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Optimal distributed energy resources and the cost of reduced greenhouse gas emissions in a large retail shopping centre

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Abstract

This paper presents a case study on optimal options for distributed energy resource (DER) technologies to reduce greenhouse gas emissions in a large retail shopping centre located in Sydney, Australia. Large retail shopping centres take the largest share of energy consumed by all commercial buildings, and present a strong case for adoption of DER technologies to reduce energy costs and emissions. However, the complexity of optimally designing and operating DER systems has hindered their widespread adoption in practice. This paper examines and demonstrates the value of DER in reducing the carbon footprint of the shopping centre by formulating and solving a multiobjective optimisation problem using the Distributed Energy Resources Customer Adoption Model (DER-CAM) tool. An economic model of the shopping centre is developed in DER-CAM using on-site-specific demand, tariffs, and performance data for each DER technology option available. Four key optimal DER technology investment scenarios are then analysed by comparing: (1) solution trade-offs of costs and emissions, (2) the cost of reduced emissions attained in each investment scenario, and (3) investment benefits with respect to the business-as-usual scenario. The analysis shows that a moderate investment in combined cooling, heat and power (CCHP) technology alone can reduce annual energy costs by 8.5% and carbon dioxide-equivalent emissions by 29.6%. A larger investment in CCHP technology, in conjunction with on-site solar photovoltaic (PV) generation, can deliver nearly 72% reductions in emissions at a 47% increase in total energy costs. The study demonstrates the effectiveness and flexibility of this type of modelling approach for the analysis, design, and ongoing assessment of new DER technologies under changing market conditions, supporting a more robust adoption of DER technologies in the commercial building sector.

Keywords: Distributed energy resources, Greenhouse gas emissions reduction, Combined cooling heating and power (CCHP) systems, Energy efficiency, Economic modelling.

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Nomenclature

<i>BAU</i>	Business-as-usual	<i>CO₂-eq.</i>	Carbon dioxide-equivalent
<i>CHP</i>	Combined heat and power	<i>CCHP</i>	Combined cooling heat and power
<i>DER</i>	Distributed energy resources	<i>DER-CAM</i>	Distributed Energy Resources Customer Adoption Model
<i>DG</i>	Distributed generation	<i>HVAC</i>	Heating, ventilation and air-conditioning
<i>kWe</i>	kW electric	<i>PV</i>	Solar photovoltaic

1. Introduction

The fourth assessment report of the Intergovernmental Panel on Climate Change posits that developed countries will need to make significant cuts in greenhouse gas emissions to limit severe impacts of climate change [1, 2]. There is evidence that greenhouse gas emissions from human activities have accelerated in recent years, and that more aggressive mitigation action may be required to avoid dangerous climate change [3–5]. This has significant implications for countries with emissions intensive economies [6, 7]. In response, emissions trading schemes have been adopted in Europe, North America, and the Asia-Pacific region as a market mechanism to reduce CO₂-eq. (carbon dioxide-equivalent) emissions and meet the agreed reduction targets [4].

Under an emission-trading scheme, uncertainty in the price of CO₂-eq. emissions translates into uncertainty in estimating the costs of meeting reduction targets [2], which adds to projected increases in electricity prices [4]. In Australia, the price for CO₂-eq. emissions introduced in 2012 increased electricity prices, compounding to recent price rises driven by the pass-through of increasing network charges [8]. Between 2008-09 and 2011-12 the cost of electricity consumed rose by 43%, even though the volume used decreased by 4% in the same period [9, 10]. Emission costs accounted for 7% of the 2012-13 annual electricity bill in the average household.

From an end-user perspective, higher retail electricity prices may mean that “on-site” or “close to load” power generation, commonly referred to as embedded or distributed generation (DG), becomes economically viable [4]. DG technologies such as combined heat and power (CHP) and combined cooling heat and power (CCHP) can be very efficient and cost-effective by use of residual heat from electricity generation in space heating and cooling, and have attracted increasing interest in the commercial building sector in recent years [11–14]. Other distributed options such as thermal energy storage [15–17] and electrical energy storage [12, 18] can reduce peak load and/or assist the incorporation of DG, reducing overall costs to the end-user. Large retail shopping centres present a strong case for adoption of DG technologies to reduce energy costs and emissions, since they lead the subsector with the largest share of energy consumed by all commercial buildings (38% in Australia in 2012) [19].

However, the adoption of DG in commercial buildings has been generally slow in practice, with deployed systems usually attaining less than expected reductions in costs and emissions [20, 21]. A main obstacle has been identified as the lack of adequate tools to tackle the optimal design and operation of systems with distributed energy resources (DER) [20, 22, 23], which entails a complex optimisation problem with a wide diversity of technology options, variable load profiles, complex tariff structures with uncertain long term energy pricing.

While the optimal design and operation problem has motivated much research in the last decade (see, for example, [22–26]), few existing tools seem to offer the flexibility required by commercial building applications such as large retail shopping centres. The majority of existing approaches require substantial expert knowledge to formulate the underlying optimisation problem. This optimisation problem is often strongly

bespoke to a specific project and requires substantial reformulation in the event of future modifications, such as changes in DER technology options and price structures. Shortfalls in existing approaches to solve this problem are discussed in detail in [22].

