

Article



# Economic, Energetic, and Environmental Performance of a Solar Powered Organic Rankine Cycle with Electric Energy Storage in Different Commercial Buildings

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**Abstract:** This paper presents an analysis to determine the economic, energetic, and environmental benefits that could be obtained from the implementation of a combined solar-power organic Rankine cycle (ORC) with electric energy storage (EES) to supply electricity to several commercial buildings including a large office, a small office, and a full service restaurant. The operational strategy for the ORC-EES system consists in the ORC charging the EES when the irradiation level is sufficient to generate power, and the EES providing electricity to the building when there is not irradiation (i.e., during night time). Electricity is purchased from the utility grid unless it is provided by the EES. The potential of the proposed system to reduce primary energy consumption (PEC), carbon dioxide emission (CDE), and cost was evaluated. Furthermore, the available capital cost for a variable payback period for the ORC-EES system was determined for each of the evaluated buildings. The effect of the number of solar collectors on the performance of the ORC-EES is also studied. Results indicate that the proposed ORC-EES system is able to satisfy 11%, 13%, and 18% of the electrical demand for the large office, the small office and the restaurant, respectively.

Keywords: electric energy storage; organic Rankine cycle (ORC); carbon emission reduction

## 1. Introduction

Recently organic Rankine cycles (ORCs) have been widely studied [1–5]. ORCs using solar energy as the heat source have also been investigated. Antonelli et al. [6] modeled an ORC using compound parabolic collectors and a volumetric expander with variable rotating speed to account for varying levels of available radiation throughout the day. Different weather conditions were modeled to determine the response of the solar ORC. Casartelli et al. [7] investigated an ORC cycle with two different types of solar collectors and modeled the cycles using sliding partial pressure for the turbine inlet pressure and partial admission into the turbine as different operational strategies. They determined that partial admission control strategy had the highest efficiency and lowest levelized cost of electricity (\$/kilowatt-hour of the power generation technology for the assumed life of the unit) under the modeled conditions. Desai and Bandyopadhyay [8] performed a thermo-economic analysis for different working fluids for concentrating solar collectors and determined levelized cost of electricity and cycle efficiency for different fluids. Georges et al. [9] provided a detailed selection criteria for components in a solar ORC cycle design.

The ability of ORCs to supply building electricity requirements has also been a focus of study. Mago et al. [10] and Fang et al. [11] investigated the potential savings from using an ORC in conjunction with a combined heat and power (CHP) system or a combined cooling, heating, and power (CCHP)

system to supply building energy needs. In a study by Ziviani et al. [12], a transient solar powered ORC was simulated and then evaluated based on its ability to meet the thermal and electrical load of a residential building for a midwinter day and midsummer day. For the midsummer day, the solar ORC produced more electricity than the midwinter day, but because of the availability of the maximum radiation during the middle of the day and the peak cooling load in the afternoon, the ORC was unable to generate enough electricity to power an electric air conditioner.

Researchers have investigated electric energy storage (EES) devices in order to use electricity generated in a more effective manner. An EES device and a thermal energy storage device were used with a CHP system in a study by Bianchi et al. [13]. They determined that when the system was properly sized, it could cover the electric and thermal load of a residential building and, when compared to a reference case, could result in primary energy consumption savings. Chen et al. [14] compared a standard CHP with a CHP with hybrid electrical energy storage when operated by following the electric load. With the EES device, the size of the engine used in the CHP system was able to be reduced when compared to that in the CHP system without the EES. The smaller engine in the CHP-EES system ran at higher efficiency and for fewer hours when compared to the standard CHP with the EES device providing electricity during nonpeak hours. Graditi et al. [15] investigated the economic feasibility of several battery EES options for use in a time of use energy cost management system, and performed a case study for a public institution in Italy. A study by Telaretti et al. [16] also considered multiple battery EES options to determine the economic feasibility for the electricity customer. They performed a parametric analysis by varying the difference between the high and low electricity prices and also varying peak demand charges. Mago and Luck [17] studied an ORC and EES system using a power generation unit (PGU) as the heat source to determine the potential for carbon dioxide emission (CDE) and cost reductions for a restaurant in four U.S. cities. They determined that location had a large effect on cost reduction and CDE savings. Of the four evaluated cities with an optimum sized PGU, all four had the potential for cost savings and three of the four had possible CDE savings. Warren et al. [18] investigated a CHP system using an ORC-EES with heat supplied by a PGU to evaluate the potential for cost savings, CDE reduction, primary energy consumption (PEC) savings, and the available capital cost for a desired payback period for a restaurant located in twelve U.S. cities.

