energies

Article

Simulation Modeling of a Photovoltaic-Green Roof System for Energy Cost Reduction of a Building: Texas Case Study

Sojung Kim [1], Burchan Aydin [2] and Sumin Kim [3,*]

[1] Industrial and Systems Engineering, Dongguk University-Seoul, Seoul 04620, Korea; sojungkim@dgu.ac.kr
[2] Engineering and Technology, Texas A&M University-Commerce, Commerce, TX 75429, USA; burchan.aydin@tamuc.edu
[3] Department of Environmental Horticulture & Landscape Architecture, College of Life Science & Biotechnology, Dankook University, Cheonan-si 31116, Korea
* Correspondence: sumin.kim@dankook.ac.kr; Tel.: +82-41-550-3644

Abstract: This study aims at introducing a modeling and simulation approach for a green roof system which can reduce energy cost of a building exposed to high temperatures throughout the summer season. First, to understand thermal impact of a green roof system on a building surface, a field-based study has been conducted in Commerce, Texas, U.S., where the average maximum temperature in summer is 104 °F (40 °C). Two types of analyses were conducted: (1) comparison of temperature between different plant type via Analysis of variance (ANOVA) and (2) polynomial regression analysis to develop thermal impact estimation model based on air temperature and presence of a green roof. In addition, an agent-based simulation (ABS) model was developed via AnyLogic® University 8.6.0 simulation software, Chicago, IL, U.S., in order to accurately estimate energy cost and benefits of a building with a photovoltaic-green roof system. The proposed approach was applied to estimate energy reduction cost of the Keith D. McFarland Science Building at Texas A&M University, Commerce, Texas (33.2410° N, 95.9104° W). As a result, the proposed approach was able to save $740,325.44 in energy cost of a heating, ventilation, and air conditioning (HAVC) system in the subject building. The proposed approach will contribute to the implementation of a sustainable building and urban agriculture.

Keywords: green roof; photovoltaic; simulation; urban agriculture; sustainability; condensate water

check for updates

Citation: Kim, S.; Aydin, B.; Kim, S. Simulation Modeling of a Photovoltaic-Green Roof System for Energy Cost Reduction of a Building: Texas Case Study. *Energies* **2021**, *14*, 5443. https://doi.org/10.3390/en14175443

Academic Editors: Mark Laser and Mariusz Jerzy Stolarski

Received: 9 July 2021
Accepted: 24 August 2021
Published: 1 September 2021

1. Introduction

As environmental sustainability becomes a critical issue to improve quality of our lives, development of green buildings in urban areas has been receiving nationwide attention. The green building refers to not only an energy-efficient building but also a vegetated building. One of the examples of the vegetated building is a green roof which contains live plants atop the roof membrane of buildings. Because the green roof provides protection against excessive solar radiation [1–3], it eventually improves the thermal efficiency and energy efficiency of a building [1–4].

In addition to the thermal efficiency, hydrological performance of a green roof was proved under a tropical area in Singapore [5]. In the study, evapotranspiration (ET) was modeled via the artificial neural network (ANN) consisting of multi-layer perceptron regressors. Chagolla-Aranda et al. [6] analyzed the thermal impact of a green roof with five plants (i.e., Sedum adolphii, Echeveria prolífica, Aeonium subplanum, Crassula ovata y, and Sedum Makinoi) in Mexico. Particularly, the study found that electricity consumption of a green roof cell could be lower than that of a conventional roof cell in semi-warm climate. On the other hand, Schade et al. [7] investigated the thermal performance of a green roof on a building in Sweden. In the study, the green roof acted as building insulation materials in a sub-arctic climate. Moreover, since plants are grown in soil, the green roof is also known as a new option to mitigate stormwater/rainwater runoff in a city [8,9].

The green roof (or a vegetation roof) can be classified as intensive, semi-intensive, or extensive based on the planting medium depth. An intensive green roof requires a planting medium of at least 1 foot to 3 feet in depth and can accommodate the growth of trees and shrubs while an extensive green medium is thinner and accommodates shallow root plants such as grasses and sedums [10]. The intensive green roof can effectively protect a building surface from direct sunshine, but it also requires thoughtful inspection of structural safety of a building because weight of soils cannot be negligible [11,12]. Therefore, the extensive green medium less than 6 inches has been widely adopted in practice [13].

Although the extensive green medium may result in cooling down a building surface due to its ability to block direct solar radiation through medium and plants, its exact impact on a building surface temperature can vary under different locations and vegetation levels [14]. For example, He et al. [15] showed the thermal performance of the green roof in tropical area, but Schade et al. [7] analyzed the thermal performance in a sub-arctic climate. It is possible that the extensive green medium is ineffective on energy consumption reduction of a building from chronic exposure to high temperature. Thus, additional studies under various high temperature conditions are needed for development of a generic evaluation and estimation model of a green roof which still requires expensive investment cost [16].