A flexible integrated economic and environmental modelling tool that has become prominent in recent studies is the Distributed Energy Resources Customer Adoption Model (DER-CAM) [27]. DER-CAM is a mixed-integer linear programming model to select optimal economic combinations of utility purchase and on-site generation to meet a site's end-use loads, on the basis of specific load profiles, and price and performance data for the DER technology options available. Arguably, DER-CAM is one of the most flexible existing tools to solve the optimal design and operation problem in commercial buildings [22, 24, 28]. DER-CAM has been used to investigate system-wide impacts of DER installations in the U.S. [12, 13, 29, 30], Japan [31], Europe, China and India [15].

This paper presents a multiobjective optimisation analysis of DER technology options for CO₂-eq. emission reductions in a large retail shopping centre in Australia. The value of DG in reducing the carbon footprint of the building is examined using site-specific demand, tariffs, and performance data for each DER technology option available. The attainable trade-offs in costs and emissions, and the real cost of reduced emissions (\$/tonneCO₂-eq.) are studied using a site-specific economic model developed using DER-CAM, in its first application to this type of buildings in Australia. The paper compares the results of four optimal DER investment scenarios to meet the centre's electricity, heating and cooling power demand profiles. Namely, a scenario that targets the minimisation of costs alone, a scenario that targets the minimisation of CO₂-eq. emissions alone, and two mixed scenarios of practical interest that target the minimisation of weighted combinations of costs and CO₂-eq. emissions. All these four scenarios lead to non-dominated solutions (in the sense of Pareto [32]). Finally, a distinctive feature of DER-CAM is exploited to compare optimal DER operation summer and winter schedules obtained to meet electricity and heating, ventilation and air-conditioning (HVAC) demand while attaining the largest savings in costs, and in CO₂-eq. emissions.

The rest of the paper is structured as follows. Section 2 outlines the adopted methodology, including a brief discussion of the DER-CAM framework, the site and load characteristics, the technology options of interest, and the electricity tariff structure. Section 3 discusses the investment scenarios considered, which vary depending on the technology set and the relative weighting given to cost and emissions. Section 4 analyses the results, focusing on the trade-off between cost and emissions for current costs of grid sourced electricity first, and then examining the typical DER operation schedules resulting to achieve minimum costs or minimum CO₂-eq. emissions. Section 5 presents the conclusions of the paper, summarising the main findings, implications, and avenues for further research.

2. Methodology

2.1. Modelling framework: DER-CAM

The Distributed Energy Resources Customer Adoption Model (DER-CAM) is a software tool developed by the Lawrence Berkeley National Laboratory [13] to model energy demand profiles of minigrids, typically in commercial buildings and precincts, and evaluate options for the adoption of DER based on a multiobjective optimisation framework. DER-CAM offers a wide range of pre-defined DER technologies and the flexibility to define new ones. DER technologies are categorised as *continuous*, if they are available in a fairly continuous range of capacities (such as solar photovoltaic panels), or *discrete*, if they are only available in a discrete set of options (such as CHP gas micro-turbines).

In comparison with the leading DER simulation software HOMER (Hybrid Optimisation Model for Electric Renewables), DER-CAM offers two distinctive features of relevance to study DER investment options for large retail shopping centres: first, more flexibility in the definition of DER technologies, specially

with the inclusion of CCHP technologies, and second, *prescriptive* (rather than *descriptive*) results, such as the generation of hourly optimal DER operation (dispatch) schedules in each optimisation scenario [22, 24]. One inherent limitation of DER-CAM is that, as it is based on a linear optimisation program, it does not capture nonlinearities such as those arising from dynamics of DER devices [22]. However, when nonlinear effects may be neglected in the optimal design and operation problem, DER-CAM offers, by the same token, a simpler formulation and faster interaction and results than more accurate approaches based on nonlinear optimisation programs [23]. See [27] for the mathematical formulation of the optimisation program run by DER-CAM.

Figure 1 shows a high-level structure of the modelling and technology optimisation process in DER-CAM (see, for example, [13] for more details). The main inputs required to build the model include a year worth of hourly data for energy consumption (separating main components, such as space heating and air conditioning, lighting, and major mechanical devices), energy and fuel tariffs, representative weather data, and the DER technology options available for DG and storage (to be selected by solving a multi-objective optimisation problem).

DER-CAM simulation settings include the selection of relevant investment scenarios that will shape the selection of DER technologies to meet desired optimisation objectives. For example, these scenarios could target the minimisation of annual costs, CO₂-eq. emissions, or a weighted combination of these. Four investment scenarios considered in the present study are described in Section 3.

Figure 1: High level structure of the adopted modelling and technology optimisation process.

DER-CAM main outputs include optimal combinations of DER technologies to meet the site's energy demand, indicative running schedules of these technologies for a typical day of each month of the year, and their associated total costs and CO₂-eq. emissions. The results obtained for the four investment scenarios from Section 3 are presented and discussed in Section 4.

2.2. Overview of site characteristics

The focus of the present study is a large retail shopping centre located in Western Sydney, NSW Australia. At the time of the study, the centre covered a gross leasable area (GLA) of 55,000 m², which is planned to be extended by a further 11,000 m² GLA in the following two years.

