Economic and Environmental Impacts of Distributed Energy Resources

Amru Alqurashi

***Abstract*—The current power system suffers from inherent inefficiencies and transmission line congestion due to the spatial split between power generation and end usage. This potentially introduces shortcomings in meeting load demands, grid liability, renewable portfolio standards, and environmental considerations such as carbon emission reduction targets. The economic and technical viability of distributed energy resource (DER) technologies may accelerate the transition to more sustainable energy production. This paper investigates the economic and environmental benefits of DERs compared to utility prices and emissions for residential dwellings using the Distributed Energy Resources Customer Adoption Model (DER-CAM). The results show a tradeoff between the CO_2 emissions and electricity costs, but improvements over purchasing the electricity.**

***Index Terms*—Distributed energy resources, residential building, energy management optimization problem, Distributed Energy Resources Costumer Adoption Model (DER-CAM).**

I. INTRODUCTION

Many countries expressed the need to make their power infrastructure more cost-effective, environmentally clean, and sociologically acceptable, thus sustainable. A considerable amount of the generated power is currently being lost due to a variety of technological reasons: a) separated generation from end usage, b) outdated transmission and distribution lines, and c) and missing demand-responsive technology and policy infrastructures. The situation is exacerbated by increasing load demands and historically declining R&D investment by power utilities. Moreover, the dependency on centralized power generation is expected to not only increase the rate of carbon (e.g. CO_2) emissions, but also raise the electricity tariff prices [1]. In addition, load congestion bottlenecks in the existing grid raise the barrier to entry of integrating renewable forms of energy. Distributed energy resources (DERs) are considered as a sustainable option to modernize the aging grid. However, this implies technical and economic DERs.

DERs are onsite generation sources located close to the load, thus naturally saving transmission and distribution overhead. Furthermore, they might have a low carbon footprint when renewable energy generation is deployed, such as found in photovoltaics, electricity storage, and natural gas-fired combined heat and power (CHP) generators.

In terms of economics, DERs not only have the potential to reduce the costs of electricity by load shifting, but also offer the opportunity to sell energy back to the grid provided such policies exist. This paper investigates the potential of DER installations for residential buildings to reduce electricity costs and CO_2 emissions by using Distributed Energy Resources Customer Adoption Model (DER-CAM) created by Berkeley lab [2].

II. DER TECHNOLOGIES

In the past, power generation plants are usually located far away from the cities and use transmission lines to transfer power to the distribution system that feeds the loads. To avoid power loss and increase the system's reliability, DER concepts are deployed to provide the consumer with independent power. DERs are small (typically <10MW) energy generators, which may include storage technologies, and are typically located close to the demand [3]. The expected economic dispatch for DERs is the added flexibility of switching the power source between grid and local power when energy costs (i.e. electricity, and/or fuel) are high [4]. DERs can also improve the reliability of the electrical service continuity by providing standby power in case of power outages or critical load periods. An added benefit of DERs is that the waste heat could be utilized and supplied to the facilities more directly compared to distributed systems [2]. For instance, CHP technologies such as combustion turbines, fuel cells, and microturbines have shown to increase energy efficiency up to 80% [3]. A brief description of the DER technologies considered in this study is provided next [5], [6]:

Natural Gas-Fired (CHP): Natural gas CHP can generate both electricity and heat. A variety of technologies use natural gas to generate heat and electricity. These include natural gas combustion turbine, fuel cells, and microturbine.

Photovoltaic (PV): converts solar energy to DC electricity generation.

Solar Thermal: Converts solar energy to thermal energy to supply the heat loads in a building.

Storage Technologies: At low demand, the facility can store the unused electrical energy from the main grid or DERs and use it at peak times, which might allow for economic benefits.

Absorption Chiller and Refrigeration: These technologies provide cooling and refrigeration for a building.

With increasing renewable energy integration such as solar and wind, the implementation of DER increases

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Manuscript received November 14, 2020; revised January 8, 2021.

