FEASIBILITY ANALYSIS OF AN INTEGRATED BUILDING ENERGY SYSTEM

Maria BRUCOLI[1], Alessandro GRIECO[2], Michele Antonio TROVATO[3]

[1] Arup, 13 Fitzroy St., London, maria.brucoli@arup.com

[2] Politecnico di Bari, Via E. Orabona,4, 70126 Bari, alexgrieco@hotmail.it

[3] Politecnico di Bari, Via E. Orabona,4, 70126 Bari, micheleantonio.trovato@poliba.it

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Abstract

There is a growing need for green energy nowadays, but this often clashes with limited space availability in buildings and several techno-economical constraints. An alternative approach based on integration and optimisation of different energy carriers can be undertaken. A feasibility analysis of Integrated Building Energy Systems (IBES) in non-residential buildings is carried out.

An IBES may represent a feasible way to go towards post-carbon cities and may be applied to different building types, making a low-carbon target profitable.

The model looks at generation, storage, heating and cooling technologies, in particular understanding the multi-carrier energy system interactions. The model seeks to optimise the choice of technologies and the dispatch of energy based on specific factors (costs or CO_2 emissions).

An office building located in Los Angeles and London is modelled using the model DER-CAM. Various optimisation scenarios are run, looking at the impact that different cost-emissions weightings have on the performance of the IBES. The outputs show the investments required to implement the scenarios designed, the optimal dispatch of energy carriers and both the cost and emission savings this approach has created.

In comparison to the business-as-usual case, each optimisation scenario leads to emission savings. Systems' reliability has increased through reduced electricity purchase. Different results have been obtained in different cities, with higher cost savings in Los Angeles than in London. Thus, an IBES approach is more efficient in cities with warmer climates.

1 Summary

The interest in multi-carrier energy system concepts has been increasing in recent years, as reported in References. In particular, Andersson et al. (2007) have identified an energy hub concept that enables new design approaches for multiple energy carrier systems, highlighting the importance of a flexible combination of different energy carriers through conversion and storage technology in order to keep potential for various system improvements. Wasilewski (2013) has proposed a multicarrier smart energy delivery microsystem, modeled as SHEMS, focusing on the problems that have to be solved for operating an existing SHEMS structure, such as conversion and control issues. Rayati et al. (2015) have introduced “smart energy hub” as a new concept, proposing reinforcement learning algorithm as a practical method to find near optimal electricity and natural gas consumptions of this system. Shabanpour-Haghighi and Seifi (2015) have underlined the importance of performing multi-objective view in order to assess optimal operation of energy networks.

The final aim of this paper is the techno-economic analysis of a multi-carrier energy system in a building. For this purpose, an Integrated Building Energy System (IBES) is defined. Later, the proposed methodology for the IBES design is outlined. A model of the building is created through DER-CAM. Then, starting from a reference case and through the definition of an objective function, it is possible to plan both investments and electricity, heating and cooling dispatch. Simulation inputs are collected, assumptions are made and restrictions are imposed to make every solution obtained from simulations feasible and physically acceptable. Finally, simulation output is analysed.

2 Integrated Building Energy System

An Integrated Building Energy System (IBES) includes technologies from some or all of the following components: Distributed Generation (DG), Combined Heat and Power (CHP), Distributed Storage (DS), Distributed Energy Management (DEM) and Heating and Cooling Technologies.

DG represents distributed electric power generators, either renewable or not. These units are often directly connected to the distribution network or to the customer side of the meter, and they are small in size compared to conventional power plants, not centrally dispatched nor planned. There could be wind turbines, gas and internal combustion engines (ICE), PV systems, fuel cells (FC), etc. Technology choice for installation may depend on maturity, space requirement, economic and technical assessment.

CHP systems are used widely at the customer level to enhance the efficiency of fuel use and to provide local power supply and income for operators, decreasing energy losses. They capture and use the by-product heat locally to provide domestic and industrial heating, providing energy-efficient power generation. They are one of the most promising Distributed Energy Resources (DER) for IBES applications. There are either electricity-driven or heating-driven CHP systems.