The shopping centre purchases grid-sourced electricity to satisfy all of its energy requirements, which produces a large carbon footprint. Since electricity in NSW is generated mainly by burning coal, each kWh consumed produces 0.987 tonnes of CO₂-eq. emissions on average, factoring in transmission and

distribution losses (calculated from [33–35]). As an illustration, in 2010 this shopping centre consumed 2,937 MWh, which accounted for the release of 2,899 tonnes of CO₂-eq. into the atmosphere.

A large component of the energy demand of the site arises from powering its central HVAC system, which comprises 27 reverse-cycle air-source heat pump units with a total load of 729.49 kW_e (kW electric). These units are controlled by a modern building management and control system (BMCS) and service a common floor area defined by an internalised shopping centre and shared public space totalling 35,000 m². Other significant energy demands of the shopping centre include lighting, escalators and travelators (moving walkways).

2.3. Estimation of load profile

In order to find optimal DER technology options for the shopping centre, an estimate of the total energy consumption attributed to both the existing shopping centre and its planned extension is required so that a baseline scenario can be determined.

The estimated total energy consumption for the planned extension was obtained by multiplying the ratio of base building total energy to common floor area by the common floor area of the planned extension. Using the energy efficiency provisions set out in Australia's National Construction Code, which stipulate energy consumption levels required to comply with building code regulations, reduction factors of 26% and 25.1% were subsequently applied to the estimated total energy consumption [36, 37]. This results in a combined energy reduction for the planned extension of 59.6% from pre-2006 compliant energy consumption levels, being when the shopping centre was first built. Note that an additional reduction factor of 20% has also been added based on organisational environmental stretch targets from the building owner.

2.4. Energy demand profile

DER-CAM requires input information about the total energy demand of the site for every hour of a whole year. With the exception of energy for space heating, this demand is specified as electric-equivalent kWh discriminated into the following load categories:

- Energy required for space cooling,
- Energy (thermal) required for space heating,
- Energy (electricity only) required for other services such as lighting and escalators.

In addition to the above load categories, DER-CAM also specifies inputs for energy demand for water heating, and natural gas demand for other services, both of which were negligible or not applicable for the shopping centre.

All energy demand of the existing shopping centre is satisfied by purchasing electricity from the grid, which has been logged since August 2010. The logged measurements available are broken down into total demand of the HVAC system (combined energy requirements for space heating, cooling and ventilation), and demand for other services (lighting and escalators).

The data collected consisted of measurements of kWh consumed every 15 min in a time series spanning a whole year from August 2010 to July 2011. Once outliers and missing entries were eliminated, the data was used to generate monthly-averaged hourly load for each month of the year, required by DER-CAM.

The total energy demand for the HVAC system was further split into energy demands for space heating and space cooling by estimating the periods of heating/cooling operation from weather data for the site, and the corresponding space temperature setpoints for the shopping centre's HVAC system. Heating and cooling periods were determined as disjoint in time and estimated according to the following rule:

- HVAC energy is assigned to cooling if outside air temperature is greater than the temperature setpoint.

- HVAC energy is assigned to heating if outside temperature is less than the temperature setpoint.
- The temperature setpoint for the shopping centre was 23°C (degrees Celsius) in the warmer months (between 1 of October and 31 of May), and as 21.5°C in the cooler months (between 1 of June and 30 of September).

While this method produces an approximation suitable for the model in DER-CAM, the end-use breakdown of heating and cooling modes for the year considered should ideally be obtained from sub-metered data, which was unavailable for the present study.

Figure 2: Annual energy demand profile showing cooling and heating energy demand split [top], and ambient outdoor temperature [bottom]

The top plot in Figure 2 shows the evolution of the total energy demand of the shopping centre through the year, split into energy for space cooling, space heating, and other services, such as lighting and escalators. For reference, the bottom plot in Figure 2 shows the evolution of ambient temperature outside the building for the same period. Figures 3 and 4 show typical weekly power demand profiles for summer and winter (top plots), and ambient temperatures for the same periods (bottom plots). Observe the strong correlation between ambient temperature and HVAC energy demand.

2.5. Technology options

While, in principle, dozens of DER technologies can be evaluated in DER-CAM, the present study considers the following subset of possible technologies, based on their ability to contribute to meeting the HVAC demand, climatic region, and feedback from the shopping centre owner and operator:

Figure 3: Sample weekly summer power demand profile for base building and HVAC demand [top], and ambient outdoor temperature [bottom]

Figure 4: Sample weekly winter power demand profile for base building and HVAC demand [top], and ambient outdoor temperature [bottom]

Combined heat and power (CHP). Also known as co-generation, this technology is considered in the form of gas micro-turbines with heat recovery for providing hot water for HVAC services. CHP is the simultaneous utilisation of heat and power from a single fuel or energy source, at or close to the point of use.

Combined cooling, heat and power (CCHP). Also known as tri-generation, this technology is CHP technology with addition of absorption chillers. CCHP utilises the heat for not only providing hot water as in CHP, but for cooling purposes as well.

Solar thermal. This technology, in the form of flat plate solar collectors, provides heat to absorption chillers and for space heating, as a source of alternative heat or complementary to CHP and CCHP based on gas micro-turbines.

Solar photovoltaic (PV). This technology, in the form of polycrystalline cells, produces electricity from solar radiation. In this study the amount of PV is constrained by the available roof space (8000 m², corresponding to a maximum capacity of 1223 kWe for the PV technology option considered). The solar resource used to model this technology at the site is the average total hourly irradiance on a north facing plane inclined at latitude angle for Sydney, NSW Australia [38, Table 4.5]. The data consists of statistical mean values accounting for reductions in beam radiation caused by actual cloud conditions.