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doi: 10.18178/jocet.2021.9.2.527

notably. The necessity of energy management for DER systems encouraged the researchers to find optimal distribution and control topology that enhance the reliability, stability, and efficiency of the power system [7]. DER-CAM is a powerful tool to find the optimal DER design by solving energy management problems.

III. DER COSTUMER ADOPTION MODEL (DER-CAM)

DER-CAM is a design tool that uses optimization algorithms to assist the user in designing and analyzing decentralized energy systems such as microgrids.

To illustrate, DER-CAM formulates the optimization as a Mixed Integer Linear Program (MILP). Using the General Algebraic Modeling System (GAMS), DER-CAM finds the globally optimal solutions by using powerful proprietary solver (C-PLEX). To find an accurate solution, DER-CAM considers several input parameters in the optimization problem. These input parameters are:

- Hourly load profiles
- Electricity tariff, and natural gas prices
- Fuel, capital, and operating and maintenance costs of each technology.
- Physical characteristics of each technology.
- Site information.

Depending on the motivations of deploying DERs, the optimization problem's objective can be reducing energy costs, CO_2 emissions, or ensuring energy security. Also, multi-objective functions can be considered in the optimization problem. It is important to note that selecting the objectives functions will affect the optimal system design significantly. In other words, the optimization algorithm finds the optimal solution based on the selected objective. Given the objective of this study to investigate the sustainability of DERs for a facility, the knowledge of the expected change in electricity costs is the key. The various factors to influence the system design considered here include:

- DER technologies combinations.
- Interest rate and payback period.
- Electricity and heat loads profile.
- Fuel and electricity rates.
- Costs and power efficiency of DERs.
- Demand response.
- Solar radiations and weather conditions.
- Utility CO_2 emissions.

Considering the system's input parameters, DER-CAM minimizes the objective function subject to system constraints. The solution of this optimization problem determines the following:

- Optimal selection of distributed energy resource technologies.
- Optimal capacity and placement of DER within the microgrid.
- Cost analysis for supplying a specific load.
- Detailed of carbon emissions for supplying a specific load.

The goal of the system design is to reduce energy imports, increase revenue from sales, shift loads form peak time, provide demand response, and ancillary services to the smart grid. DER-CAM provides data libraries for building load profiles, solar insulation, and electricity tariff database. Also, the libraries have several DERs technologies that help the user to customize their models based on the optional data fields. The user can run multiple scenarios to investigate the impacts of different DER technologies. The scenarios can also include the effect of energy policy, load profiles, tariffs, and energy rates. In stochastic optimization, scenario analysis is instrumental in developing a design solution that delivers adequate technical and economic performance despite the uncertainty of the system. In short, a select the DER-CAM economic and environmental model towards finding optimal solutions in terms of cost and CO_2 emissions, where the model input parameters are considered. The outputs are optimized 1) DERs technology choices, 2) operating schedule, 3) electricity cost, and 4) CO_2 emissions (Fig. 1).

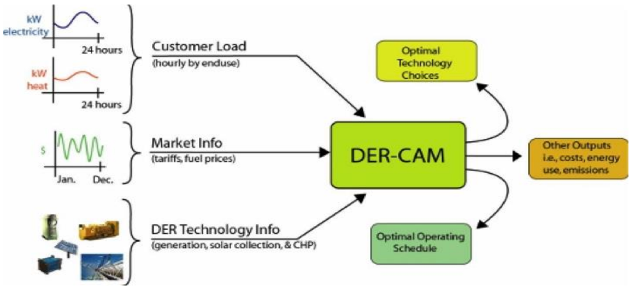


Fig. 1. Distributed Energy Resources Customer Adoption Model (DER-CAM) [8].