DS includes electric small-size storage devices such as batteries and electric vehicles (EV). It is mostly used in order to decrease disadvantages related to the intermittent nature of renewable energy generation sources, which has effects on the stability of the grid and availability of power.

DEM is defined as a set of measures, control systems and management methodologies and technologies applied to an IBES, leading to a more efficient use of the electricity system and reduced electricity-related costs, aiming at controlling locally DG, DS and load. DEM refers to energy efficiency measures, demand side response (DSR), which consists of several methods. Mostly, DEM systems are enabled by the availability of data coming from sensors and meters.

Several heating and cooling technologies can be utilized in an IBES. They are fundamental elements in order to achieve the interaction and optimisation of different energy carriers, as some of them, along with CHP systems, represent the link between electricity, heating and cooling. They include Solar Thermal, Heat Pumps, Hot Water Boilers, Heating, Ventilating, Air Conditioning & Refrigeration (HVAC&R) Systems, Electric Heating and Thermal Energy Storage systems.

The difference between the IBES concept and the microgrid one does not stand in its basic components, but in the way those are managed and they interact each other. There are various reasons leading to the shift to an IBES rather than the business-as-usual approach for electricity, heating and cooling load-meeting purposes. Some potential benefits resulting from an IBES approach are savings and possible additional revenues, along with significant social and environmental co-benefits resulting by an IBES deployment at scale, involving on-site generation and energy management measures. Decentralized generation, which incorporates multiple forms of energy into its core, leads to reduced electricity purchase and thus higher reliability of the energy system, peak load reduction and stronger independency from energy prices volatility. As an IBES relies on clean energy generation, or hybrid systems with low-carbon technologies, its diffusion can yield reduced impact on environment and air quality. Furthermore, deployment at scale of multi-carrier energy systems, including renewable energy resources such as PV systems and wind turbines, would easily help boosting technology maturity, making research and development for renewable energy (RE) resources easier. IBES-related benefits may be more important for fast-growing economies, which are involved into the implementation of several electrification projects as they are establishing their power networks, especially in rural areas.

3 Proposed Methodology for IBES Design

First of all, it is necessary to identify the typology of the analysed building and the year it was constructed in. Different types of building and construction years lead to different energy requirements and load profiles, along with different available space for DERs installation, such as PV, solar thermal and engines. The definition of the building location is important as well in order to decide whether to take into account investments for a specific technology. In addition to this, the location is also related to weather data, which affect both load profiles and the power generation by solar PV and wind turbines.

Once both typology and location of the building are defined, the model has to be built. The first necessary step in order to build the model is setting load data, both for electricity (electricity-only, cooling and refrigeration loads) and natural gas (space-heating, water-heating and natural-gas-only loads) consumption. Hourly load profiles for week, weekend, and peak day-types per month are defined, for each of the load types included into the model. With regard to load data format, it is assumed that one daily load profile with hourly time steps coincides with the load profile for the entire month.

The second step, strongly related to the building location, is the definition of weather data. It consists of ambient hourly temperature for each month (°C) and hourly solar radiation for each month (kW/m^2), along with the hourly wind power potential (kW/unit).

The third step for building the model is linked to the CO_2 emissions and the utility tariffs, for both electricity and fuel. It is possible to define marginal CO_2 emissions (kgCO_2/kWh) and fuel CO_2 emissions rate, average kg of CO_2 released per kWh of energy content consumed in the combustion (LHV). Electricity rates and fuel prices, on the other hand, include fixed (monthly access fee) and variable charges (volumetric and power demand charges), which could be defined as Time-Of-Use rates, and need to be collected for the proper country and location considered. Financial incentives for the development of renewable energy sources can be included into the model as well, such as feed-in tariffs (FIT) and net metering programs.