HVAC technologies. The shopping centre's existing HVAC system consists of reverse-cycle air-source heat pump units, which provide both heating and cooling. Thus, the HVAC system is modelled as part of the existing electric load input to the selection of additional technologies for space heating and cooling. These include the use of heat from CHP and CCHP for space heating and cooling through absorption chillers.

Key assumptions on the DER technology options considered in this study are shown in Table 1. CHP technologies are restricted to two types of gas micro-turbines with maximum rated peak powers of 30 and 65 kW, due restrictions in electrical power capacity of the existing distribution boards and related circuits of the site. The solar PV technologies are assumed based on silicon crystalline panels, which have a large market penetration and are appropriate for roof-mounted commercial and residential applications. Solar thermal collectors are assumed based on flat plate panels, which for the site's geographic location and warm temperate climate, are one of the most cost effective collector technologies based on thermal efficiency. A comprehensive comparison of solar collector technologies can be found in [39]. Capital, fuel and maintenance costs assumed are representative for equipment available in Australia at the time of the study based on trade quotes sourced by the authors and publicly available pricing information [40].

2.6. Electricity tariffs

The shopping centre purchases electricity under a four-year retail contract. The energy usage charge when combined with network use of system charges is the tariff that the operator pays for grid electricity. The tariff varies by time of the day and the rates are shown in Table 2.

In addition to network use of system charges, the shopping centre also pays a peak demand charge. This is the maximum half hourly kVA reading that occurred in peak times during the month. The units are dollars per kVA per month (\$/kVA/month). This demand charge varies according to season. For the period 1 July 2011 - 30 June 2012, the seasonal peak demand charge is \$14.2243/kVA/month and applies to summer (November-March) and winter (June-August) months. The non seasonal peak demand charge is \$13.3248/kVA/month for all other months (September, October, April and May).

Table 1: Parameters for DER technology options

Technology	Installed capital cost (\$/kW)	Monthly O&M cost (\$/kWh)	Gas fuel cost (\$/kWh)	Coefficient of performance	Economic life (years)
C30 gas micro-turbine	3,700	0.015	0.063	-	20
C65 gas micro-turbine	2,545	0.015	0.063	-	20
Absorption chiller	685	1.88	-	0.7	20
Solar PV	4,000	0.25	-	-	20
Solar thermal	500	0.5	-	-	15

Table 2: Tariff usage charge for grid electricity (cents/kWh)

Time of day	Weekday	Weekend
Peak: 7am to 10pm	18.168	6.14156
Off-peak: 10pm to 7am	6.14156	6.14156

3. DER investment scenarios

The shopping centre is located in the Australian Temperate Zone (warm summer, cool winter) classed as Building Code of Australia Zone 6, and is thus characterised by reasonably stable seasonal energy demands. Therefore, only profiles for a typical summer weekday in January, and a typical winter weekday in July are shown and discussed. These profiles are modelled in DER-CAM using the energy demand data supplied for the site discussed in Section 2.4. The original data is forecast to account for the shopping centre with its planned extensions, which adds an expected additional load proportional to the area of the extensions and calculated according to the current building codes, as discussed in Section 2.3.

The adopted approach is to guide the multiobjective optimal selection of DER technologies by the notion of Pareto optimality (see for example [32]). As is well-known, the minimisation of an optimisation cost involving conflicting objectives, such as energy costs and CO₂-eq. emissions, will not in general have a solution that simultaneously achieves global minima on both objectives. Rather, a suitable trade-off solution will need to be selected from a set of solutions between those that minimise each of the two objectives independently. Pareto optimality offers a way to select practically attractive solutions for the efficient allocation of DER.

The present study focuses on four select DER investment scenarios that lead to Pareto optimal solutions, as discussed in Section 4.1. These investment scenarios are compared to a base case, the business-as-usual (BAU) scenario, where no investment in DER technologies is made. The BAU scenario assumes typical load profiles where all energy requirements for the existing shopping centre with the new extension are met by buying electricity from the grid.

The selected investment scenarios target the joint minimisation of costs and CO₂-eq. emissions in four levels of prioritisation:

- (1) *Minimum Costs*: Targets the minimisation of total energy costs regardless of CO₂-eq. emissions.
- (2) *Minimum CO₂-eq. Emissions*: Targets the minimisation of CO₂-eq. emissions regardless of costs.
- (3) *Balanced, 94% Costs, 6% CO₂-eq. Emissions*: Targets a heavily weighted minimisation of costs (94%) that allows for some reduction of CO₂-eq. emissions (6%).
- (4) *Balanced, 60% Costs, 40% CO₂-eq. Emissions*: Targets a weighted minimisation of costs and CO₂-eq. emissions with a 3/2 relative prioritisation.

Scenarios (1) and (2) are of interest because they target the minimisation of costs or CO₂-eq. emissions as single optimisation objectives. That is, DER technologies are chosen to minimise each objective regardless of the value obtained for the other. These two scenarios clearly dominate and contextualise other solutions, in that no other solution can produce lower costs than Scenario (1), nor lower CO₂-eq. emissions than Scenario (2). However, the minimum-cost and minimum-emission solutions may be impractical, as the emissions associated with Scenario 1, or the costs associated with Scenario 2, may be prohibitively high.

