



HAL
open science

Feasibility analysis of an electricity, cooling and heating microgrid developed for a University Campus in Lisbon, Portugal using Combined Heat, Cooling and Power

M. Sandoval-Reyes, Monica Eskander, Joao Pires, Bruno Lacarrière, Carlos A Silva

► To cite this version:

M. Sandoval-Reyes, Monica Eskander, Joao Pires, Bruno Lacarrière, Carlos A Silva. Feasibility analysis of an electricity, cooling and heating microgrid developed for a University Campus in Lisbon, Portugal using Combined Heat, Cooling and Power. The 29th international conference on efficiency, cost, optimization, simulation and environmental impact of energy systems, Jun 2016, Portoroz, Slovenia. hal-02570112

HAL Id: hal-02570112

<https://hal.science/hal-02570112>

Submitted on 11 May 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Feasibility analysis of an electricity, cooling and heating microgrid developed for a University Campus in Lisbon, Portugal using Combined Heat, Cooling and Power Template for manuscripts

M. Sandoval-Reyes^a, Monica M. Eskander^b, João M. Pires^c, Bruno Lacarrière^d and Carlos A. Silva^e

^a IN+, Instituto Superior Técnico, Universidade de Lisboa, Portugal,
mexitli.sandoval@tecnico.ulisboa.pt (CA)

^b IN+, Instituto Superior Técnico, Universidade de Lisboa, Portugal,
monica.shenouda@tecnico.ulisboa.pt

^c IN+, Instituto Superior Técnico, Universidade de Lisboa, Portugal, *joao.m.pires@tecnico.ulisboa.pt*

^d Dept. Energy Systems and Environment, Ecole des Mines de Nantes, Nantes, France,
Bruno.Lacarriere@mines-nantes.fr

^e IN+, Instituto Superior Técnico, Universidade de Lisboa, Portugal,
carlos.santos.silva@tecnico.ulisboa.pt

Abstract:

In an energy system with notable amount of renewable sources and distributed generation, the concepts of microgrid and district heating networks are useful approaches to segregate utility network into smaller and easily operable clusters. Various authors have suggested supplying energy to a microgrid by means of small Combined Heat, Cooling and Power (CHCP) facilities. This paper presents a feasibility analysis for the deployment of an electricity, cooling and heating microgrid at a University Campus with large energy demand throughout the year. The advantages of using a small CHCP as the main supplying source are looked into and it is explored how this type of facility may encourage the integration of Photovoltaic Energy. The analysis is conducted using the EnergyPLAN software as a tool to assess different scenarios technically and economically; those scenarios include diverse supply system size in order to obtain higher diversification. Finally the results are used to discuss the potential of a new business model that may arise with the concept.

Keywords:

Combined heat, cooling and power; Distributed generation; Electricity, cooling and heating microgrid; University campus.

1. Introduction and Background

Energy consumption is closely related to climate change issues, but also it is directly correlated with life quality of the population. To maintain a suitable life standard while reducing environmental impact, it is necessary to support energy efficiency technologies.

When the need of thermal and electrical energy is coupled, a feasible option is Combined Heat and Power (**CHP**), also known as **cogeneration**; this process allows the simultaneously generation of useful thermal and electrical energy from a single fuel or energy source –either fossil or non-fossil–.

According to CODE2 reports [1], CHP saves upwards 25% of the primary energy compared to separate production of both outputs. Nowadays [2], 10% of the electricity consumed worldwide is produced with CHP; however, the usage of this technology is mainly concentrated in countries with focused governmental policies such as Denmark, Finland, Russia, Germany and Italy.

With the addition of other technologies such as heat pumps or absorption cooling systems, it is possible to produce cooling from the heat and power generated at the CHP, and then the whole system receives the name of Combined Heat, Cooling and Power (**CHCP**), also known as **trigeneration**.

The economic viability for a CHP or CHCP in a specific building, industry or district, strongly depends on the heat and power demand, as well as the price of electricity and the fuel (nowadays, natural gas is the most spread fuel across CHP technology).

Due to the capital investment required for a CHP, to make it economically feasible, it is important to have the unit or plant operating as many hours as possible [3]. As a general rule, applications which have a simultaneous demand for heat and power for more than 5000 hours are good candidates for this technology.

One of the advantages of CHP and CHCP systems is that they contribute greatly to the development of Distributed Generation Microgrids, because while electrical energy can be delivered to consumers over very long distances, cogenerated heat must be used at close proximity of the production place [4]. The capacity of CHCP systems ranges from less than 1 kW in domestic dwellings (micro-cogeneration) to more than 10MW in hospitals, airports [5] or university campus, and as much as 300MW to supply energy to an urban district [6].