Techno-economical information about generation and storage technologies and infrastructures related to them, either already existing or that have to be installed, has to be included in the model. For each technology it is possible to model existing equipment and/or force equipment in the solution. Some evaluations must be done about excluding or forcing solutions into the optimisation output, as the availability of some generation and storage technologies may depend on the building typology, on its location and on the country the project is located in. Also costs and technological specifications may vary with the location.

Load management measures such as Load Shifting (LS), Demand Response (DR), and Direct Controllable Loads (DCL), along with Load Curtailment parameters, can be defined. However, applying load management measures is often difficult because of lack of information related to load curtailment costs for different building typologies, both for electricity and heating loads, although some interruption costs can be estimated.

After building the model of the energy system, it is necessary to define a reference case by taking into account the existing on-site technologies only (if any). The base case run allows applying an optimisation function to the model that is built. The simulation is realised through the model DER-CAM and could aim at minimising costs, CO_2 emissions or both of them through a weighted function.

The economic objective function is shown in (1):

$$\min C = \sum_i C_i \tag{1}$$

where C_i are different addend, each representing part of the total energy costs. They consist of facilities and customer charges, monthly power demand charges, time of use power demand charges, time of use energy charges inclusive of carbon taxation, costs of demand response measures and revenue from electricity sales. In addition, the objective function also considers on-site generation fuel and O&M costs, carbon taxation on on-site generation, and annualized technologies investment costs. Finally, natural gas used to meet heating loads directly incurs variable and fixed costs (inclusive of carbon taxation). This economic objective function is subjected to several constraints, related to generation and storage technologies, heat recovery, investments, electricity, heating and cooling supply.

For example, the electricity balance for each time interval is shown in (2):

$$CL_E - \sum CDRL_E + \sum \left(\frac{SI_E}{SCE_E} \right) = \sum Gen_E + URL + \sum \left(SO_E \cdot SDE_E \right) \tag{2}$$

where CL_E represents customer electric load, $CDRL_E$ represents customer electric load not met due to energy efficiency measures, SI_E and SO_E are electric storage charge and discharge power from EV and batteries, respectively, linked at charge efficiency SCE_E and at discharge efficiency SDE_E, Gen_E is electric power produced by generators to meet electricity-only end-use loads, URL is electricity purchased from distribution utility company.

The heat balance for each time interval is described in (3):

$$CL_H - \sum CDRL_H + \left(\frac{SI_H}{SCE_H} \right) + AL = \sum Gen_H + \left(SO_H \cdot SDE_H \right) + \left(\beta \cdot NGP \right) + \sum RECH \tag{3}$$

where CL_H represents customer heating load, $CDRL_H$ represents customer heating load not met due to energy efficiency measures, SI_H and SO_H are thermal storage charge and discharge heat, respectively, linked at charge efficiency SCE_H and at discharge efficiency SDE_H, AL represents the amount of heat used to drive absorption chillers, Gen_H is heating produced by generators, NGP is natural gas purchase, generated at efficiency β, RECH is the amount of useful heat recovered.

The weighted objective function for multi-objective optimisation purpose is shown in (4):

$$\min f = WCost \cdot \left(\frac{TotalAnnualCost}{MaxCost} \right) + WCO_2 \cdot \left(\frac{TotalAnnualCost}{MaxCO_2} \right) \quad (4)$$

where MaxCost, which is the scaling factor for costs, is determined as the cost corresponding to a CO_2 minimisation run, while the weighting factor for CO_2, MaxCO_2, is the value of CO_2 emissions corresponding to a cost minimisation run. WCost and WCO_2 respectively are the weighted factors of the function, TotalAnnualCost represent the annual cost of the assessed optimisation scenario.

Different optimisation scenarios for the selected case study and model are then considered. The simulation output is composed of the dispatch of different energy carriers, investment decisions regarding onsite technologies and economic and environmental results. Economic and financial results are shown, in order to underline some important criteria in the project analysis, such as its NPV and its overall costs and revenues.