A practical solution may be obtained by considering the minimisation of both objectives simultaneously. This, however, leads to multiple solutions, depending on the priority placed on each objective. The two balanced scenarios (3) and (4) target the multiobjective optimisation of costs and CO₂-eq. emissions with an option for heavily weighted minimisation of costs (with some reduction of CO₂-eq. emissions), and another for the minimisation of costs and emissions in a 3/2 weighting ratio. These two specific scenarios were chosen from an extensive sensitivity study conducted by solving 28 multiobjective optimisations with DER-CAM with optimisation weights ranging between the pure minimisation of costs and the pure minimisation of CO₂-eq. emissions. The two chosen balanced scenarios ([94%,6%], [60%,40%]) led to non-dominated (Pareto optimal) solutions of key practical significance, as discussed in more detail in Section 4.

The four investment scenarios considered assume fixed prices and a common 12-year amortisation period for all technology investments. All distributed energy equipment installed is assumed to be completely reliable, namely, presenting no faults or maintenance interruptions during the scheduled operation periods, which would otherwise affect demand charges and operating schedules.

All energy generated on-site was constrained to be used on-site. While electricity exports to the grid may increase the uptake of DER technologies and would be beneficial in minimising costs, they were not enabled in the model to prevent uncertainty in DER investment decisions from ill-defined feed-in tariffs.

Gas micro-turbines for CCHP technologies were constrained to use units of two sizes only, 30 kW and 65 kW, due to electrical power capacity restrictions of the existing distribution boards and related circuits. The maximum roof area for solar DER technologies (photovoltaics and solar thermal) was 8,000 m².

The existing 729.49 kW_e HVAC system was imposed as a constraint in all the optimisation scenarios, but other HVAC technologies, such as absorption chillers, were available as potential technologies for investment. Space cooling demand is modelled in DER-CAM as consumed electricity of an equivalent electric chiller with a coefficient of performance equal to 2.7 being that of the existing HVAC system.

4. Results and discussion

4.1. Trade-offs in cost and emissions reduction

Table 3 summarises the DER technologies selected by DER-CAM in each of the above scenarios, together with their associated total energy costs and CO₂-eq. emissions. Figure 5 illustrates the trade-off between costs and CO₂-eq. emissions realised by each of the optimal investment scenarios considered.

Table 3: DER-CAM optimal investment results

	Optimisation scenario				
	BAU	(1) Minimum costs	(3) Balanced, 94% costs, 6% CO ₂ -eq. emissions	(4) Balanced, 60% costs, 40% CO ₂ -eq. emissions	(2) Minimum CO ₂ -eq. emissions
Optimisation weights					
Costs	-	1	0.94	0.60	0
CO ₂ -eq. emissions	-	0	0.06	0.40	1
Annual costs and CO ₂ -eq. emissions					
Costs (k\$/year)	569	521	680	838	1647
savings (% BAU)	0	8.5	-19.5	-47	-189
Emissions (tonnes/year)	4227	2975	2113	1201	1193
savings (% BAU)	0	29.6	50	71.6	71.8
Cost of reduced emissions (\$/tonne)		-38.34	52.51	88.90	355.31
DER technologies	Installed capacities				
Photovoltaic (m ²)	0	0	4783	8000	8000
Micro-turbine (kWe)	0	390	520	585	975
Exist. HVAC (kWe)	0	729	729	729	729
Absorp. chiller (kWe)	0	152	0	262	8513

The four selected optimisation investment scenarios (1)–(4) lead to solutions identified as *non-dominated* (Pareto optimal) in a sensitivity analysis conducted by running 26 multiobjective optimisation scenarios in DER-CAM with a combination of costs/emissions optimisation weights between 1/0 (Minimum Costs) and 0/1 (Minimum CO₂-eq. Emissions). The solutions produced by the investment scenarios (1)–(4) are non-dominated in the sense that no other solution in the sensitivity analysis could further reduce one optimisation objective (either costs or CO₂-eq. emissions) without increasing the other [32]. As can be seen in Figure 5, the BAU scenario is a solution dominated by all four selected scenarios.

Figure 5: Carbon-cost trade-off curves: annual CO₂-eq. emissions (tCO₂-eq./year, left vertical axis) and cost of reduced emissions (\$/tCO₂-eq., right vertical axis) versus annual energy costs (k\$/year) achieved in each DER investment scenario. Base-case CO₂-eq. emissions and annual energy costs also shown (BAU scenario).

Naturally, the minimum-costs and minimum-CO₂-eq. emissions scenarios always lead to non-dominated (single-objective optimal) solutions. On the other hand, non-dominated balanced solutions could be further explored by conducting more extensive sensitivity analysis. The two balanced scenarios (3) and (4) chosen have special practical significance:

- the Balanced 94% Costs/6% Emissions Scenario offers 50% savings in CO₂-eq. emissions at a moderate 19% increase in costs.
- the Balanced 60% Costs/40% Emissions Scenario can practically attain the maximum savings in CO₂-eq. emissions at a quarter of the costs in the Minimum CO₂-eq. Emissions Scenario. At the technology prices considered, this trade-off solution already maximises the use of available roof space for PV generation, and is thus the most cost-effective option to *maximise* CO₂-eq. emission reductions.