1.1 - CHP usage in Universities

Universities are good cases for CHCP implementation because they are equipped with heating and air-conditioning systems, lighting, electric equipment and energy requests from many facilities such as labs and sporting units, throughout the year.

In 2002, Wu and Wang [6] made a literature review of CHCP system and they mentioned three specific university examples. As microsystem, the Shanghai Jiao Tong University with a gas-fired reciprocating engine of 12 kWe and a 10 kW adsorption chiller. As medium size system, the Chesapeake Building of the University of Maryland having a micro-turbine that generates 60kWe and a 65 kW single effect absorption chiller. As large-scale system, the University of Illinois in Chicago with a 20.2MWe CHCP plant coupled with two-stage absorption chillers and electrical centrifugal chillers.

In 2002 also, Oliveira et al. [7] in the University of Porto, ran a numerical simulation and prototyped an absorption cooling unit running with a hybrid solar and gas turbine system; the latter also generates electricity while running. They achieved cooling capacities up to 5 kW and electrical output up to 1.5 kW and concluded that the system competitiveness is higher in hotter climates.

In 2010, Pagliarini et al. [4] evaluated technically and economically a cogeneration facility coupled with a thermal energy storage system, using as case a buildings belonging to University of Parma Campus. The results showed the optimal heat storage volume and how does it affect the auxiliary boiler contribution (reducing CO₂ emissions), the waste heat and the annual income.

In 2013, Bracco et al. [8] described the Savona Campus Smart Polygeneration Microgrid (SPM) in the University of Genoa, Italy. The system includes three CHP gas turbines with combined ratings of 160kW electrical and 284kW thermal outputs, an H₂O–LiBr (Water – Lithium Bromide) absorption chiller that is used for cooling the student library during summer, among other technologies. Today, they have even implemented a mathematical model to optimally manage the SPM and reduce even more the CO₂ emissions and primary energy consumption [9].

The list of cases where CHP or CHCP are installed in Universities is long [10-12] and includes among others the Massachusetts Institute of Technology, which has a CHP installed capacity of 20MWe; the Queens Medical Centre-University Hospital in Nottingham, UK with a 4.9MWe CHP; the University of Florida's Shandis Cancer Hospital with a 4.3MWe installed capacity; the Liverpool University, UK with 3.6MWe; the York University, UK with 1.03MWe (supplying 60% of its electricity demand and 20% of the heat); the Coventry University, UK with 600kWe as installed capacity; the Harvard University's Hotel that supplies from 10 to 15% of its electricity demand with a 75kWe CHP and the Bangor University, UK also with 75kWe installed capacity.

From the literature review, it is evident that there are two types of applications for CHCP in the Universities, and the classification depends on the scale of the system installed. The first group includes the CHCP systems with capacities up to 1MW, which are used to supply energy to small Campus or even individual buildings; the second group comprises capacities from 3.6 to 20MW, which provide service for the entire Campus.

1.2 - Portugal current status and legal framework

According to the CODE2 Report, in 2014, the CHP installed capacity was 1.3 GWe –around 14% of the electricity supplied in Portugal–, with applications embedded in major industrial activities where heat at suitable conditions is required [13].

There are few applications in buildings and in district heating; regarding the latter, there is one in Parque das Nações, Lisbon, where the company ClimaEspaço has an installed capacity of 79 MW of cooling energy, 81 MW of heat and 5MW of electricity [14].

Starting in 1996, aimed by EU policies regarding energy efficiency, Portugal established a transparent and stable legal framework for CHP, allowing CHP installed capacity to reach 1.45GWe in 2012, mostly based on natural gas and with an overall equivalent efficiency of 65%. This installed capacity share was achieved mainly among industries such as pulp and paper, textile, chemicals and refined products, which use the additional income of selling the surplus of power produced by CHP to the grid, to increase businesses' competitiveness, especially for the exporting industry. However, over the period 2010-2012 the Government made changes in existing legislation which impacted negatively on CHP promotion and development. Following the transposition of the Cogeneration Directive 2004/8/CE, the main change in the legal framework for CHP is the cogeneration facilities have to be excluded from the regulated electricity tariff after 20 years.

Then, since 2012, the CHP installed capacity in Portugal has decreased due to the financial economic crisis coupled with a less favorable regulation; even though, the latter still promotes the installation of cogeneration units with a regulated tariff.