Many researchers used DER-CAM to find the optimal DER design for a microgrid by solving energy management problems [9]-[14]. In [9], the authors did a case study that compared multi-node and single single-node for a microgrid. In [10], security constraints in optimal microgrid design were modeled in DER-CAM. Researchers in [11] investigated the effect of ancillary services in the investment decisions of DER while the investment decisions of CHP were studied in [12]. Thermal energy storage was modeled in [13] to track the losses of the storage temperatures. Considering the uncertainty of solar irradiance on the microgrid design, the authors in [14] applied a stochastic approach to formulating the problem of sizing and scheduling microgrid. This paper investigates the economic and environmental benefits of DERs compared to utility prices and emissions for residential dwellings using the Distributed Energy Resources Customer Adoption Model.

IV. CASE STUDIES

An owner of a residential dwelling located in San Francisco wants to have an investment decision to install DERs. The main objectives of installing DERs are to reduce energy costs and CO_2 emissions. To make an investment decision, an optimization problem has to be solved considering these objectives as cost function. Therefore, the following information must be known to act as input parameters for the model. These parameters are:

- Load profile.
- Electricity tariffs.
- DER specific costs and efficiency.

- Emissions data
- Payback period.

DER-CAM facilities the DER design by providing the input parameters in its platform [6]. The average annual load profile of a typical dwelling in this region is shown in (Fig. 2). The selected appropriate tariffs were chosen from the local utility Pacific Gas and Electric Company (PG&E) that match the dwelling's electricity load. The flat electricity rates for the summer and winter are $0.2/kWh and $0.14/kWh, respectively. In this study, the advantage of DER-CAM's flexibility in providing DER specific costs and efficiency was utilized. The fixed and variable costs of the batteries and the PV system are provided within the DER-CAM. For PV and solar thermal technologies, the geographical specific solar radiation was used from [6]. The payback period for this investment plan should not exceed 12 years; otherwise it will not be economically feasible. Lastly, hourly utility emissions data (in $kgCO_2/kW$) from the year 2008 were taken for the chosen residential dwelling. In the next section, the optimal solution for this energy management optimization problem is investigated.

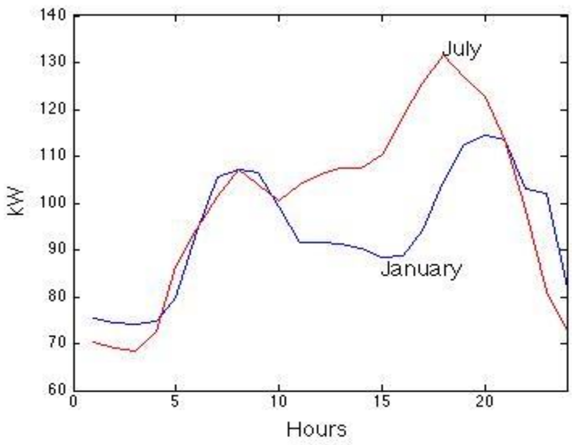


Fig. 2. Electricity load of a residential dwelling in San Francisco.

V. SIMULATION RESULTS

The multi-objective function of our optimization problem is to minimize energy costs and CO_2 emissions. However, our results show that there is no win-win scenario, which is expected because focusing on reducing CO_2 emissions increases the electricity costs (Fig. 3). In other words, the simulation results indicate a relatively linear correlation between the incurred annual energy costs and CO_2 emissions.

Fig. 3 shows four different solutions represent by points 0 to 4. Form now and forward, these points (solutions) will be called cases. Thus, each one of these five cases (solutions) is investigated. The lower-left corner in Fig. 3 is the sweet spot where both the annual costs and emissions are minimized. Case 0 is the reference case when 100% of the energy is purchased from the utility, while other cases use DERs. In terms of CO_2 emissions, case 0 is the worst-case scenario. However, cases 3 and 4 represent the worst-case scenarios in terms of energy cost. Therefore, the reasonable cases to be investigated are cases 1 and 2, where case 1 is the best solution for minimizing energy cost, while case 2 is a better solution for reducing CO_2 emissions. Next, the benefits, outcomes, and installation technologies utilized for cases 1 and 2 are discussed.