One of the challenges with using solar energy to power an ORC is the unsteady nature of the solar energy that powers the ORC. Previous studies have attempted to mitigate this challenge by adding an energy storage device to the system. These energy storage devices include thermal energy storage (TES) devices and to a lesser extent electric energy storage devices. In a study by Bhagat and Saha [19], the authors presented a numerical model on the transient response of spherical encapsulated phase change materials (PCMs) in order to remove temperature fluctuations in the heat transfer fluid caused by the variation in available radiation for a solar powered ORC. Chacartegui et al. [20] analyzed a solar powered ORC using parabolic trough collectors with a direct TES system which uses one fluid to transfer and store heat and an indirect TES system which uses one fluid to transfer heat and another fluid to store heat. They determined that the indirect TES system had a higher specific investment cost but lower levelized energy cost than that of the direct TES system. The authors also determined that including a TES system results in a higher investment cost but reduces the electricity generation costs. Li et al. [21] studied the effect of different working fluids for a solar powered ORC with a TES system using phase change materials. In a study by Rodriguez et al. [22], the feasibility of two different TES technologies, a two tank system and a thermocline system, were investigated for 1 MWe concentrating solar power ORC. The authors determined that the two-tank system performed better than the thermocline system, but the thermocline system provided a significant cost reduction. Ji et al. [23] combined wind and solar power to store energy and produce electricity using a turbo-generation unit and an ORC. They used a two-tank system to store thermal energy from the solar collector. Patil et al. [24] compared a solar powered ORC with TES and a solar photovoltaic system with EES based on annual energy generation, capacity utilization factor, capital cost, levelized cost of electricity, and energy wasted.

In a study by Hassoun and Dincer [25], an ORC using solar power was modeled to provide electricity, hot water, heating, and cooling for a net zero energy house in South Lebanon. In their study, the solar panels supplied hot water to the ORC with ammonia as the working fluid, hot water tank system, and the absorption chiller system. In addition, a battery bank was used to supply electricity when necessary during the night or non-sunny days or electricity was purchased from the grid when the battery bank could not supply the needed electricity. The authors performed an optimization study on the system using a genetic algorithm. They determined the present cost of the system with and without connection to the grid and determined the overall system efficiency and exergetic efficiency.

In a previous study by Spayde et al. [26], an hourly model for both a solar powered ORC and a solar powered regenerative ORC was developed using flat plate collectors in place of an evaporator for the ORC. Both ORC systems were evaluated using five different dry working fluids. A dry fluid has a positive slope of the saturation curve in the T–s diagram. Local weather data from Tucson, AZ and Jackson, MS were used to evaluate the effect of different climate zones on the ORCs. A thermo-economic analysis was performed to determine first and second law efficiencies as well as the potential for PEC and CDE savings and the available capital cost. They determined that the regenerative ORC generated more power than the basic ORC cycle with the same working fluid and that the working fluid R236ea performed the best of the evaluated fluids. The ORC modeled in Tucson, AZ generated more power than the ORC modeled in Jackson, MS which resulted in a higher potential for PEC and CDE savings and higher available capital cost.

This paper investigates the performance of a novel solar powered ORC that directly charges an EES device that is designed to supply electricity generated by the solar powered ORC to one of the following potential facilities: a small office, a large office, and a restaurant, all located in Tucson, AZ. Previous studies have modeled storing excess electricity from a solar powered ORC in a battery bank whereas the model presented in this paper stores all generated electricity from the solar ORC in the electric energy storage device before supplying electricity to the building. The ORC system used in this study is based on the model presented in a previous study by Spayde et al. [26]. The operational strategy of the ORC-EES system consists in the ORC charging the EES device when there is adequate solar irradiation to generate power from the ORC. The proposed system is evaluated based on its potential to reduce cost, CDE, and PEC when compared to a conventional system. The available capital cost to implement the ORC-EES, the effect of the number of solar collectors in the ORC, and the battery size, battery discharge hours, and percentage of energy supplied to the building are also investigated in this paper.