From a perspective of minimising the costs of reducing annual emissions, the Minimum Costs scenario is clearly the most effective, as seen in Table 3. Under this scenario the cost of annual reduced emissions (\$/tonne) is in fact negative (namely, savings), since both costs and emissions are reduced in this scenario (win-win) with respect to the BAU scenario. It is interesting to compare what it would cost to achieve further reductions in CO₂-eq. emissions with the price of CO₂-eq. emissions regulated by the Australian

Government from 2012 to 2014. The regulated pricing was \$23.00/tonne for 2012-13, \$24.15/tonne for 2013-14, and \$25.40/tonne for 2014-15. This CO₂-eq.-emission trading scheme was repealed by the Australian parliament in July 2014, although Australia's target to reduce overall emissions by 5% of 2000 levels by 2020 remains in place.

4.2. Typical daily DER dispatch schedules

A distinctive feature of DER-CAM is its ability to prescribe typical 24-hour dispatching schedules for the DER technologies selected for each month of the year. While DER-CAM does not consider dynamic constraints in the operation of DER, it provides a fast first step to the design of optimal operation strategies according to season and day of the week. The inclusion of dynamic constraints in the optimisation of DER scheduling requires a more complex formulation of the optimisation problem, as discussed in [22].

Figures 6 to 10 show typical 24-hour dispatching schedules to satisfy the shopping centre's demand for electricity, heating and cooling for the minimum cost and minimum CO₂-eq. emission solutions. The DER technologies that apply are shown on Table 3. The minimum cost schedules are shown on the left-hand side subfigures, labeled (a), while the minimum CO₂-eq. emission schedules are shown on the right-hand side subfigures, labeled (b). The original demands for electricity and space heating and cooling is shown by a thick dot-line envelope, which is broken down into contributions for each of the invested DER technologies.

Summer results (for a typical day in January) are shown in Figure 6 (electricity), Figure 7 (space heating) and Figure 8 (space cooling). Winter results (for a typical day in July) are shown in Figure 9 (electricity) and Figure 10 (space heating). There is no cooling load for winter.

Observe on the minimum CO₂-eq. emission schedules how the PV generation takes precedence when the resource is available, shifting the operation of CCHP technologies to earlier and later in the day. This contrasts with the minimum cost schedules, where CCHP generation is scheduled in the middle of the day, when the greatest demand for electricity arises from the HVAC system. The cooling offsets shown on the electricity demand plots represent electricity that is replaced by thermal energy from CCHP technologies using absorption chillers.

Figure 6: Summer electricity supply: optimal DER dispatching schedules to meet electricity load on a typical day in January. Figure 6a: minimum cost scenario. Figure 6b: minimum CO₂-eq. emissions scenario.

5. Conclusions

A DER-CAM model was developed for a large retail shopping centre in Western Sydney to analyse optimal investments in distributed energy resources targeting minimisation of annual energy costs and CO₂-

a) Minimum-cost scenario.

b) Minimum-CO₂-eq. emissions scenario.

Figure 7: Summer space-heating supply: optimal DER dispatching schedules to meet space heating load on a typical day in January. Figure 7a: minimum cost. Figure 7b: minimum CO₂-eq. emissions.

a) Minimum-cost scenario.

b) Minimum-CO₂-eq. emissions scenario.

Figure 8: Summer space-cooling supply: optimal DER dispatching schedules to meet cooling load on a typical day in January. Figure 8a: minimum cost. Figure 8b: minimum CO₂-eq. emissions.

a) Minimum-cost scenario.

b) Minimum-CO₂-eq. emissions scenario.

Figure 9: Winter electricity supply: optimal DER dispatching schedules to meet electricity load on a typical day in July. Figure 9a: minimum cost. Figure 9b: minimum CO₂-eq. emissions.

a) Minimum-cost scenario.

b) Minimum-CO₂-eq. emissions scenario.

Figure 10: Winter space-heating supply: optimal DER dispatching schedules to meet space-heating load on a typical day in July. Figure 10a: minimum cost. Figure 10b: minimum CO₂-eq. emissions.

eq. emissions. This model was constructed using a year of historic energy demand and meteorological data, and building information about the existing building and planned extension.

The model was used in DER-CAM to generate and analyse optimal investment scenarios for the shopping centre with its planned extension, including a BAU, base-case scenario, a minimum annual costs scenario, a minimum CO₂-eq. emissions scenario, and two balanced investment scenarios combining a weighted optimisation of costs and CO₂-eq. emissions. The analysis of these scenarios indicates that investment in gas-fired CCHP (tri-generation) units will bring substantial savings in energy costs and CO₂-eq. emissions.

While the costs of the BAU scenario appear not far from those in the minimum costs scenario, investments in DER technologies can reduce these costs further with significant savings in CO₂-eq. emissions:

- Investment in six 65 kWe CHP (co-generation) units and a 152 kWe absorption chiller yields the minimum cost scenario with 8.4% savings in annual energy costs and 29.5% savings in annual CO₂-eq. emissions. This is a genuine win-win scenario where savings in both costs and emissions are achieved with respect to the BAU scenario, with \$38.34 *saved* per ton of reduced CO₂-eq. emissions.
- Investment in nine 65 kWe CHP (co-generation) units and a 262 kWe absorption chiller, and 8,000 m² of PV generation practically achieves the maximum reduction of CO₂-eq. emissions at 47% extra annual costs with respect to the BAU scenario, at \$88.90 per ton of reduced CO₂-eq. emissions.