In order to tailor the procedure to the specific case, the optimisation run is suitably bounded by filtering DER and DS technologies according to specific availability and by ideating a resources installation strategy, according to available spaces, to be imposed into the tool.

The outlined dispatch strategy should undergo a Building Energy Management System, which actually supervises and controls the system state and the energy flow. Its function is to actually supervise and control the system state and, possibly, move the system away from the optimal dispatch strategy whether environmental conditions or technical feasibility evaluations do not allow following the optimisation output.

4 Case Studies

The model refers to an office building that is located in Los Angeles (USA, Case Study n.1) and London (UK, Case Study n.2). The office building is located in the city centre and it represents a non-residential case study. The building is newly constructed and it includes nine storeys above ground and three below, i.e. a lower ground floor and two basement floors. Its Gross Internal Area (GIA), measured to the internal face of the perimeter walls at each floor level, is 32,379 m^2. The maximum total building demand reaches 2,848 kVA, to which a future capacity allowance of 263 kVA is added. To this sum, a building diversity factor of 0.75 is applied. A maximum demand of 2,333 kVA follows those assumptions, and the incoming supply has to be 2,500 kVA. Assuming a 0.94 power factor, a maximum active power demand of 2,193 kW is considered. Consequently, the building has an equivalent specific demand per GIA of 72 W/m^2.

For IBES purpose, roof and basement are the two key points in the building: here it is possible to install additional generation equipment, being the available physical space a fundamental constraint in this study. On the rooftop, 400 m^2 are available in order to install solar PV panels. The upper basement floor hosts a delivery office, storage rooms, loading bays, a cycle storage, recycling storage and a plant room, including chillers, main electrical room, risers and air handling plant room. Storage rooms could be used to locate IBES and to install different technologies, such as generators, turbines, heat pumps, and electrical and heating storage. The lower basement floor hosts a staff room, some offices and another plant room, including a generator room, fuel storage, chillers and boilers.

Modeling and simulation of the energy system are developed through DER-CAM. This is a mixed-integer linear model that allows finding out the global minimum to different optimisation problems.

Reference is a business-as-usual case, taking from utilities the whole amount of electricity and natural gas required for electricity, heating and cooling purposes and assuming that a central HVAC&R is available in order to meet cooling and heating loads. Later, cost-minimisation, CO_2-minimisation and multi-objective optimisation studies are carried out, through possible additional investments in IBES technologies.

Los Angeles load data profiles are obtained from DER-CAM database, based on ASHRAE climate zones. Similarly, London profiles are collected through ASHRAE climate zones-based assumptions and Seattle, WA weather data is used, as London is also located into ASHRAE climate zone 4. Annual electricity purchase is assumed to depend on the maximum power demand that results from the electric load profile. Annual natural gas purchase depends on typical natural gas consumption for similar buildings in the two locations.

Weather data are obtained from DER-CAM database, based on Typical Meteorological Year (TMY) data collections provided by the National Renewable Energy Laboratory (NREL), for Los Angeles, and taken from "Los Angeles International Airport" data included in TMY3. For the second case study, London Weather Centre weather data from 2003 included into CIBSE TM49 is used in this work.

Discrete and continuous energy production technologies are defined. The distinction is justified by the commercially available sizes of technologies and their economies of scale. Techno-economic characterisation of DERs is directly obtained by DER-CAM database for discrete technologies, while continuous technologies data is collected from several resources, as reported in References, and where it was not possible to find data assumptions are made.

Marginal CO_2 emissions and fuel CO_2 emissions rate are taken from DER-CAM database, where data is obtained from Californian Independent System Operator in combination with the U.S. Energy Information Administration. The same data is used for both case studies.

Electricity prices follow PG&E E-20 Secondary tariff for customers with maximum demands of 1,000 kW in Los Angeles, whereas they are derived from a similar building electricity bill for London case study. It is necessary also to tweak the model in order to include some UK tariffs that are not included in the tool, as it is designed for California-located projects. PG&E gas schedule G-NR2 are used for natural gas consumption in Los Angeles, while natural gas tariffs for London case study are obtained by npower.

