Figure 10, the sum of the irreversibility rate occurring at the two most inefficient sub-systems (the chiller and the boiler at Scenario A) is represented as function of humidity ratio and inlet temperature. Considering the same output desired conditions, $T_4 = 18$ ºC and $\omega_4 = 0.008$ kg/kg, the results show that the irreversibilities levels are more sensible to variations of inlet humidity ratio than of inlet temperature levels.

The relative irreversibilities savings (*RIS*) between heating systems can be shown by changing different parameters through the use iso-line diagrams. In Figure 11, considering as reference (Scenario A), *RIS* is shown as function of boiler efficiency and share of solar thermal renewable sources, assuming $F_{r,hs}^{ex} = 0.15$. The results show that improvements on heating efficiency or fraction of renewable thermal sources lead to reductions of the irreversibility rates, leading to the increase of irreversibility differences between reference and alternative system. As example, from Figure 11, the best represented scenario ($\eta_{vii} = 1$ and $\varphi_r = 0.8$) corresponds to a *RIS* about 75 %.

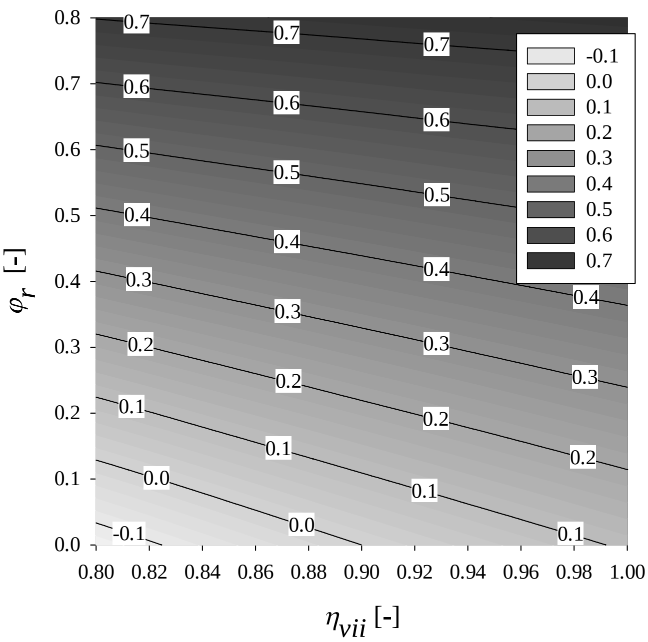


Figure 11: Relative irreversibilities savings considering the integration of renewables from solar thermal.

5 Conclusions

In this paper, an energy and exergy analysis was applied for a novel, non-conventional DCS, in order to locate and quantify the most inefficient sub-components of the plant. The overall primary energy performance of the DCS, *PER* was estimated as

32.2 % and the exergy performance 11.8 %, a quite low value, showing a high potential for performance improvement. Using the parameter exergy efficiency defect, the results indicate the boiler as the most inefficient component of the plant (69 %), followed by the chiller (12.3 %). The other components are relatively insignificant for the total irreversibilities of the plant.

The replacement of the natural gas boiler by alternative heating technologies, such as, low-temperature solar thermal renewable sources or high efficient heat pump systems are those that mostly improve the DCS exergy performance. The results also show that the use of renewables reduces effectively the primary energy demand of the plant, although does not always corresponding to the best exergy scenario. For a complete and detail assessment, both primary energy-based indicators (*PER*) and exergy efficiency should be used. From the examples, the wood fuelled heating system has highest value in terms of *PER* (107.2 %), but the lowest exergy efficient option (11.4 %). On other side, the heat pump system (*COP* = 4) is the heating system with the highest exergy efficiency (about 27 %), but with a moderate *PER* value (50.6 %). The effectiveness of the exergy method for analysis is demonstrated through this paper, where the exergy efficiency defect was found a helpful method to assess and locate high sources of irreversibilities, showing the direction to minimize the xergy losses and to approach the ideal system. Moreover, the irreversibility rate was found as highly dependent of inlet conditions, therefore for fixed outlet conditions, the maximum irreversibility rate value was obtained for high temperature and humidity ratio differences between inlet and outlet conditions.

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