2. Case Study and Methodology

The objective of this paper is to present a technical and economic feasibility analysis for the deployment of an electricity, cooling and heating microgrid developed for a University Campus located in Lisbon, Portugal.

As a case study, the IST – Alameda Campus was selected and the idea is to analyze if the use of a CHCP system is feasible under the climate, and regulatory and operational framework available.

The IST – Alameda Campus has a compound area of 107,137.00m² and comprises of 26 buildings including classrooms, labs, multiple cafeterias with cooking installations, sport facilities and a day nursery. The campus serves more than 10,000 users every day (students, faculty members, researchers and general staff). It has a large demand of electricity, over 10 GWh per year, and a significant share of it is being use for heating and cooling services; while natural gas is used only for the campus pool and the heating system in two of the newest and largest buildings.

2.1. EnergyPLAN as a modelling tool

To model the case study, Energy Plan [15] will be used. This is a bottom-up free modelling software that assists the design of energy planning strategies by running mid-term scenarios for the entire energy system, based on hourly basis, for a region (nation, municipality or district, building). The output allows to compare different scenarios technically and economically through energy balance of annual productions, fuel consumption, import and export of electricity and the total costs related to the system.

The structure of EnergyPLAN allows to consider the heat, cooling and electricity demand from individual households or districts. On the other hand, the supply could come from a centralized or distributed generation, including the industrial sector as a producer and consumer. Finally, different renewable energy sources, including CHCP, could be combined among them to comply with the energy system demand.

Some of the outputs that are used as discrimination factors among different scenarios are the total energy required within the energy system, the amount of CO₂ emitted, the annual costs and the amount of electricity imported or exported.

The software has been widely used in Denmark [16] and UK [17] for different academic and non-academic projects.

For this work, the results will be presented in terms of Total Annual Cost and amount of CO₂ emitted.

2.2. IST – Alameda Campus Reference Data

The total IST Alameda Campus energy demand and distribution profiles are as follows [18].

Table 1. IST Alameda campus total energy demand.

	Installed Capacity* [kW]	Consumption [GWh/y]
Electricity	1,673.50	8.82
Electric Heaters	30.36	0.16
Heaters through NG Boilers	75.89	0.40
Electric Coolers	204. 92 kW \approx 58.27 RT	1.08 GWh/y \approx 307,079.90 RT-h/y

*Considering 24hr/day, 366days/year and a 0.6 plant usage factor.

The data shown in Table 1 includes the energy required for all the activities inside the Campus throughout the year and it is important to highlight two aspects; first, that the electricity demand is bigger than the heat and cooling demand; and second, that 71.4% of the heat demand is already supplied with a Natural Gas Boiler, however, the cooling demand is completely supplied with electric units, which leaves room for improvement of the system through Absorption Cooling Units implementation.

The **Absorption Cooling System** uses heat, instead of mechanical energy, to provide cooling. Compared to mechanical chillers, this has lower COP (Coefficient of Performance), but it can be energized by lower-grade heat. On the other hand, there are two types of Absorption Cooling Systems, the Single-effect and the Double-effect; basically the difference is that the latter could reach up to 40% higher COP than the first one, but it also needs higher grade of thermal input (more pressurized steam) [19].

The pattern in Fig. 1 reflects the electricity demand distribution throughout the year in hourly basis. From here, it is important to notice that the electricity profile increases up to 20% during winter, when more electric heat is required, and up to 15% during summer, when electric cooling needs reach their maximum. Also, there is a drop in electric demand during August and is basically due to the fact that the campus is closed. Same, but in lower scale, happens during Christmas, New Year and weekends.