PV FIT for both case studies, along with Renewable Heat Incentives (RHI) program for UK case study, are included in the model starting from DER-CAM optimisation results. It amounts to 0.065 $/kWh in U.S. and 9.98 p/kWh in UK, while RHI ASHP-related incentive is 2.54 p/kWh.

Only proper technologies that may be installed in a non-residential building located in the city centre have been analysed. A filter has been studied and applied, considering both tool limits and building constraints. ICE CHP units have been limited to small ones (75 and 250 kW). Large ICEs have been included in the set of inputs (1,000 and 2,500 kW) in order to have an electricity generation base and to allow CHP units to run and fully recover waste heat. Also, FCs have been considered to allow having more low-emissions technologies among the potential installed DG sources. Furthermore, PV systems, EV charging stations, air source heat pumps (ASHP), lithium iron phosphate ($LiFePO_4$) batteries and thermal energy storage (TES) systems can be installed. Other technologies have been excluded, such as wind turbines. Furthermore, capacity limits have been imposed, e.g. the space limit for TES. According to available space in the building basement, it is assumed to be 60 m^2, while a TES unit has a volume of 2.7475 m^3. As a 30 kWh/m^3 capacity is considered, a maximum number of 33 units can be installed, roughly providing 2,720 kWh heat storage. Similarly, a maximum batteries capacity of 1,080 kWh is imposed and only 300 kW FC are included.

The distribution in week and weekend days follows the 2015 calendar. Among weekdays, 3 peak days per month have been defined. The interest rate on investment is assumed to be 12%, as the investment in an IBES would be risky since it represents a new approach for energy supply of buildings.

5 Simulation and Results

Several optimisation studies are run for both locations and for different weights in the multi-objective function. An example of simulation output is given, while an overview is provided later in this paper.

Considering Los Angeles case study, a multi-objective optimisation, 50% cost – 50% CO_2 emissions, is shown. Costs and emissions resulting from this scenario, compared to the reference, are shown in table 1.

Table 1 Costs and CO_2 emissions in 50-50 optimisation scenario – Los Angeles

	Total Annual Energy Costs ($)	Total CO_2 Emissions (tons)
Reference	1,988,000	4,061.7
Investment Scenario	1,653,942	3,528.4
Total Savings (%)	16.8%	13%

The IBES resulting from this optimisation scenario is shown in Fig. 1. Two 1,000 kW internal combustion engines, a 75 kW CHP internal combustion engine, a 61 kW PV system, corresponding to the whole available PV area, and a 280 kW air source heat pump are the generation technologies involved in this investment scenario. Also stationary batteries with overall 1,080 kWh capacity, 1,600 kWh EV fleet and 2,720 kWh capacity of heat storage have been included. There is about 12% of electricity purchased from the utility. 131,667 kWh/year are generated by PV system, which allows accessing to the FIT.

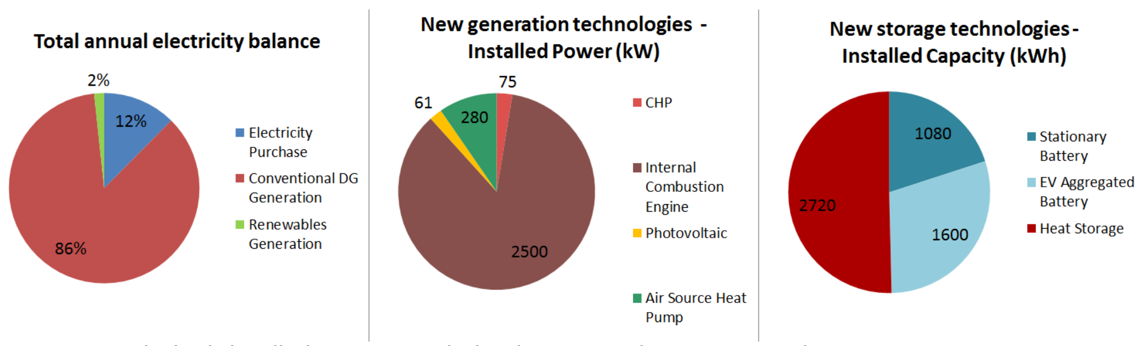

Figure 1 IBES technical details in 50-50 optimisation scenario – Los Angeles

Investments in new technologies are 5,554,114 $, It could be observed that the cost of the ICE is the 75% of the overall investment and that annualized costs are composed for their 54% by energy costs and OPEX.