In this study, a field study was conducted to evaluate the thermal impact of a green roof system on a building surface at the Keith D. McFarland Science Building at Texas A&M University, Commerce, TX, USA (33.2410° N, 95.9104° W) where the average maximum temperature in Summer is 104 °F (40 °C) [17]. Then, based on the collected field data and literatures, an agent-based simulation (ABS) model for estimating energy cost of a building with a green roof system was developed via AnyLogic® University 8.6.0 simulation software, Chicago, IL, USA. Although Ávila-Hernández et al. [18] developed a thermal simulation model via EnergyPlus® software 9.5.0, Golden, CO, USA for eight cities in Mexico, it was limited to thermal performance estimation under specified building materials. Because this study focuses more on a green-roof design, operation, and its cost, the ABS model is devised. AnyLogic® is a well-known multimethod simulation platform so that it is reliable and flexible to develop a generalized estimation model of a green roof in future [19]. To be more specific, the green roof model can be extended with existing smart grid models for cleaner city design or Agrophotovoltaic systems which have photovoltaic (PV) solar panels over green roof grids in an urbanized farming environment [20–22]. The proposed simulation consists of multiple estimation models such as surface temperature model, energy consumption model, and water usage model. Particularly, the water usage model includes tap water source and condensate water source given by heating, ventilation, and air conditioning (HVAC). The proposed approach is applied to estimate energy reduction cost of the Keith D. McFarland Science Building in order to demonstrate its performance in terms of energy cost reduction of a building. As a result, the proposed approach will contribute to implementation of a sustainable building and urban agriculture.

The rest of the paper is organized as follows. Section 2 reviews the existing studies on a green roof system. The detail information and results about the field study on a green roof system at the Keith D. McFarland Science Building at the Texas A&M University-Commerce, Commerce, TX are addressed in Section 3. Section 4 introduces the proposed ABS modeling approach and its results. Section 5 concludes the study and findings.

2. Green Roof System

As air pollution becomes a significance problem to continue life in an urban area, urban agriculture (UA) has received worldwide attention. In 2018, 4.2 billion people (i.e., 55% of the world's population) are living in urban areas [23], which causes multiple problems involving air and water pollution, urban heat island (UHI), high energy consumption, and shortage of resources (e.g., water). Moreover, the urbanization with high density areas accelerates speed of the spread of infectious disease such as COVID-19 due to its high density of population [24]. Of course, it also generates greenhouse gas (GHG) involving carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and trioxygen (O_3) [25]. In 2050, 68% of the world's population will live in urban areas [23]. This implies that all the problems associated with the urbanization will become more serious in future.

UA is referred to the production and distribution of food at an urban area (or a city) [26]. Particularly, most studies on UA focus on cultivating plants at an urban area because it can potentially contribute to the reduction of GHG emission [25]. UHI problem can be mitigated, as green space in the urban areas increases [27]. The most popular way to implement UA in high-density urban cities is utilization of a green roof [28]. This is because it can enhance the community functions (e.g., community participation, education, and aesthetic value) in addition to mitigation of the environmental problems [27]. Moreover, installation cost of a green roof system is relatively easy and inexpensive compared to a new building construction project [29]. As mentioned in Section 1, there are three types of a green roof based on the planting medium depth: (1) intensive (from 30.48 cm (one foot) to 91.44 cm (three feet)), (2) semi-intensive (from 15.24 cm to 30.48 cm), and (3) extensive (under 15.24 cm or 6 inches). An intensive green roof is used to cultivate large plants such as trees and shrubs, and an extensive green roof is devised to accommodate shallow root plats such as grasses and sedums [10]. The most popular type of a green roof is an extensive green roof because of its inexpensive investment cost and maintenance cost [30]. According to HomeAdvisor [31], cost of an extensive green roof system per square meter is approximately from \$107.64/m^2 to \$215.28/m^2; and cost of an intensive green roof system per square meter is from \$215.28/m^2 to \$430.56/m^2. Annual maintenance cost (e.g., fertilizer, soil, and plant replacement and water bill) of a green roof is from \$8.07/m^2 to \$16.15/m^2. The maintenance cost can be reduced if the green roof only requires storm water or cultivates low-maintenance plants.