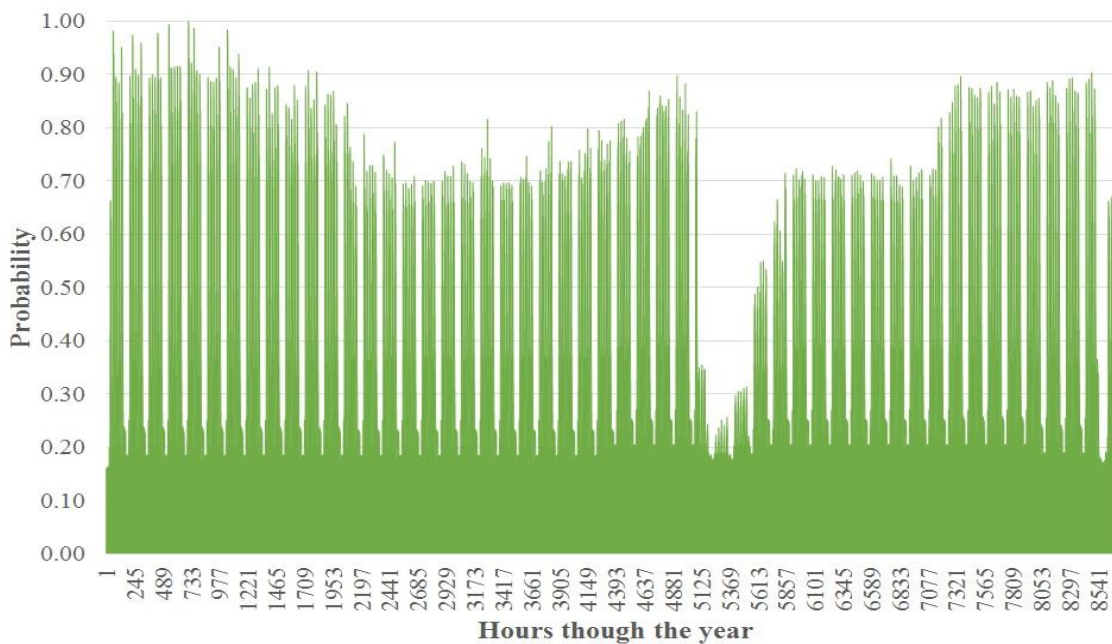


Fig. 1. Electricity demand distributions through the year for the IST Alameda campus in hourly basis.

Fig. 2 and 3 show the heat and cooling demand patterns throughout the year in hourly basis. These profiles are representative of the Atlantic climate and characterizes Lisbon; with large heat demands from November to February, large cooling demand from June to August, and a mixed heat and cooling demand in mid-seasons (from March to May and from September to October).

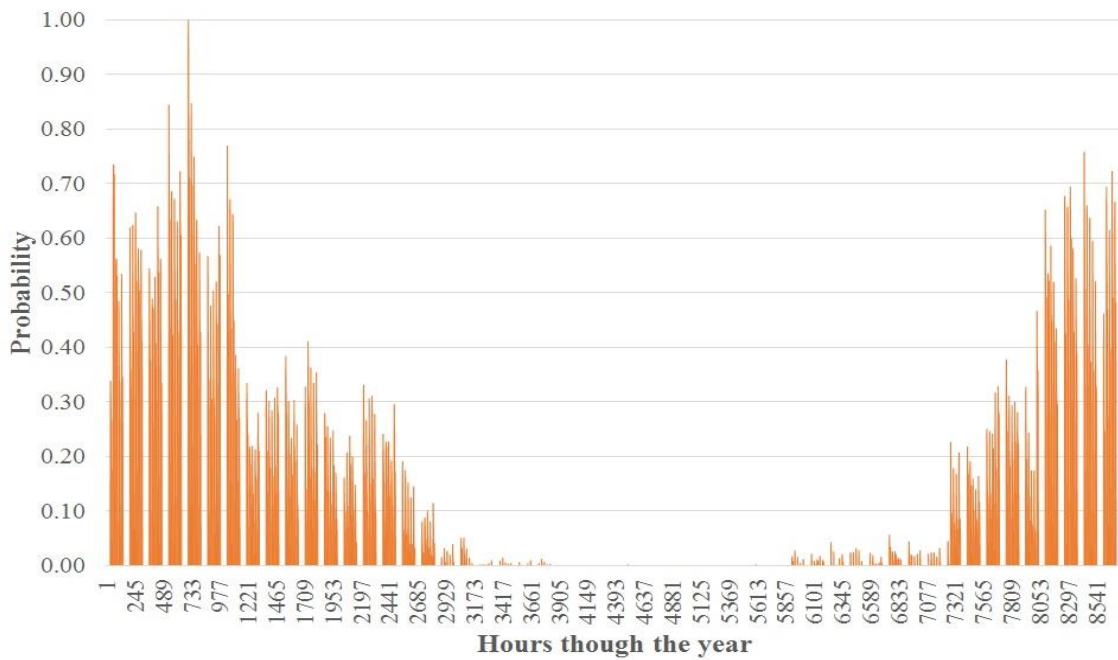


Fig. 2. Heat demand distributions through the year for the IST Alameda campus in hourly basis.