Electricity dispatch in a weekday in January is shown in fig. 2. This dispatch strategy limits the use of the 2,500 kW ICE to central hours, when load is high enough. Purchasing electricity from the grid cannot be avoided, as there is no modularity of smaller ICEs, but a single larger engine only. During central hours, an example of PV, DS and load coupling is given. In the presence of PV and large ICE generation there has to be a higher load, thus DS and ASHP contribute by increasing it. Dually, batteries output helps providing electricity in intervals when load is too high to be met with a small CHP unit and too low for a large ICE.

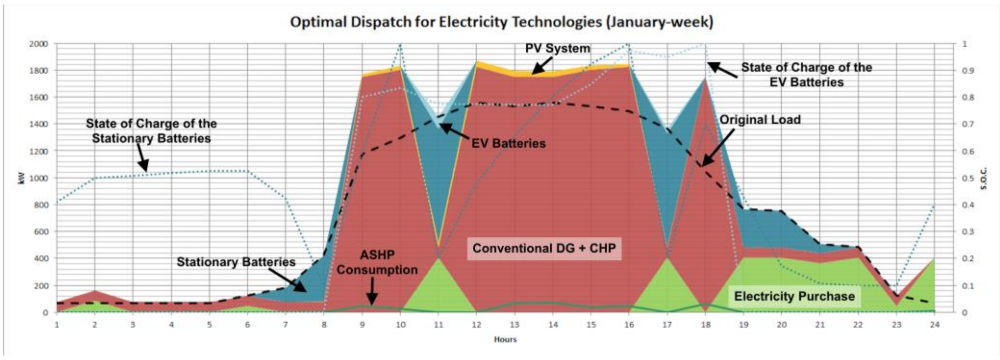

Figure 2 Example of electricity dispatch in 50-50 optimisation scenario – Los Angeles

Heating dispatch in a weekday in January is shown in fig. 3. ASHP runs during electricity-peak hours in order to increase electricity load. 75 kW CHP represents a base of heating supply during night-time, when electricity load is low enough to be supplied by CHP and utility. Excess heat output is stored in heat storage units, in order to cover almost the whole heating peak load and to contribute during night-time heat dispatch.

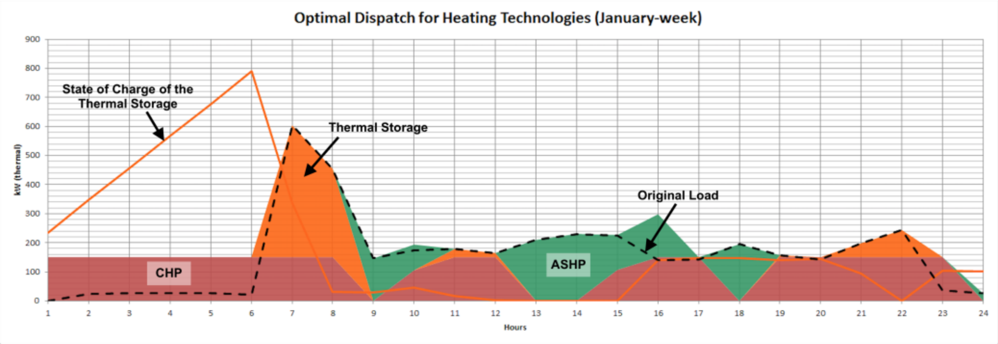

Figure 3 Example of heating dispatch in 50-50 optimisation scenario – Los Angeles

Cooling loads are mainly fed by chillers for the entire year, and ASHP is exploited in some intervals only.

