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Optimising the installation costs of renewable energy technologies in buildings: A Linear Programming approach

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ABSTRACT

This paper demonstrates how Linear Programming (LP) can be applied to assist in the choice of renewable energy technologies for use in buildings to meet CO_2 emissions reduction targets. Since there are many possibilities for combining different renewable technologies, the capital costs associated with the installation of one or more renewables can vary widely. In terms of capital investment the preferred solution will be the one at least cost, and LP provides an effective way to find this minimum through the so-called "objective function". This project has used "lp_solve", a free-source Mixed Integer Linear Programming solver that has been embedded in a Microsoft Excel application called Carbon emissions And Renewables for Building OPtimisation Toolkit (CARB-OPT) developed by RES Ltd in collaboration with London South Bank University (Renewable Environmental Services Ltd. (RES) is the environmental consultancy of Long and Partners Engineering Group. RES is currently involved in a Knowledge Transfer Partnerships (KTP) project in conjunction with the Faculty of Engineering, Science and the Building Environment (ESBE) at London South Bank University). This paper reports the application of this LP optimisation process for an office building case study with four alternative combinations of renewables. The process showed the technology mix that would lead to the smallest investment needed to comply with UK Building Regulations requirements and regional planning targets. In addition, the process offers a robust methodology to test the impact that the key assumptions may have upon the optimum solution.

1. Introduction and background

The UK has a range of policies to meet its international and domestic targets to reduce CO_2 emissions. Since almost half of CO_2 emissions in the UK come from buildings, the UK Building Regulations set specific targets reductions for new buildings, which includes a 10% contribution to reductions from renewables [1]. Local Planning conditions often apply an even higher percentage, for example the reduction target set by the Greater London Authority (GLA) is (at the time of writing) 20% [2]. The required CO_2 emissions reduction must be achieved by using one or a mix of renewable energy technologies (RETs). The RETs that the Greater London Authority indicates as applicable to London's developments are [3]: wind generators (W), photovoltaic systems (PVs), solar thermal water heating (ST), biomass heating (BH), biomass CHP (BCHP) and ground sources heat pumps (GSHPs).

There are a number of factors that impact on the viability of RETs that need to be considered at the earliest phase of a project. These include the geometry, orientation and local overshadowing of the building (for PV and ST), the geographical position and meteorological conditions of the site (for W), the plant room and fuel storage space availability (for BH and BCHP), and the building site geological characteristics (for HP). Once a set of "feasible renewables" is determined, the next step requires an assessment of the financial viability of these technologies. Capital costs, maintenance costs and payback of RETs investment are some of the financial factors that are normally taken into consideration. Since detailed design considerations are not known at this stage it is often difficult to fix these investment costs, and yet it is at this point in the design where best value decisions need to be made.

This paper presents a linear programming (LP) algorithm that can assist in minimising the RETs capital cost to achieve mandatory carbon dioxide emission reductions. The study is based on the use of

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the "Carbon emissions And Renewables for Building OPtimisation Toolkit" (CARB-OPT), a VBA-based user interface Excel application developed by RES Ltd in collaboration with London South Bank University. On the basis of statistical models that are drawn from the RES Ltd. energy and cost benchmark database, CARB-OPT computes (with an acceptable level of accuracy at the very first phase of a project): Part L Building Regulations carbon emissions and energy performance certificate (EPC) benchmarks, simple combined heat and power and tri-generation analysis and RET feasibility studies. With respect to the last of these, CARB-OPT employs an embedded LP calculation tool, which uses data for the feasible renewables while applying constraints that limit their application. The LP calculation tool returns a set of RET plant sizes that can meet CO_2 emissions reductions requirements at least cost. The LP calculation routine takes into account a number of key parameters including the geometry of the building, the investment cost of each RET (per kW installed), the average annual meteorological conditions of the site under investigation (solar irradiation and wind speed impact on the CO_2 saved per kW installed of PV, ST and W) and constraints for installation such as available area. To our knowledge, there have been no published reports on the use LP models to address the economic viability of a mix of RETs that can be installed in a building; hence the results presented here are the first innovative attempt at such an application.

2. Literature review

Any strategic decision making process that requires the maximisation or minimisation of some quantity that is modelled by linear functions, and that is constrained by certain limits, can be modelled in a LP problem [4]. LP algorithms are widely accepted as a robust quantitative problem solving approach, and can therefore be adapted to a wide range of applications. Driebeek [5] reported that such algorithms are often very useful in planning processes which involve people, machines, materials, land or other financial assets. Moreover the author describes how LP is a powerful technique to optimise production plans in the industrial sector, in particular for petroleum, steel, textile and electronic equipment companies. Salkin and Kornbluth [6] presented some financial and accounting implications of LP. They showed how LP can be applied to both the long term problem of net present value maximisation and the short term problem of organisation cost minimisation.