While there exist some current limitations around the selection of available capacities/sizes of continuous technologies, DER-CAM has proven a very powerful tool to support flexible economic and environmental analysis of investments in energy technologies for buildings. A key advantage of a DER-CAM approach in commercial applications is that users are spared from the complexities of formulating a mixed-integer, multi-objective optimisation problem, and can thus focus on the analysis of optimal solutions, as is demonstrated in the present paper. Using a model developed in DER-CAM, there are opportunities to explore carbon-cost trade-off solutions and compute Pareto efficient solutions. As illustrated in Section 4.1, such solutions display alternative optimal balances between minimisation of cost and CO₂-eq. emissions, which may reveal more practical scenarios than the minimum cost or the minimum emission solutions. Re-evaluation of scenarios to reflect changes in DER technologies and market conditions may be directly implemented and analysed in future studies.

Finally, observe that the availability of accurate historical data for the HVAC system energy demand, which is a substantial component of the total demand in shopping centres, is important for the selection of

DER technology options. For model accuracy, such data should also include not only HVAC/total energy split logs (typically available from modern sub-metering systems), but also an end-use breakdown of heating and cooling modes throughout the year.

References

- [1] Fisher, B., Nakicenovic, N.. Issues related to mitigation in the long term context. In: Metz, B., Davidson, O., Bosch, P., Dave, R., Meyer, L., editors. *Climate Change 2007: Mitigation, Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change*; chap. 3. United Kingdom and New York, USA: Cambridge University Press; 2007, p. 169–250. Accessed 28 April 2015; URL https://www.ipcc.ch/publications_and_data/ar4/wg3/en/contents.html.
- [2] Gupta, S., Tirpak, D.A.. Policies, instruments and co-operative arrangements. In: Metz, B., Davidson, O., Bosch, P., Dave, R., Meyer, L., editors. *Climate Change 2007: Mitigation, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; chap. 13. United Kingdom and New York, USA: Cambridge University Press; 2007, p. 745–807. Accessed 28 April 2015; URL https://www.ipcc.ch/publications_and_data/ar4/wg3/en/contents.html.
- [3] Garnaut, R.. *The Garnaut Review 2011: Australia in the global response to climate change*. Cambridge University Press; 2011.
- [4] Priddle, R., editor. *World Energy Outlook 2013*. Paris: International Energy Agency; 2013.
- [5] IPCC, . *Ipcc 2013: Summary for policymakers*. In: Stocker, T., Qin, D., Plattner, G.K., Tignor, M., Allen, S., Boschung, J., et al., editors. *Climate Change 2013: The Physical Science Basis*. Cambridge University Press; 2013,.
- [6] World Bank. *Understanding the links between climate change and development*. Tech. Rep.; World Bank; Washington DC, USA; 2010. Accessed 28 April 2015; URL <http://siteresources.worldbank.org/INTWDRS/Resources/477365-1327504426766/8389626-1327510418796/Chapter-1.pdf>.
- [7] ABARES. *Energy in Australia*. Tech. Rep.; Australian Bureau of Agricultural and Resource Economics and Sciences; 2011.
- [8] IPART. *Changes in regulated electricity retail prices from 1 July 2012*. Tech. Rep.; Independent Pricing and Regulatory Tribunal; Sydney, Australia; 2012.
- [9] ABS, . *Energy account, Australia (eaa) 2011-12*. Tech. Rep. Catalogue No. 4604.0; Australian Bureau of Statistics; Canberra, Australia; 2014.
- [10] Wood, T., Carter, L., Harrison, C.. *Fair pricing for power*. Tech. Rep. 2014-8; Grattan Institute; 2014. Accessed 28 April 2015; URL <http://grattan.edu.au/wp-content/uploads/2014/07/813-fair-pricing-for-power.pdf>.
- [11] Lasseter, R.. *Smart distribution: Coupled microgrids*. *Proceedings of the IEEE* 2011;99(6):1074–1082.
- [12] Stadler, M., Marnay, C., Siddiqui, A., Lai, J., Coffey, B., Aki, H.. *Effect of heat and electricity storage and reliability on microgrid viability: A study of commercial buildings in California and New York states*. Tech. Rep. LBNL-1334E; LBNL; Berkeley, CA, USA; 2009.
- [13] Marnay, C., Venkataramanan, G., Stadler, M., Siddiqui, A.S., Firestone, R., Chandran, B.. *Optimal technology selection and operation of commercial-building microgrids*. *IEEE Transactions on Power Systems* 2008;23(3):975–982.
- [14] Rezaie, B., Esmailzadeh, E., Dincer, I.. *Renewable energy options for buildings: Case studies*. *Energy and Buildings* 2011;43(1):56–65.
- [15] DeForest, N., Mendes, G., Stadler, M., Feng, W., Lai, J., Marnay, C.. *Optimal deployment of thermal energy storage under diverse economic and climate conditions*. *Applied Energy* 2014;119:488–496.
- [16] Li, G.. *Review of thermal energy storage technologies and experimental investigation of adsorption thermal energy storage for residential application*. Master of science; University of Maryland, College Park; 2013.
- [17] Barbieri, E., Melino, F., Morini, M.. *Influence of the thermal energy storage on the profitability of micro-chp systems for residential building applications*. *Applied Energy* 2012;97:714–722.
- [18] Stadler, M., Kloess, M., Groissbck, M., Cardoso, G., Sharma, R., Bozchalui, M., et al. *Electric storage in Californias commercial building*. *Applied Energy* 2013;104:711–722.
- [19] ClimateWorks Australia. *Tracking Australia's progress towards a low carbon economy. Part 4: buildings*. Tech. Rep. ISBN 978-0-987-13417-2; ClimateWorks Australia; Melbourne, Victoria; 2013. Accessed 28 April 2015; URL http://www.climateworksaustralia.com/sites/default/files/documents/publications/climateworks_trackingprogress_buildings_full_report_july2013_1.pdf.
- [20] Ruan, Y., Liu, Q., Zhou, W., Firestone, R., Gao, W., Watanabe, T.. *Optimal option of distributed generation technologies for various commercial buildings*. *Applied Energy* 2009;86(9):1641–1653.
- [21] Jradi, M., Riffat, S.. *Tri-generation systems: Energy policies, prime movers, cooling technologies, configurations and operation strategies*. *Renewable and Sustainable Energy Reviews* 2014;32:396–415.