Economic analysis of this optimisation study is shown in fig. 4. Costs include initial investments in new technologies and investments in technologies whose lifetimes are less than 20 years. Yearly savings, including the PV FIT, amount to 1,122,459 $. Project's NPV is 2,588,179 $ and the payback period is 8 years, thus the project would be profitable.

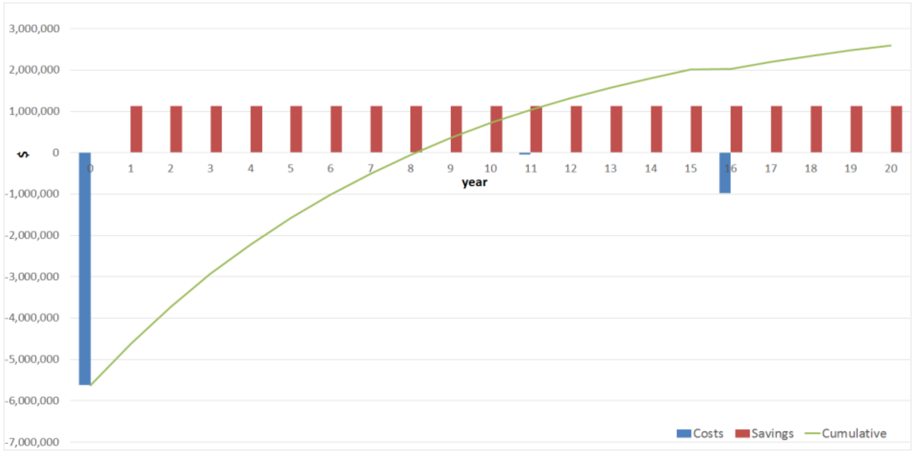

Figure 4 Economic analysis of 50-50 optimisation scenario – Los Angeles

An overview of optimisation scenarios carried out in this paper is shown in fig. 5. The main similarity lies in the broadly technology choice the tool makes during the different scenarios of the optimisation analysis. This is true for the choice of installed technologies and dispatch strategies. Main differences between case studies are related to simulation outputs, electricity and gas purchase strategies and installed capacities in respective IBES. This is due to the higher impact of the IBES peak lowering on Los Angeles and to the shift from electricity to natural gas in order to meet electric loads and decreasing electricity purchase from the grid, which generates more savings in Los Angeles. Thus, an IBES approach is more efficient in cities with warmer climates, as it is easier to completely meet electric loads through a IBES rather than heating loads, due to technical, economic and space constraints. This economical result also depends on different utility tariff structures, as lowering electricity purchase peak brings higher savings in Los Angeles.

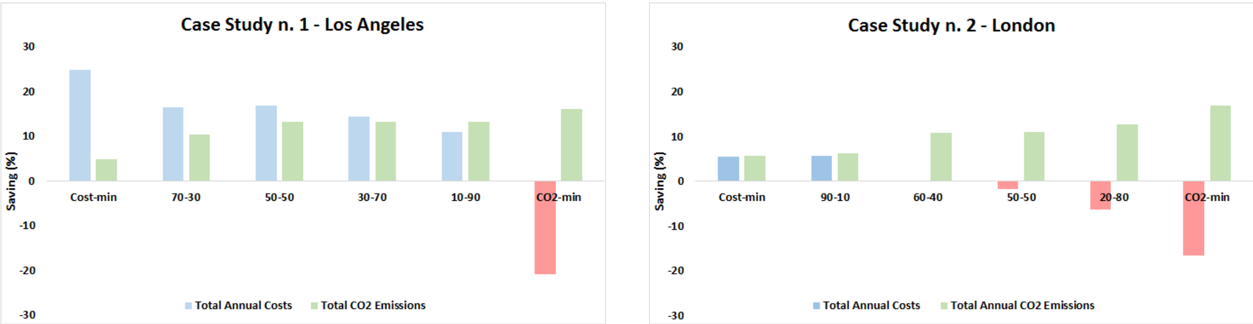

Figure 5 Optimisation scenarios comparison in the two case studies

6 Discussion and Conclusions

A feasibility analysis of an Integrated Building Energy System in commercial buildings has been carried out, taking into account space and techno-economical constraints that an IBES would actually have to face, and looking for benefits resulting from the interaction between different energy carriers.