LP algorithms are applied also in the health-care and biomedical fields. Jacobson et al. [7] illustrated a pilot study where a powerful LP methodology addressed a vaccine selection and procurement strategy. American Edwards Laboratories, a biological heart valves manufacturing company in California, used a LP methodology in 1980 to address the necessity of optimising the excess and shortage of different sizes valves in its biological component inventory [8].

LP optimisation techniques are not new in the field of RETs, energy planning policy and building services. Akella et al. [9] described how a LP based commercial software, LINDO 6.10, could address the electricity demand of a remote region in India. Iniyan and Sumathy [10] developed an optimal renewable energy mathematical model (OREM) based on LP which aimed to optimise the use of RETs for 6 different end-uses (lighting, cooking, pumping, heating, cooling and transportation) in rural areas in India. Cormio et al. [11] used a LP process to support the energy flow optimisation model (EFOM) they implemented for the analysis of the entire energy system of the Apulia region of Italy. LP is also the algorithm that supports the optimisation process performed by the "Market Allocation" (MARKAL) family of energy systems models. MARKAL has been developed by Brookhaven National Laboratory for the IEA Energy Technology Systems Analysis Programme (ETSAP) and is broadly used to compute the optimal configuration of energy systems subject to certain environmental constraints and system limitations. For example, Kanudia and Loulou [12] applied a MARKAL approach to the analysis of greenhouse gases abatement in Québec. A specific application of MARKAL (MARKAL-Macro) has also been used to support policy makers in addressing UK long term energy policies [13], such as the Energy White Paper 2007 [14]. Gustafsson used a Mixed Integer Linear Programming (MILP) methodology to minimise the Life Cycle Cost for a building. This methodology has been applied to find an optimum mix of technologies to heat the building [16] and to find the optimum mix of fenestration alternatives and heating technologies according to different energy prices [17]. A MILP approach has also been applied by Bojic et al. [18] to a district heating/building heat distribution system, with the purpose of optimising the thermal comfort of a specific building under certain changes of the system's characteristics.

3. Case study: identification of the problems

The goal of any LP algorithms is to find the optimum solution of a given problem. The problem is formulated by an objective function, which needs to be minimised or maximised under a set of limits and constraints. In the present case study, the objective function is represented by the total installed cost of a number of RETs to meet compliance targets. Thus, in our case the optimisation problem becomes one of minimisation, and the aim is to answer the following questions:

- Which optimal mix of RETs should be installed in the building under investigation?
- What are the installed capacities for each of these RETs?

To illustrate the process a new three storey air conditioned office building in a Greater London borough will act as a case study. The building has a gross internal floor area of 11,500 m^2, corresponding to about 3800 m^2 per store. It has a 3400 m^2 south facing terrace above the top floor which is suitable for installing PV, ST and W plant; no other space is available for these. Preliminary calculations based on benchmarks showed that the building total carbon dioxide emissions, after the application of energy efficiency measures, would be 903.3 tonnes/year. Since the GLA requires a 20% emissions reduction using renewables (180.66 tonnes/year), it will need to be shown how this can be achieved with a mix of RETs. The building and site characteristics do not allow the possibility of BCHP and HP, while PV and ST are shown to be feasible, and W and BH are possible technologies. Such early feasibility decisions are generally based on issues of aesthetics and space availability. Thus, for our case study we have:

- Feasible renewables: PV, ST.
- Possible renewables: W, BH.
- Non-feasible renewables: BCHP, HP.

The LP optimisation process requires assumptions on the typology and efficiency of the PV and ST panels. The PV panels simulated in this study are 1.28 m^2 standard polycrystalline 160 W_p modules with an efficiency of 12.5%, and the ST panels are glazed flat-plate collectors rated at 1.75 kW_p. The inclination of the PV and ST panels is assumed to be 30°. For the W plant three different kinds of commercial wind turbines have been considered: small (S, rotor ∅: 5 m – 2.5 kW), medium (M, rotor ∅: 6 m – 6 kW) and large (L, rotor ∅: 7 m – 10 kW). The energy production of PV and ST is strongly linked with the solar radiation incident upon the panels, while the W energy production is related to the wind speed and direction, both of which are location specific. There-