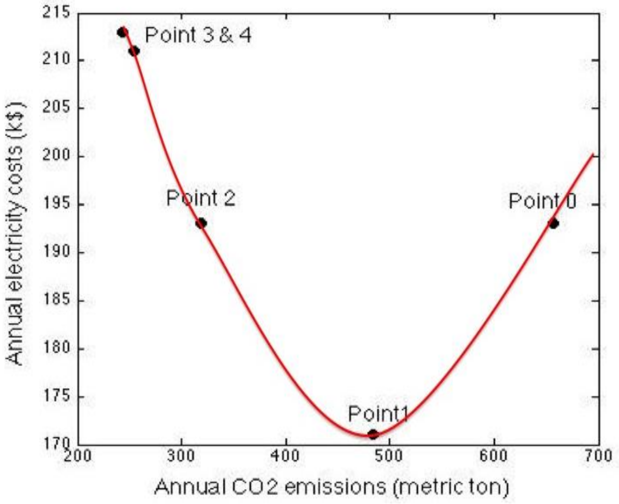


Fig. 3. Costs and CO_2 emissions tradeoff.

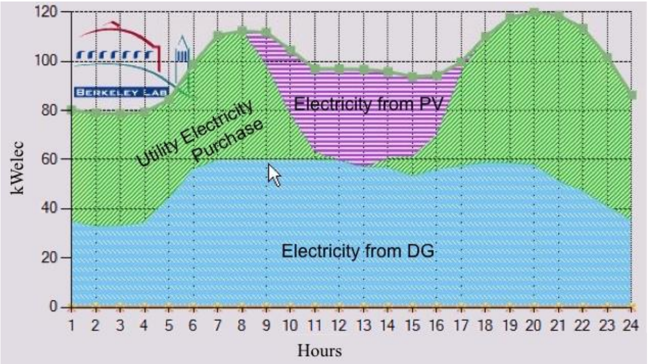


Fig. 4. Optimal dispatch of DERs and utility electricity purchase in January (case 1).

Investment Case 1: this investment case represents results in the lowest costs while trading in emission. Compared to the reference (case 0), it reduces the electricity costs and CO_2 emissions by 11% and 26%, respectively, and a system payback time of 7.3 years. The DERs technologies used are a natural gas-fired CHP (60 kW), and 68kW of PV (area = 442 m^2).

The results for electricity and heat load for seasonal sensitivity analysis are illustrated in (Fig. 4 & Fig. 5). In a winter month, electrical energy is received from both the DERs and utility. Fig. 4 shows the optimal dispatch of DERs and utility electricity purchase in January. As can be seen, the blue area represents the electricity generated from the distributed generators (DG). The green area represents electricity purchase from the utility while the violet color is PV generation. The DG is able to cover the base load for the entire day. While the total load naturally fluctuates within a day, the amount of electricity purchase from the utility varies between 0-55%. The PV system is able to offset grid power entirely around noon, which was a design choice. The results also show that this DER combination does little to mitigate the grid peak in the early evening. The heat load is investigated to gain insights into the DER's dispatch profile (Fig. 5).

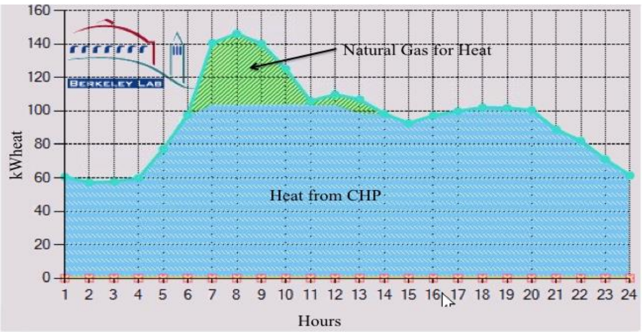


Fig. 5. Optimized dispatch of DERs and utility gas purchase in January (case 1).