- [22] Pruitt, K.A., Braun, R.J., Newman, A.M.. Evaluating shortfalls in mixed-integer programming approaches for the optimal design and dispatch of distributed generation systems. *Applied Energy* 2013;102:386–398.
- [23] Pruitt, K., Braun, R., Newman, A.. Establishing conditions for the economic viability of fuel cell-based, combined heat and power distributed generation systems. *Applied Energy* 2013;111:904–920.
- [24] Mendes, G., Ioakimidis, C., Ferrão, P.. On the planning and analysis of integrated community energy systems: A review and survey of available tools. *Renewable and Sustainable Energy Reviews* 2011;15(9):4836–4854.
- [25] Piacentino, A., Barbaro, C., Cardona, F., Galea, R., Cardona, E.. A comprehensive tool for efficient design and operation of polygeneration-based energy μ grids serving a cluster of buildings. Part I: description of the method. *Applied Energy* 2013;111:1204 – 1221.
- [26] Piacentino, A., Barbaro, C.. A comprehensive tool for efficient design and operation of polygeneration-based energy μ grids serving a cluster of buildings. Part II: analysis of the applicative potential. *Applied Energy* 2013;111:1222 – 1238.
- [27] Siddiqui, A.S., Marnay, C., Bailey, O., Lacomme, K.H.. Optimal selection of on-site generation with combined heat and power applications. *International Journal of Distributed Energy Resources* 2005;1(1):33–62. Accessed 5 May 2015; URL <http://emp.lbl.gov/sites/all/files/JOURNAL%201bnl%20-%2056774.pdf>.
- [28] Litchy, A., Young, C., Pourmousavi, S., Nehrir, M.. Technology selection and unit sizing for a combined heat and power microgrid: Comparison of webopt and homer application programs. 2012,.
- [29] Firestone, R., Marnay, C.. Distributed generation dispatch optimization under various electricity tariffs. *International Journal of Electronic Business Management* 2007;5(3):197–210.
- [30] Stadler, M., Marnay, C., Siddiqui, A., Lai, J., Cardoso, G., Megel, O., et al. The influence of a CO₂ pricing scheme on distributed energy resources in California's commercial buildings. Tech. Rep.; LBNL; 2010.
- [31] Zhou, N., Marnay, C., Firestone, R., Gao, W., Nishida, M.. An analysis of the DER adoption climate in Japan using optimization results for prototype buildings with u.s. comparisons. *Energy and Buildings* 2006;38(12):1423–1433.
- [32] Giorgi, G., Guerraggio, A., Thierfelder, J.. *Mathematics of Optimization. Smooth and nonsmooth*; chap. 6: Vector Optimization. Elsevier Science; 2004, p. 503 – 591.
- [33] AEMO. Distribution Loss Factors for the 2011-12 Financial Year. Australian Energy Market Operator; 2011.
- [34] AEMO. List of Regional Boundaries and Marginal Loss Factors for the 2011-12 Financial Year. Australian Energy Market Operator; 2011.
- [35] ESAA. Electricity Gas Australia 2011. Energy Supply Association of Australia; 2011.
- [36] Australian Building Codes Board. Regulation impact statement (RIS 2006-02). Proposal to amend the building code of Australia to include energy efficiency requirements for class 5-9 buildings. 2006.
- [37] Australian Building Codes Board. BCA 2010 energy efficiency commercial building final decision RIS Classes 3 and 5-9 (RIS 2009-07). Available from: <http://www.abcb.gov.au/consultation/regulation-impact-analysis/final-ris-for-decision>; 2009. Accessed 28 April 2015.
- [38] Australian and New Zealand Solar Energy Society. Australian Solar Radiation Data Handbook (ASRDH); 4 ed.; 2006.
- [39] Kohlenbach, P., Jakob, U.. *Solar Cooling: The Earthscan Expert Guide to Solar Cooling Systems*. Routledge; 2014.
- [40] Alternative Technology Association. Solar panel buyers guide 2012: Whats new and where to buy. *ReNew* 2012;(118):41–48.