However, the use of storm water under desert climate or areas with strong solar radiation such as Texas, U.S., is impossible to maintain a green roof system because storm water can easily evaporate. For example, the average net-evaporation rate of East Texas in U.S., is approximately 104.14 cm/year even though rainfall ranges from between 66.04 cm/year and 101.60 cm/year [32]. Particularly, 49.51% of annual evaporation happens from June to September so that it is challenging to cultivate plants on the extensive green roof. The popular solution of this problem is to utilize water tank as a storage of stormwater [33]. In 2020, prices of a polyethylene water tank and steel water tank are \$0.40/L and \$0.08/L, respectively [34]. Since the steel water tank only supports for large capacity (greater than 25,000 L), its unit price is smaller than polyethylene water tank. In fact, the water tank is an essential component of a green roof system to prevent shortage of irrigation water. However, due to the space limit and weight regulation of a roof, its size must be restricted. This implies that other water sources have to be considered in addition to stormwater to keep plants alive, particularly in areas with a high evaporation rate.

In a building, there is another popular water source called condensate water given by heating, ventilation, and air conditioning (HVAC). Similar to the stormwater, condensate water is clean, energy-efficient and cost-effective [35]. According to Guz [36], a downtown mall in San Antonio could generate 39.4 L/h, and a central library system could produce 216 L/h. Moreover, a building generally generates 36 L/h. Similarly, the study conducted at Texas A&M University at Qatar showed that 683.93 L/h of condensate water can be generated from one building with 32,500 m^2 [37]. Although this amount may be insufficient to maintain the green roof, it can be used with other water sources such as stormwater, tap water, and grey water [17].

Another critical component is an irrigation system to manage the water supply to a green roof [38]. The irrigation system used for an extensive green roof consists of a reservoir (or a water tank), irrigation pipe, and water supply pump [39]. If the system tends to reuse the water, additional drainage pump and water collecting pipe is required. The most popular pumps in an irrigation system are a horizontal centrifugal pump due to its low price and maintenance cost [40]. However, if we consistently operate the centrifugal pump which is driven by a fully loaded 100 kW motor, it requires 111.07 kWh per hour and costs $11.07/h when average electricity costs 10 cents per kWh and a 90% motor efficiency [40].

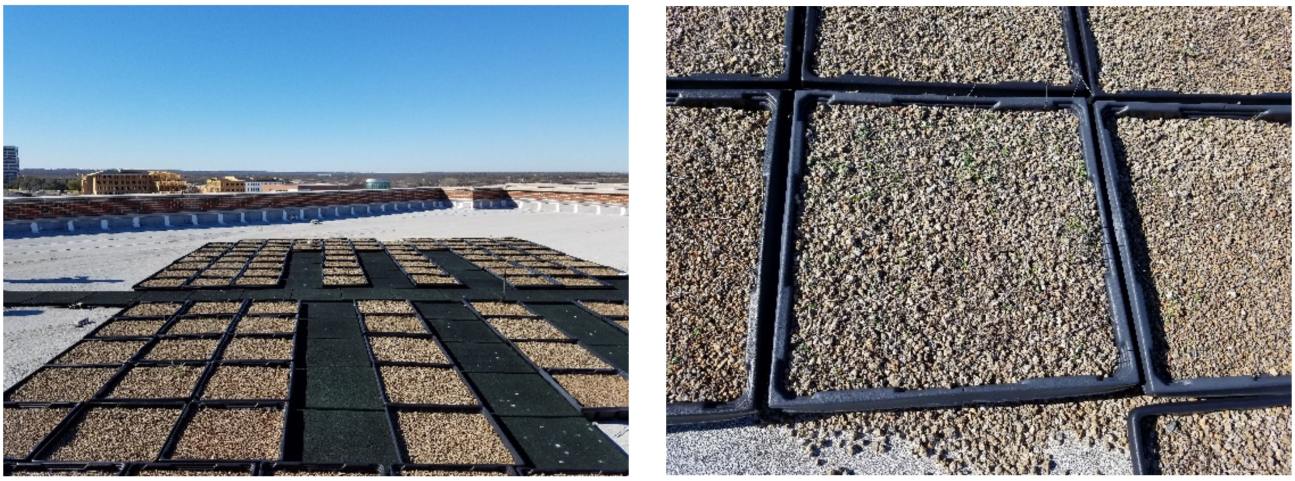
The green roof system requires multiple components, and its implementation cost can vary [16]. Although the extensive green roof is popular due to relatively low investment cost as mentioned in Section 1, its impact on a building surface temperature is still questionable. Thus, we are going to conduct a field study to understand thermal impact of a green roof system on a building surface (see Section 3.1 for more detail). Moreover, to accurately estimate impact of the green roof on energy cost reduction of a building in summer, this study is going to develop a simulation model via ABS (see Section 4). Unlike the existing studies on a green roof, the simulation model will help an engineer evaluate multiple alternatives under various conditions.