#### 2. System Model

The model presented in this paper is an hourly model for a solar powered ORC using dry fluids. The ORC is used to charge an EES device that is used to supply electricity to a commercial building. The EES device (battery) is discharged according to the electricity requirements of the selected buildings. The ORC-EES is modeled as charging when there is adequate solar irradiation to power the ORC and then the EES is discharged when there is insufficient radiation to generate power, which is primarily during night time. The ORC system was sized based on the electricity requirements of the modeled building and the amount of solar irradiation available for that location. The ORC system was simulated during one year and the size of the EES system was selected based on the maximum daily electric production of the ORC. The electricity requirement for the building was determined using EnergyPlus [27]. To determine the performance of the proposed ORC-EES, the PEC, CDE, and operational cost obtained from the ORC-EES operation were compared with a conventional system for the evaluated buildings in which electricity is purchased from the utility grid.

A schematic of the ORC-EES is illustrated in Figure 1. The working fluid at State 1 is pumped to the cycle high pressure at State 2. The working fluid then enters the flat plate solar collector where heat is transferred to the working fluid before entering the turbine at State 3. The power that is generated in

the turbine is transferred to the EES device. The working fluid exits the turbine (State 4) and enters the condenser where heat is rejected so that the working fluid returns to State 1 to start the cycle again. The power generated in the ORC is transferred to the electric energy storage device where it is stored until there is no longer sufficient radiation to generate power in the ORC. The energy is then discharged from the EES device per the building's electricity requirements.



Figure 1. Schematic of the organic Rankine cycle (ORC) with electric storage. EES: electric energy storage.

#### System Model

(a) Pump (Process 1–2): The pump power is determined as:

$$\dot{W}_{p,i} = \frac{W_{ps,i}}{\eta_p} = \frac{\dot{m}_i(h_1 - h_{2s})}{\eta_p} = \dot{m}_i(h_1 - h_2) \tag{1}$$

where  $W_{ps,i}$  is the hourly ideal work of the pump,  $\dot{m}_i$  is the hourly mass flow rate,  $h_1$ ,  $h_{2s}$ , and  $h_2$  are the enthalpies for the pump inlet, the ideal pump exit, and the pump exit, respectively.

(b) Solar Collector (Process 2–3): An isobaric process where heat is added to the working fluid before the turbine inlet. The flat plate solar collector replaces the evaporator in a traditional ORC system. The hourly mass flow rate for the working fluid can be found from the following equation:

$$\dot{m}_i = \frac{Q_{in,i}}{(h_3 - h_2)}$$
 (2)

where  $Q_{in, i}$  is the hourly heat transfer rate from the solar collector and  $h_3$  is the enthalpy of the working fluid as it leaves the solar collector. State 3 was assumed to be a saturated vapor at the high pressure of the working fluid which was 2 MPa.

The hourly solar collector heat transfer rate is determined from the following equation:

$$Q_{in,i} = \eta_{solar,i} I_i A \tag{3}$$

where  $\eta_{solar, i}$  is the hourly solar collector efficiency,  $I_i$  is the hourly irradiation, and A is the solar collector area.

The solar collector efficiency is determined using the relationship:

$$\eta_{solar,i} = y_{int} - m\left(\frac{T_{in} - T_{amb,i}}{I_i}\right) \tag{4}$$

where  $y_{int}$  is the y-intercept, *m* is the slope,  $T_{in}$  is the inlet temperature of the working fluid, and  $T_{amb, i}$  is the hourly ambient temperature which is taken from TMY3 (Typical Meteorological Year, version 3) weather data. The y-intercept and slope are terms provided by the manufacturer or third party certification; in the presented model the values for the y-intercept and slope are 0.760 and 6.125 W/(m<sup>2</sup> °C), respectively [28]. The solar efficiency equation is the Hottel-Whillier-Bliss equation [29] where  $y_{int}$  and *m* correspond to:

$$y_{int} = F_R \tau \alpha \tag{5}$$

$$m = F_R U_L \tag{6}$$

where  $F_R$  is the collector heat removal factor,  $\tau$  is the transmissivity of the glass cover plates,  $\alpha$  is the absorptivity of the absorber plate, and  $U_L$  accounts for the losses due to conduction and radiation.