An office building in two different locations, Los Angeles and London, has been modelled, collecting several input data and filtering technologies that could be potentially installed. Various optimisation scenarios have been run in both locations, looking at the impact that different cost-emissions weightings had on the performance of the IBES. The outputs have shown the investments required to implement the scenarios designed, the optimal dispatch of energy carriers and both the cost and emission savings this approach has created.

In comparison to the business as usual case, each optimisation scenario has led to CO_2 emission savings, from a minimum of 5% in the Los Angeles cost-minimisation scenario to a maximum of 16.2% in the London CO_2-minimisation scenario. From an environmental point of view, plenty of solutions would produce bigger benefits than the business as usual scenario.

Every optimisation scenario has lead to net cost savings, but net costs increase when more ambitious CO_2 reduction targets are proposed, i.e. when the aim is to minimise the produced building carbon emissions. Redundancy increases annual costs because of investments in new expensive and low-emissions technologies. However, the results do not take account of any CO_2 pricing policies, which depending on local policies could improve the financial performance of lower emission scenarios.

System reliability has heavily increased through an IBES approach, as electricity purchase has reduced, with almost a 100% reduction in some scenarios, like the cost-minimisation ones.

Internal combustion engines, coupled with a remarkable installed distributed storage capacity, result as the main DG technology, in order to integrate renewable energy resources and lower electricity purchase from the grid. As this leads to extremely increased natural gas consumption, attention must be paid in order to avoid creating a different fossil fuel dependency that could not be fulfilled.

Different results have been obtained in both cities, with higher cost savings in Los Angeles (24.7% in the cost-minimisation scenario) than in London (5.4%), mainly because of different electricity, heating and cooling loads. Thus, an IBES approach is more efficient in cities with warmer climates, as it is easier to completely meet electric loads through a IBES rather than heating loads, due to technical, economic and space constraints.

Obtaining input data has been challenging and time consuming. For example, it has been difficult to find any database or public information for the characterization of several technologies. Concerning London case study, input collection has even been more difficult, as tool's load and weather database is for US-located projects only. Obtaining real UK data has represented an important obstacle during the development of this work, and several assumptions have been made. For example, California grid marginal CO_2 emissions have been included in London model, though the generation mix in California is different from the UK one. Load data has been chosen following Seattle typical profiles because of climatic similarities, but this does not necessarily mean that demand profiles are similar, as building insulation standards and controls may differ. Creating a database that includes weather data and typical load profiles for different countries and building types, along with technologies characterization, would make modelling easier and would boost the development of an IBES approach.

A tool-related issue has been the impossibility to include some RE policies as an optimization input, such as UK's RHI program, and some utility tariff elements, such as UK's availability charge. It has been necessary to tweak the model in order to take into account actual constraints, e.g. including financial incentives in the optimisation output. Those amendments have cleaned model imperfections but they have affected the optimisation process, probably not leading to the absolute optimum. Although they have been considered in a post-optimisation analysis only, UK RE policies have had greater impact on the net cost savings, as RHI program involves ASHP, an important link between electricity and heating. This communicates how the development of renewable heating-related policies would help spreading a multi-carrier energy system approach.

Taking into consideration those evaluations, and supposing multi-carrier energy systems modelling easier to undertake in the future, IBES may represent a first feasible and profitable way to go towards post-carbon cities, and may be applied to different building types, making a low-carbon target profitable. If IBES was deployed at scale, it could actually represent a remarkable step in the balancing of the energy trilemma, among energy security, environmental sustainability and energy equity.

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