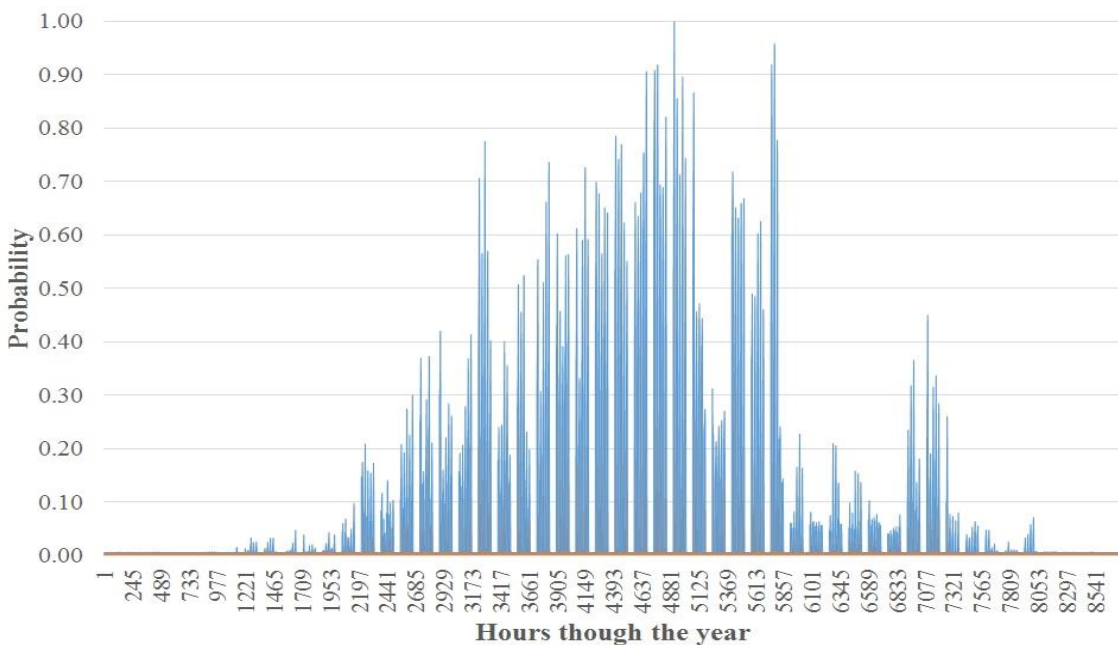


Fig. 3. Cooling demand distributions through the year for the IST Alameda campus in hourly basis.

On the other hand, the information used for the model regarding energy market in Portugal is provided in the Table 2.

Table 2. Other costs included at the model.

CO ₂ emissions price [20]	8.19 € / ton CO ₂
CO ₂ emissions per electricity sold in Portugal [21]	295 grams CO ₂ / kWh
Electricity Price [18]	0.137 € / kWh
Natural Gas price [18]	26.66 € / GJ

2.3. General description of the different scenarios explored and the costs considered

Using EnergyPLAN as a tool, the different Scenarios that will be explored and compared are:

REFERENCE SCENARIO: It considers that all the electricity is bought from the national electrical grid and reflects that all the cooling demand is provided through electrical cooling systems and the heat demand is covered by a mix of Natural Gas boilers and electric heaters (as shown in Table 1).

SCENARIO 1 – 100kW CHP, 3MW Boiler, 211kW Absorption Cooling System: It considers the full substitution of electrical cooling systems by absorption cooling systems, as well as the installation of a 100kW CHP and a 3MW back-up Boiler.

SCENARIO 2 – 633kW CHP, 2MW Boiler, 211kW Absorption Cooling System: It considers the full substitution of electrical cooling systems by absorption cooling systems, as well as the installation of a 633kW CHP and a 2MW back-up Boiler.

SCENARIO 3 – 1,121kW CHP, 2MW Boiler, 211kW Absorption Cooling System: It considers the full substitution of electrical cooling systems by absorption cooling systems, as well as the installation of a 1,121kW CHP and a 2MW back-up Boiler.

Among all mentioned until now, the Scenario 2, which is the better from the last group, is selected (see following section for more detail) and then it is combined with PV (Photovoltaic) modules to construct the next scenarios.

SCENARIO 4 – 300kW PV, 100kW CHP, 3MW Boiler, 211kW Absorption Cooling System: It considers the installation of a 300kW PV system inside the Campus.

SCENARIO 5 – 544kW PV, 100kW CHP, 3MW Boiler, 211kW Absorption Cooling System: It considers the installation of a 544kW PV system inside the Campus and in the neighboring buildings.