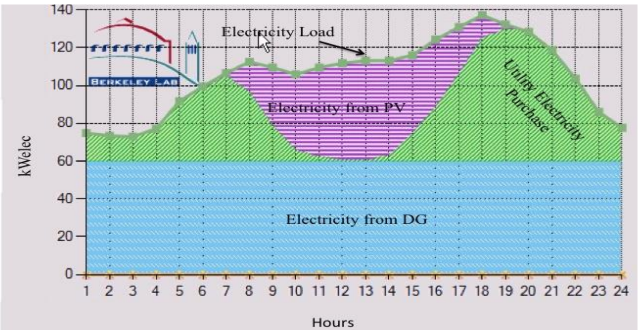


Fig. 6. Optimal dispatch of DERs and utility electricity purchase in July (case 1).

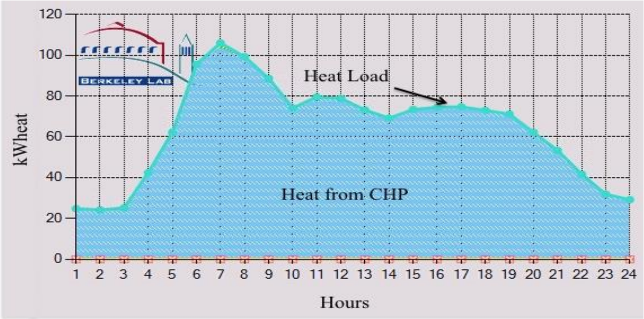


Fig. 7. Optimal dispatch of DERs and utility gas purchase in July (case 1).

The initial total heat load (light blue line, Fig. 5) shows that the CHP unit is unable to surly the required amount of heat in the morning hours, and the natural gas system (green area, Fig. 5) has to support it. It is interesting to note that the peak heat load occurs during the morning and not evening hours. This can be understood by the dwelling cooling down overnight, and residents demanding warmth when getting up. This finding is interesting since it shows an opportunity to reduce peak loads, if behavioral wedges might be used, such as (in) decreasing the thermostat by 2 degrees in (summer) winter. To gain insights into the seasonal effects, a typical summer month should be investigated as well. Our results indeed show that the optimal operation of onsite DERs depends on seasonal effects (Fig. 6 & Fig. 7). The peak electricity load in July increases by 20kW from January, reaching its maximum at 140kW (Fig. 6). This increase of electricity load is due to a higher cooling load in summer. The DER feeds the 60kW of the electricity load for the whole day while the rest of the electricity is received from utility and PV. Moreover, the heat load decreases by 40% relative to January, thus the CHP covers the entire heat load. As a result, no natural gas purchase is needed from the utility (Fig. 7).

Investment Case 2: This investment case represents an improved solution for minimizing CO_2 emissions, and flat electricity costs relative to the reference case (case 0). Here CO_2 emissions are cut by 52% (339 tons), with a payback time just over ten years. DERs technologies used are natural gas-fired CHP (60kW), battery storage (523kWh), PV (243kW, area =1587 m^2), and solar thermal (159kW, area = 227 m^2). In this case, the oversized PV system is able to provide the majority of electricity between 10 AM and 4 PM (Fig. 8). In addition, the access electricity from the PV system is used to charge the battery unit; whose stored energy is used to reduce the purchased electricity in the early morning and evening.

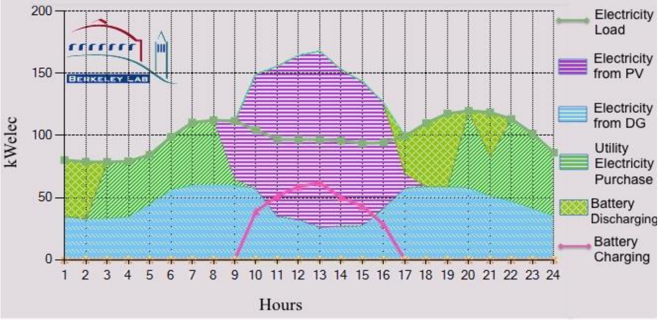


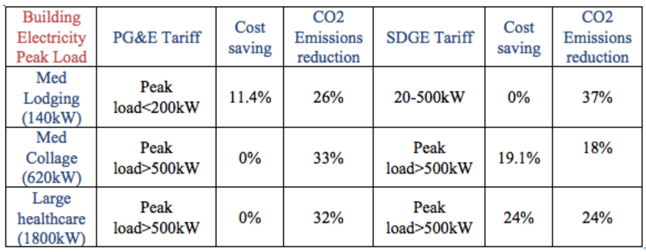
Fig. 8. Optimal dispatch of DERs and utility electricity purchase in January (case 2).