The hourly irradiation values can be found from:

$$I_{t,i} = I_{DN,i}\cos\theta + I_{dh,i}\left(\frac{1+\cos\Sigma_i}{2}\right) + I_{tH,i}\rho\left(\frac{1-\cos\Sigma_i}{2}\right)$$
(7)

where  $I_{t,i}$  is the hourly total radiation,  $I_{DN,i}$  is the hourly direct normal irradiation,  $\theta$  is the incidence angle,  $I_{dH,i}$  is the hourly diffuse horizontal irradiation,  $\Sigma_i$  is the hourly surface tilt angle,  $I_{tH,i}$  is the hourly total horizontal irradiation, and  $\rho$  is the ground reflectance. Hourly direct normal irradiation, diffuse horizontal irradiation, and total hourly irradiation can be found from the National Renewable Energy Laboratory TMY3 data [30]. The ground reflection value used is 0.2 which was found in literature [31]. The incidence angle and surface tilt angle are dependent of the solar collector configuration. In this study, the solar collectors were modeled as two-axis tracking solar collectors which allow for the absorption of the maximum solar irradiation. The incidence angle for a two-axis tracking system is zero. Having a two-axis tracking system yields the following hourly surface tilt equation:

$$\Sigma_i = 90 - \beta_i \tag{8}$$

where  $\beta_i$  is the hourly solar altitude, which can be found using [31]:

$$\beta_i = \sin^{-1}(\cos L \cos \delta \cos H + \sin L \sin \delta) \tag{9}$$

where *L* is latitude,  $\delta$  is declination, and *H* is the hour angle. Declination can be found from [32]:

$$\delta = 23.45 \sin\left(360 \frac{284 + n}{365}\right) \tag{10}$$

where *n* is the day of the year.

(c) Turbine (Process 3–4): The turbine power is determined from the following equation:

$$\dot{W}_{t,i} = \eta_t \dot{W}_{ts,i} = \eta_t \cdot \dot{m}_i (h_3 - h_{4s}) = \dot{m}_i (h_3 - h_4) \tag{11}$$

where  $\eta_t$  is the isentropic efficiency of the turbine,  $W_{ts,i}$  is the hourly ideal power output of the turbine, and  $h_{4s}$  and  $h_4$  are the enthalpies of the ideal state and the actual state of the working fluid at the turbine outlet, respectively.

(d) Condenser (Process 4–1): The hourly heat rejected by the ORC is determined from:

$$\dot{Q}_{out,i} = \dot{m}_i(h_1 - h_4)$$
 (12)

(e) Electric Energy Storage Device: The charging of the EES device (battery) depends on the power available from the solar powered ORC, while the discharging of the EES device depends on the power requirements of the building. While different operation strategies could be selected in the proposed model, the EES device was charged while solar irradiation levels were high enough to generate power from the ORC, and it was discharged when there was insufficient irradiation to power the ORC, which was primarily at night. This operational strategy could potentially be used for a back-up system to supply electricity if the building lost power. The following equation determines how the EES device charges and discharges:

$$E_{bat,i} = E_{bat,i-1} - E_{b,i}, W_{ORC,i} = 0 \text{ and } E_{bat,i-1} > 0$$
 (13)

$$E_{bat,i} = 0, W_{ORC,i} = 0 \text{ and } E_{bat,i-1} = 0$$
 (14)

$$E_{bat,i} = E_{bat,i-1} + W_{ORC,i} \cdot \xi_{bat}, \quad W_{ORC,i} > 0$$
(15)

where  $E_{bat,i}$  is the battery capacity for the current hour,  $E_{bat,i-1}$  is the battery capacity of the battery for the previous hour,  $E_{b,i}$  is the electricity required by the building for the current hour,  $W_{ORC,i}$  is the net work supplied by the ORC for the current hour, and  $\xi_{bat}$  is the battery efficiency factor that accounts for losses from charging and discharging the battery. These losses were accounted for using the battery efficiency factor during charging of the battery to simplify the simulations. Work from the ORC is defined as:

$$W_{ORC,i} = W_{t,i} - W_{p,i} \tag{16}$$

(f) Primary Energy Consumption (PEC) Savings: Using the electricity generated and stored on site has the potential to generate PEC savings when compared to electricity purchased from the grid. The PEC Savings are calculated from the following equation:

$$PEC_{savings} = PEC_{conv} - PEC_{ORC-EES} = E_{bat,dis} \times ECF_{PEC} - E_{bat,dis} \times SCF_{PEC}$$
(17)

where  $PEC_{conv}$  is the primary energy consumption of the conventional system,  $PEC_{ORC-EES}$  is the primary energy consumption of the ORC EES model,  $E_{bat,dis}$  is the electricity discharged from the battery,  $ECF_{PEC}$  is the site to source conversion factor for purchased electricity that varies depending on location [33,34], and  $SCF_{PEC}$  is the conversion factor for electricity generated from an onsite solar system which has a value of 1 [35,36].

(g) Carbon Dioxide Emission (CDE) Savings: Using on site solar generated electricity can also result in CDE savings versus electricity purchased from the grid. CDE savings are determined as:

$$CDE_{savings} = CDE_{conv} - CDE_{ORC-EES} = E_{bat,dis} \times ECF_{CDE}$$
(18)

where  $CDE_{savings}$  is the carbon dioxide emission savings,  $CDE_{conv}$  is the carbon dioxide emissions from the conventional system,  $CDE_{ORC-EES}$  is the carbon dioxide emissions from the ORC-EES, which is zero, and  $ECF_{CDE}$  is the conversion factor for purchased electricity for CDE which is location dependent [37].

(h) Available Capital Cost (ACC) and Cost Savings: The savings from using on site electricity versus purchased electricity can be used to determine the capital cost that would be available to implement the ORC-EES system for a desired payback period. This can be used to determine the economic feasibility of installing an ORC-EES system. The savings are calculated using the following equations:

$$Cost_{savings} = E_{bat,dis} \times Cost_e \tag{19}$$

$$ACC = \sum_{PBP} Cost_{savings}$$
(20)

where  $Cost_e$  is the forecasted yearly cost of electricity and *PBP* is the desired payback period. The forecasted yearly cost of electricity is determined by plotting the average year to date commercial electricity cost in Arizona from 2008 to 2017 [38] and performing a linear regression to estimate the future cost of electricity from 2018 to 2027.

## 3. Discussion

The model presented in Section 2 was evaluated in different buildings located in Tucson, AZ. Tucson, AZ was selected because of the high levels of direct normal irradiance available [39]. The selected organic working fluid is R236ea since it has shown to have a good performance in ORC applications [26]. There are 16 commercial reference building models developed by the U.S. Department of Energy (DOE), which can represent almost 70% of the commercial buildings in the U.S [40]. These reference building models are used in the EnergyPlus simulation software to generate simulation data of building energy usage profiles. In this paper, three building types were selected: a large office, a small office, and a full-service restaurant. The floor area and electricity requirements for each building are shown in Table 1. For the model presented in this paper, weather data for Tucson, AZ was used in the EnergyPlus simulations. Figure 2 presents the modeled hourly total irradiation available and hourly building electricity requirements for a representative day (15 June) for the full service restaurant. Table 2 lists values for the parameters used in the model including pump and turbine isentropic efficiencies, conversion factors for PEC and CDE, and the battery efficiency factor.

Table 1. Areas and electricity requirements for the modeled buildings [27].



**Figure 2.** Hourly total irradiation available and hourly electricity requirements for 15 June for the modeled full service restaurant.