SCENARIO 6 – 800kW PV, 100kW CHP, 3MW Boiler, 211kW Absorption Cooling System: It considers the installation of an 800kW PV system inside the Campus and in the neighboring buildings.

3. Detailed description of the costs considered in each scenario and results

At the **REFERENCE SCENARIO**, the costs included are shown in Table 3.

Table 3. Equipment cost considered at the reference scenario.

	Period [years]	Operation & Maintenance [% of investment]	Total Investment cost [k€]
Electrical Chillers	25	5	126,26
Electrical Heat Pumps	25	5	2.85
MCC system	25	5	15.18
Boiler [22, p. 20]	25	1	0.135/MWe* 76kW = 10.3 k€

*The total investment costs include equipment, transportation and installations costs.

The results from the Reference Scenario, which will be useful to assess the feasibility of the other scenarios proposed, are shown in Table 4.

Table 4. EnergyPLAN output from the reference scenario.

Scenario	Total Annual Cost [k€]	CO ₂ annual emissions [kt]	Electricity used from the national grid [GWh/y]
REFERENCE	1,423.30	3.05	10.06

In **SCENARIOS 1, 2 AND 3**, the use of a Single effect H₂O–LiBr (Water – Lithium Bromide) Absorption Cooling System is assumed. This systems was selected based on the annual cooling demand for the IST Alameda Campus, and as long as the cooling demand is fixed, the implementation of this Absorption Cooling System will be permanent throughout all the scenarios, allowing the substitution of the electric cooling system in the Reference scenario. The objective is to use heat energy and a small amount of electricity to produce cooling. The characteristics of Absorption System are displayed in Table 5 [23].

Table 5. Characteristics of the single effect H₂O–LiBr absorption cooling system selected.

COP	0.67
Cooling capacity needed	60 RT ≈ 211 kW
Power demand	0.6kW/RT
Installed Costs per RT*	1168.26 € / RT
O&M Costs*	3% of the installation costs
Life time cycle	25 years

* US GDP Deflator data and currency exchange rate (1 US Dollar = 1.09 Euro) was used to adjust the prices.

The scenarios vary depending on the size of the CHP unit and the back-up Boiler. Table 6 shows the characteristics of each selection [24].

Table 6. Characteristics of CHP systems selected for scenarios 1, 2 and 3.

	SCENARIO 1 100kW CHP, 3MW Boiler, 211kW Absorption Cooling System	SCENARIO 2 633kW CHP, 2MW Boiler, 211kW Absorption Cooling System	SCENARIO 3 1,121kW CHP, 2MW Boiler, 211kW Absorption Cooling System
Base load Electric Capacity [kW]	100	633	1,121
Electrical efficiency [%]	27.0%	34.5%	36.8%
Total Heat recovered [kW]	196	815	1,266
Thermal efficiency [%]	53.0%	44.4%	41.6%
Installation Cost* [€/kW]	2,660.54	2,602.74	2,170.64
O&M Cost [% of installation cost]	1.69 %	1.69 %	1.69 %
Back-up Boiler capacity [MW]	3	2	2

* US GDP deflator data and currency exchange rate (1 US dollar = 1.09 euro) was used to adjust the prices.

The importance of the inclusion of a backup Boiler is to produce only heat whenever two situations arise; first, when it is not economically feasible to run the CHP and produce both electricity and heat; or second, when the installed capacity of the CHP is not enough to cover the heat demand.

The characteristics of the backup boiler are shown in Table 7 [22].

Table 7. Back-up boiler characteristics and prices.

Installed Costs per RT*	135 € / kWth
O&M Costs*	1% of the installation costs
Life time cycle	25 years

As a result of running these three scenarios with the characteristics described above, the Table 8 was generated. It shows clearly that the best option in term of Total Annual Cost is the 2nd Scenario using a 211 kW Single effect H₂O–LiBr Absorption Cooling Unit coupled with a 633kW CHP and a 2MW Boiler; however, the CO₂ emissions are higher than the Reference. This is mainly because electricity in Portugal has in general a share of renewable resources higher than 50%.

Table 8. EnergyPLAN output from the reference, 1st, 2nd and 3rd scenarios.