It should be noted that all the investment cases studied here can reduce the annual carbon footprint regardless of the electricity cost (Fig. 3). However, this argument holds only for the operational time window of these units since this work did not include life-cycle-analysis data such as production and end-of-life emissions [15]. Still, investment case 1 not only reduces emissions by 26% but also the electricity costs by 11.4%. However, within this study's scope, the best option for environmentally cautious investors is investment case 2, which reduces the emissions by 52% without incurring additional costs relative to the business-as-usual case (Case 1). These results also validate the expected decreased dependency on utility power for scaled-up DER capacities. However, the DER can also become oversized (Case 3 & 4, Fig. 3), which inflates electricity prices above the reference case. In this regard, it might be essential to clarify personal targets and objectives with dwelling residents prior to DER installations. It is interesting to note that if ~1.5% (about 1000) residential dwellings in San Francisco were to adopt case 1 DERs, the CO_2 emissions of the city would 3.2% (172,000 tons) annually [16].

VI. IMPACT OF TARIFFS ON DER INVESTMENTS

Utility companies are not consistent in the cost of the services provided by them. The tariffs for electricity and gas are different from a utility company to another. For instance, the Pacific Gas and Electric Company (PG&E) applies different tariffs in comparison to the San Diego Gas and Electric (SDGE). These utility tariffs could affect the feasibility of a DER investment. The impact of PG&D and SDGE tariffs on three different facilities investments in San Francisco are compared in Table I. As can be seen in Table I, the achievable electricity cost savings depend strongly on tariff policies. On the other hand, the CO_2 emission reduction is less sensitive to the change in tariff. For loads that are less than 200kW, applying the PG&E tariff reduces the electricity cost using the DERs; however, there was no cost-saving for loads that are higher than 200kW using the PG&E tariff. In contrast, applying SDGE tariff reduces the electricity cost for loads that are more than 200kW, and it did not impact the electricity cost for the loads that are less than 200kW. Therefore, utility tariffs play a significant role in determining optimal DER investments.

TABLE I: PG&E AND SDGE TARIFF'S IMPACTS ON DERS INVESTMENTS



Building Electricity Peak Load	PG&E Tariff	Cost saving	CO2 Emissions reduction	SDGE Tariff	Cost saving	CO2 Emissions reduction
Med Lodging (140kW)	Peak load<200kW	11.4%	26%	20-500kW	0%	37%
Med Collage (620kW)	Peak load>500kW	0%	33%	Peak load>500kW	19.1%	18%
Large healthcare (1800kW)	Peak load>500kW	0%	32%	Peak load>500kW	24%	24%

VII. CONCLUSIONS

Distributed Energy resources are promising technologies for reducing both electricity costs and CO_2 emissions. A case study was done for a residential dwelling using DER-CAM towards optimizing both CO_2 emissions and electricity cost. The results show a tradeoff in terms of CO_2 emissions and electricity costs. The two investment cases investigated in detail showing distinct benefits; reduce electricity costs and emissions by 11% and 26%, for smaller DER systems, and a flat cost but about 52% emissions saving relative to purchasing from the utility (i.e. PG&E) directly. Finally, it is noted that the utility tariff and electricity peak load affect the viability of DERs, whereas implementing DER technologies reduces CO_2 emissions regardless of electricity costs.

CONFLICT OF INTEREST

The author declares no conflict of interest.

AUTHOR CONTRIBUTIONS

The author, A. Alqurashi, confirms sole responsibility for the case studies, analysis and interpretation of results, and manuscript preparation.

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