Parameter	Value
Turbine isentropic efficiency, $\eta_t$	0.8
Pump isentropic efficiency, $\eta_p$	0.8
Site-to-source conversion factor for electricity (purchase), ECF <sub>PEC</sub> [34] (kWh/kWh)	3.06
Site-to-source conversion factor for electricity (solar), SCF <sub>PEC</sub> [35] (kWh/kWh)	1
Conversion factor for purchased electricity for CDE, ECF <sub>CDE</sub> [37] (kg/kWh)	0.397
Battery efficiency factor, $\xi_{bat}$ [18]	0.95

**Table 2.** Parameter values used in the model.

The ORC-EES was sized based on the electricity needs of the different buildings. The number of solar collectors and battery size were based on the electricity requirements of the building at night so the battery is able to meet the nightly electricity requirements for each building's design day. The number of solar collectors, battery size, amount of onsite energy generated in one year, and percentage of yearly electricity supplied by the ORC-EES for each of the selected buildings are presented in Table 3. The number of solar collector used to obtain the results presented in this paper has an area of 39.72 ft<sup>2</sup> for a single collector [28]. The amount of energy generated and percentage of electricity supplied by the ORC-EES in one year is a direct result of the size of the ORC-EES system. The ORC-EES system is able to supply 10.6%, 13.2%, and 18.2% of the required electricity for the large office, small office, and full service restaurant, respectively. For the large office building, the ORC-EES system generates the highest amount of electricity because it has the largest system, but the ORC-EES for the restaurant supplies the highest percentage of the required electricity to the restaurant.

**Table 3.** Number of solar collectors, battery size, amount of usable onsite energy generated in one year, and percentage of yearly electricity supplied by the ORC-EES for each of the evaluated buildings.

Building	No. Solar Collectors	Total Collector Area (ft <sup>2</sup> )	Battery Size (kWh)	Usable Onsite Energy Generated (kWh/year)	Percentage of Electricity Supplied by ORC-EES
Large Office	702	27,928	2,837	639,039	10.6%
Small Office	11	438	45	10,013	13.2%
Full Service Restaurant	70	2785	283	63,722	18.2%

Figure 3 shows the monthly percentage of the required electricity that is supplied by the ORC-EES to each of the evaluated buildings. The ORC-EES for the restaurant building provides the highest percentage of required electricity to the building every month. For the restaurant building, the ORC-EES is able to generate between 14% and 23% of the monthly electricity required by the building. This can be explained due to the fact that the restaurant building required more electricity at night than the two office buildings when the ORC-EES is supplying the electricity to the building. For the small office building, the ORC-EES is able to generate between 11% and 17% of the monthly electricity required by the building while for the large office building. All three buildings have the highest percentage of electricity supplied by the ORC-EES during the spring and early summer months when more solar irradiation is available for the selected location. In the later summer months, there is a high amount of solar irradiation, but the required building electricity is also higher than during the spring and early summer, therefore, the ORC-EES is not able to supply a higher percentage of the required electricity.

The number of hours the EES supplies energy to the building in one year is presented in Figure 4. The battery discharge hours follow the same trend as the percentage of onsite energy production. The restaurant has the highest number of hours where the battery is supplying electricity to the building while the large office has the lowest.



**Figure 3.** Percentage of the building load provided by the ORC-EES for each of the evaluated buildings. The number of hours the EES supplies energy to the building in one year is presented in Figure 4. The battery discharge hours follow the same trend as the percentage of onsite energy production. The restaurant has the highest number of hours where the battery is supplying electricity to the building while the large office has the lowest.

Since the ORC-EES generates onsite electricity, from solar energy, there is a potential for primary energy consumption savings compared to purchasing electricity from the utility grid. The monthly percentage of PEC savings is shown in Figure 5 for each of the evaluated buildings. Once again, the restaurant building shows the best PEC savings followed by the small and large office buildings. The yearly PEC savings are 20,628 kWh/year, 1,316,421 kWh/year, and 131,267 kWh/year for the small office, large office, and restaurant, respectively. The average yearly percentage savings are: 8.9%, 7.1%, and 12.2% for the small office, large office, and restaurant, respectively. As can be seen in Figure 5, the percentage PEC savings are the highest in the spring and early summer for each of the evaluated buildings for the same reasons explained above. This follows the same trend as the percentage of building electricity provided by the ORC-EES. The large office has the highest PEC savings because its ORC-EES system produces the most energy onsite; conversely, the small office has the smallest potential for PEC savings because the small office ORC-EES system is the smallest system for the evaluated buildings.