Scenario	Total Annual Cost [k€]	CO ₂ annual emissions [kt]	Electricity used from the national grid [GWh/y]
REFERENCE	1,423.30	3.05	10.06
SCENARIO 1: 100kW CHP, 3MW Boiler, 211kW Absorption Cooling System	1,323.80	3.15	8.61
SCENARIO 2: 633kW CHP, 2MW Boiler, 211kW Absorption Cooling System	1,298.50	3.16	7.66
SCENARIO 3: 1,121kW CHP, 2MW Boiler, 211kW Absorption Cooling System	1,304.00	3.16	7.27

In **SCENARIOS 4, 5 AND 6**, the 2nd scenario is taken and adjusted by adding PV modules to generate electric energy. The proposal is to use as base a 300W PV module made of Monocrystalline Silicon and an area of 2m². The objective is to make different arrangements of it to reach diverse PV installed capacity at the different scenarios.

Table 9. PV system characteristics and prices.

Installed Costs per W [25-26]	3.34 € / W
O&M Costs	2% of the installation costs
Life time cycle	25 years

In order to find out the amount of PV modules that could be installed at the IST Alameda Campus, the team performed a measurement of the area available at the roofs inside the Campus (4th Scenario) and in the neighboring buildings (5th and 6th scenario). The latest two scenarios are conceived as an option to create an electricity, cooling and heating microgrid which extends further the University Campus. From Table 10, it is evident that as larger the PV system, the larger the savings and lowest the CO₂ emissions, but then the limit is the available space to install the PV system.

Table 10. EnergyPLAN output from the reference, 2nd, 4th, 5th and 6th scenarios.

Scenario	Total Annual Cost [k€]	CO ₂ annual emissions [kt]	Electricity used from the national grid [GWh/y]
REFERENCE	1,423.30	3.05	10.06
SCENARIO 2: 633kW CHP, 2MW Boiler, 211kW Absorption Cooling System	1,298.50	3.16	7.66
SCENARIO 4 – 300kW PV, 100kW CHP, 3MW Boiler, 211kW Absorption Cooling System	1,285.35	3.01	7.14
SCENARIO 5 – 544kW PV, 100kW CHP, 3MW Boiler, 211kW Absorption Cooling System	1,276.20	2.88	6.73
SCENARIO 4 – 800kW PV, 100kW CHP, 3MW Boiler, 211kW Absorption Cooling System	1,270.29	2.76	6.33

4. Discussion and future work

This work intends to be a preliminary technical and economical assessment of an electricity, cooling and heating microgrid located in the Alameda Campus of the Instituto Superior Técnico. The different scenarios analyze the feasibility of using a CHCP system and PV modules in different scales.

Evaluating the Total Annual Cost and the CO₂ emissions results, it can be concluded that the optimal combination is the 6th scenario with a 211 kW Single effect H₂O–LiBr Absorption Cooling Unit coupled with a 633kW CHP, 2MW Boiler and 800kW PV.

Still, there are some further interesting discussions regarding this case study.

First, if the 2nd scenario is analyzed carefully, it is evident that the usage of the CHCP is economically feasible; this is because the electricity demand is bigger than the thermal demand, which allows to use the CHCP at its maximum capacity supplying the heat demand as much as possible and on the other hand, the electricity produced is used in situ.

Second, the CO₂ emissions in the 1st, 2nd and 3rd scenarios, when using the CHCP system, increases compared with the Reference scenario. This is because the share of renewables in the Portuguese electricity production system is around 50%, which makes it relatively clean electricity.

Third, in a case study like this, which has a large electricity only demand, the installation of PV helps to reduce the Total Annual Cost and CO₂ emissions, but the constrain factor is the space to install the system.

Fourth, scenarios 5th and 6th are considering the integration of neighboring areas to install PV panels, which in fact could lead to the creation an electricity, cooling and heating microgrid which extends further the University Campus to the neighboring buildings.

As future work, two tasks are evident. For the energy system suggested inside the University Campus, a proper lay-out and management strategy must be assessed. On the other hand, regarding the creation of an electricity, cooling and heating microgrid which extends further the University Campus to neighboring buildings, a careful feasibility analysis must be done.

Acknowledgments

The authors of this work thank Rui Pereira and João Patricio from the Project “Campus Sustentável” at the Instituto Superior Técnico, as well as, Diana Neves, from IN+, Instituto Superior Técnico, Universidade de Lisboa; for their help to get the data used in this model.

Acronyms

CHCP – Combined Heat, Cooling and Power

CHP – Combined Heat and Power

CO₂ – Carbon Dioxide

CODE - Cogeneration Observatory and Dissemination Europe

COP – Coefficient of Performance

H₂O – Water
LiBr – Lithium Bromide
NG – Natural Gas
O&M – Operation and Maintenance
PRE – Special Regime Production

References

- [1] CODE2 - Cogeneration Observatory and Dissemination Europe, "European Cogeneration Roadmap," 2015, January 27th.
- [2] OCDE-IEA, "Cogeneration and District Energy," 2009.
- [3] Combined Heat and Power Association, "Combined heat and power for buildings. Selecting, installing and operating CHP in buildings - A guide for building services engineers," 2004.
- [4] G. Pagliarini and S. Rainieri, "Modeling of a thermal energy storage system coupled with combined heat and power generation for the heating requirements of a University Campus," *Applied Thermal Engineering*, vol. 30, p. 1255–1261, 2010.
- [5] E. Cardona, A. Piacentino and F. Cardona, "Energy saving in airports by trigeneration. Part I: Assessing economic and technical potential," *Applied Thermal Engineering*, vol. 26, p. 1427–1436, 2006.
- [6] D. Wu and R. Wang, "Combined cooling, heating and power: A review," *Progress in Energy and Combustion Science*, vol. 32, p. 459–495, 2006.
- [7] A. Oliveira, C. Afonso, J. Matos, S. Riffat, M. Nguyen and P. Doherty, "A combined heat and power system for buildings driven by solar energy and gas," *Applied Thermal Engineering*, vol. 22, p. 587–593, 2002.
- [8] S. Bracco, F. Delfino, F. Pampararo, M. Robba and M. Rossi, "The University of Genoa smart polygeneration microgrid test-bed facility: The overall system, the technologies and the research challenges," *Renewable and Sustainable Energy Reviews*, vol. 18, p. 442–459, 2013.
- [9] S. Bracco, F. Delfino, F. Pampararo, M. Robba and M. Rossi, "A mathematical model for the optimal operation of the University of Genoa Smart Polygeneration Microgrid: Evaluation of technical, economic and environmental performance indicators," *Energy*, vol. 64, pp. 912–922, 2014.
- [10] U.S. ENVIRONMENTAL PROTECTION AGENCY, "Combined Heat and Power. A guide to developing and Implementing Greenhouse Gas Reduction Programs." 2014.
- [11] Chartered Institution of Building Services Engineers (CIBSE) CHP Group, "Combined heat and power for buildings. Selecting, installing and operating CHP in buildings - a guide for building services engineers," 2004.
- [12] Combined Heat and Power Association, "Combined heat and power (CHP) in Universities," 1996.
- [13] CODE2 - Cogeneration Observatory and Dissemination Europe, "D5.1 Final Cogeneration Roadmap non pilot Member State: Portugal," 2014, July.
- [14] ClimaEspaço, "A Origem de ClimaEspaço," [Online]. Available: http://www.climaespaço.pt/duplo_clima.htm. [Accessed 13 February 2016].
- [15] EnergyPLAN, [Online]. Available: <http://www.energyplan.eu/>.
- [16] B. V. Mathiesen, H. Lund and K. Karlsson, "100% Renewable energy systems, climate mitigation and economic growth," *Applied Energy*, vol. 88, p. 488–501, 2011.

- [17] D. Connolly, H. Lund, B. Mathiesen and M. Leahy, "The first step towards a 100% renewable energy-system for Ireland," *Applied Energy*, vol. 88, p. 502–507, 2011.
- [18] IST Alameda Campus, Data provided by the Department "Campus Sustentável" at the IST Alameda Campus, Lisbon, Portugal.
- [19] DOE - Energy, Efficiency and Renewable Energy, "Use Low-Grade Waste Steam to Power Absorption Chillers - Energy Tips: STEAM," 2012.
- [20] Bloomberg Energy, [Online]. Available: <http://www.bloomberg.com/energy>. [Accessed 16 12 2015].
- [21] Enerdata - Odyssee, Portugal - Energy efficiency report, 2013.
- [22] Commission of the European Communities, "Energy Sources, Production Costs and Performance of Technologies for Power Generation, Heating and Transport (Unofficial Version)," Brussels, 2008.
- [23] Midwest CHP Application Center, Combined Heat and Power (CHP) Resource Guide, 2nd Edition ed., Chicago, 2003.
- [24] EPA & Combined Heat and Power Partnership, "Catalog of CHP Technologies - Section 2. Technology Characterization - Reciprocating Internal Combustion Engines," 2015.
- [25] Personal estimations based on current market price taking as reference <<http://www.amazon.com/GTSUN-Monocrystalline-Photovoltaic-Solar-Module/dp/B00DGNF1H0>> (February, 2016).
- [26] NREL & Lawrence Berkeley National Laboratory, "Photovoltaic System Pricing Trends" September, 2014.