**Figure 4.** Number of hours that energy is supplied by the battery to each of the evaluated buildings in one year.



Figure 5. Percentage of monthly PEC savings for each of the evaluated buildings.

In addition to PEC savings, there is a potential CDE savings since the electricity generated from the solar powered ORC generates practically zero CDE. The monthly percentage of CDE savings is the same as percentage of building electricity supplied. This is shown in the monthly percentage of CDE savings for the evaluated buildings presented in Figure 6. The yearly CDE savings for the small office, large office, and restaurant are 3979 kg/year, 253,920 kg/year, and 25,320 kg/year, respectively. Similarly, because the ORC-EES system is providing electricity to the selected buildings, there is a potential for operational cost savings. The monthly percentage of operational cost savings is the same percentage as the percentage of building energy supplied as shown in Figure 7. The yearly cost savings for the small office, large office, and restaurant are \$972/year, \$62,051/year, and \$6187/year, respectively. The cost of electricity value used in the results was the average year to date commercial electricity cost for Arizona [38].



Figure 6. Monthly percentage of CDE savings for each of the modeled buildings.

Furthermore, the available capital costs (ACC) for the selected buildings are presented in Figures 8–10. The ACC is determined from the savings of generating some of the building's required electricity using ORC-EES system rather than purchasing electricity from the grid. Figures 8–10 show the amount of available capital cost for a desired payback period which ranges from 1 to 10 years.

For a 10-year payback period using a forecasted commercial electricity cost discussed previously from 2018 to 2027, the ACC for a small office, large office, and restaurant in Tucson, AZ is \$10,916, \$696,617, and \$69,463, respectively. The predicted electricity cost value for 2018 is 0.10 \$/kWh and for 2027 is 0.12 \$/kWh. Therefore, for a 10-year payback period for a restaurant, the capital cost must be less than \$69,463.



Figure 7. Monthly percentage of cost savings for each of the modeled buildings.



Figure 8. The available capital costs (ACC) for a small office in Tucson, AZ.

The results presented above indicate that the ORC-EES has the potential of reducing operational cost, PEC, and CDE as compared to buying electricity from the utility grid. However, the amount of savings will strongly depend on the number of solar collectors used in each building. Therefore, how the number of solar collectors affected the performance of the ORC-EES system was also investigated in this paper. For this analysis, the restaurant building was chosen because the ORC-EES system supplied the highest percentage of the electricity required by the building. The effect of solar collectors on the battery size and cost savings of the ORC-EES system, the percentage of the building load supplied by the ORC-EES, and the number of battery discharge hours were investigated.

Figure 11 shows how the battery size of the ORC-EES system changes as the number of solar collectors increases. It is important to remember that the EES system is sized based on the amount of electricity generated by the ORC-EES system. The results illustrate that the battery size increases linearly at first, then exponentially as the number of solar collectors increases. The battery size increases exponentially due to that fact that the nightly building load is no longer large enough to fully discharge what the ORC stored in the battery during the previous day. Figure 11 also shows how the number of collectors affects the potential cost savings. As with the battery size, the cost savings increases linearly with the number of solar collectors, but then levels off with a higher number of solar collectors. This is due to a smaller increase in the percentage of building electricity supplied by the ORC-EES which can be seen in Figure 12. Figures 12 and 13 present the percentage of building electricity load the ORC-EES supplies and the number of hours the battery discharges versus the number of solar collectors, respectively.



Figure 9. The ACC for a large office in Tucson, AZ.



Figure 10. The ACC for a restaurant in Tucson, AZ.



**Figure 11.** Battery size and cost savings of the ORC-EES verses number of solar collectors for a restaurant in Tucson, AZ.



**Figure 12.** Percentage of the building load supplied by the ORC-EES verses number of solar collectors for a restaurant in Tucson, *AZ*.



**Figure 13.** The number of battery discharge hours of the ORC-EES verses number of solar collectors for a restaurant in Tucson, AZ.

As the number of solar collectors increases, the percentage of the building load that the ORC-EES supplies increases until it approaches the percentage of the building load electricity that occurs during hours where the ORC-EES is not generating power, which is the only time that the battery discharges. With 160 solar collectors in the ORC-EES system, the ORC-EES system supplies 37.8% of a possible 41.8% of the building's electricity load. Likewise, the number of hours the battery discharges increases until it approaches the number of hours that the building load occurs during non-generating hours for the ORC-EES. The battery discharges 4199 h of a possible 4629 h which is 91% when the ORC-EES is sized for 160 solar collectors. However, it is important to note here that even though increasing the number of collectors increases the cost savings, a complete economic analysis must be performed to determine the point when it is not economically feasible.

#### 4. Conclusions

An hourly model of a solar powered ORC-EES system in Tucson, AZ was presented in this paper. The modeled solar powered ORC used R-236ea as the working fluid and charged the EES system. Three different facilities were investigated with respect to the potential savings using an ORC-EES system: a small office, a large office, and a restaurant, all in Tucson, AZ. The size of the ORC-EES system was based on the electricity requirements of the building. The hourly electricity requirements for each building were determined from EnergyPlus simulations. The ORC charged the EES system when there was adequate irradiation to generate power, and the EES discharged to offset the building electricity needs when the ORC was not generating power, which was primarily at night. The potential for PEC, CDE, and cost savings was also evaluated for each of the evaluated buildings.

The large office building ORC-EES supplied the highest amount of electricity because it was the largest ORC-EES system among the three evaluated buildings. The restaurant ORC-EES supplied the highest percentage of required building electricity using the operational strategy presented in this paper. This could be explained from the restaurant building having a higher electricity requirement at night, when the ORC-EES is discharging, than that of the office buildings. The number of hours that the EES is discharging corresponds to the percentage of required buildings had the potential for PEC, CDE, and cost savings. The large office had the highest value for potential PEC, CDE, and cost savings while the restaurant had the highest percentage of PEC, CDE, and cost savings. The ACC was also determined for the three evaluated buildings. The large office buildings had the highest ACC, but it was also the largest ORC-EES system.

The effect of the number of solar collectors on the battery size, cost savings, supplied electricity percentage, and battery discharge hours is also investigated. The restaurant is chosen since it supplies the highest percentage of required building electricity. The number of solar collectors affects the battery size linearly at first, then exponentially, indicating that the ORC system is overdesigned as the building electricity requirements at night are smaller than the energy capacity of the EES system. The cost savings, supplied electricity percentage, and battery discharge hours increase linearly with the number of solar collectors in the beginning but then level off as the number of solar collectors continues to increase. The supplied electricity percentage levels off as it approaches the percentage of building electricity load that occurs during hours that the ORC-EES system discharges. To determine the optimum size of the ORC-EES, a full economic analysis needs to be performed.

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## Nomenclature

α	absorptivity
ACC	available capital cost
β	solar altitude
CDE	carbon dioxide emissions
ξ <sub>bat</sub>	battery efficiency factor
E <sub>bat</sub>	battery capacity
E <sub>b</sub>	required building electricity
ECF	electricity conversion factor
EES	electric energy storage
δ	declination
$F_R$	collector heat removal factor
Ι	solar irradiation, kW/m <sup>2</sup>
Н	hour of the day
h	specific enthalpy, kJ/kg
θ	incidence angle
L	latitude
m	mass flow rate, kg/s
η	isentropic efficiency
$\eta_{solar}$	solar collector efficiency
m	slope for solar collector efficiency
п	day of the year
PBP	payback period
РСМ	phase change material
PEC	primary energy consumption
PGU	power generation unit
Ò	heat rate, kW
ρ	ground reflectance
$\Sigma$	surface tilt angle
SCF	solar conversion factor
Т	temperature, K
TES	thermal energy storage
τ	transmissivity
$U_{I}$	conduction and radiation losses
Ŵ	power, kW
Vint	y-intercept for solar collector efficiency
Subscripts:	, i ,
amb	ambient
с	condenser
conv	conventional
dH	diffuse horizontal
DN	direct normal
е	evaporator
f	feedwater heater
i	hour
in	inlet condition for solar collector
р	pump
p1	pump 1
p2	pump 2
0	ambient
ORC	organic Rankine cycle
t	turbine
tH	total horizontal

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