3. Simulation-Based Management of a Green Roof System

3.1. Data Collection

In order to understand the impact of a green roof on building surface temperature, we collected temperature data from three different locations: (1) the roof temperature close to the green roof grids, (2) the plant surface temperature on the green roof grids, and (3) the temperature beneath the surface of the green roof grids. The data collection was performed every forty-eight hours from 30 May 2017 to 6 October 2017. The subject extensive open roof was installed on the roof of the Keith D. McFarland Science Building at Texas A&M University, Commerce, Texas (33.2410° N, 95.9104° W) consisting of 2-squre feet (0.18581 m^2) as interlocked grids of soil media. Commerce has 44 inches of rainfall in a year, which is slightly higher than an average rainfall of 39 inches in the United States. Particularly, a total precipitation of 3.15 inches in July, and the average temperature of summer is 102.9 °F (39.39 °C). Tap water was used to maintain the green roof, and the watering interval time is between 12 and 48 h according to daily heat index in East Texas. This study utilizes the data set collected in [17].

Figure 1 shows 86 interlocked pad grids with a soil mixture involving sand, compost, expanded shale and peat. Four plant types named New Gold Lantana (*Lantana x hybrida* 'New Gold'), Purple Trailing Lantana (*Lantana montevidensis*), Hardy Ice Plant (*Delosperma cooperi*), and White Trailing Lantana (*Lantana montevidensis* 'White') were planted on extensive green medium with 4 inches (10.16 cm) in depth. They were planted on the 10 May 2017 (see Figure 2).



(**a**) (**b**)

Figure 1. Extensive green roof system: (**a**) system overview; (**b**) individual grid.

Figure 2. Four species considered in this study: (**a**) New Gold Lantana; (**b**) Purple Trailing Lantana; (**c**) Hardy Ice Plant; (**d**) White Trailing Lantana.

3.2. Results

In the experiment, we tested whether the temperatures under the grids with four species are different or not. Table 1 represents results of two-way ANOVA to test the following null hypotheses:

- The temperatures under the grids planted with New Gold Lantana, Purple Trailing Lantana, Hardy Ice Plant, and White Trailing Lantana are all equal (species effect);
- The temperatures of the roof surface, grid surface, and underneath the grid are equal (surface type effect);
- No interaction between species and surface types.

Table 1. Comparison of temperatures between four species.

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F [1]	*p*-Value	F Crit [2]
Between species	1.55×10^{0}	3.00×10^{0}	5.16×10^{-1}	9.07×10^{-3}	9.99×10^{-1}	2.62×10^{0}
Between surface types	3.59×10^{4}	2.00×10^{0}	1.80×10^{4}	3.16×10^{2}	5.30×10^{-86}	3.02×10^{0}
Interaction	1.79×10^{0}	6.00×10^{0}	2.99×10^{-1}	5.25×10^{-3}	1.00×10^{0}	2.12×10^{0}
Error	2.53×10^{4}	4.44×10^{2}	5.69×10^{1}			
Total	6.12×10^{4}	4.55×10^{2}				

[1] The statistic is given by an F-distribution under the null hypothesis; [2] the critical Type-1 error at α = 0.05.

R^2 of the test was 0.5871. Because the R^2 is close to 60%, we use the results to understand the impact of the subject green roof. Average temperatures under New Gold Lantana, Purple Trailing Lantana, Hardy Ice Plant, and White Trailing Lantana are 36.44 °C (Std.: 5.82 °C), 36.10 °C (Std.: 5.58 °C), 36.18 °C (Std.: 5.88 °C), and 36.10 °C (Std.: 5.40 °C), respectively. Since the *p*-value is greater than a significance level of α = 0.05, we can conclude that there is no difference in temperatures between four species. It implies that any plant type among the four species can be planted on the green roof in future.

In the second hypothesis test, we compare the temperature differences between the grid surface, roof surface, and underneath the grid. In Table 1, the *p*-value is less than a significance level of α = 0.05 so that there is significant difference between the three locations. Average temperatures of the grid surface, roof surface, and underneath the grid are 44.59 °C (Std.: 7.27 °C), 57.77 °C (Std.: 9.18 °C), and 36.21 °C (Std.: 5.59 °C), respectively. In addition, there is no interaction between species and surface types because the *p*-value is greater than a significance level of α = 0.05.

The temperature difference between grid surface and roof surface is 13.17 °C. According to Schindler et al. [41], building surface made of cement concrete absorbs solar radiation so that its temperature is higher than air temperature. In the experiment, average temperature was 33.76 °C. Although the grid also absorbs the solar radiation, shade made by plants can reduce the amount of solar radiation. Moreover, the temperature under the grid is only 36.21 °C which is 21.56 °C less than the roof surface temperature. In other words, about 37.32% of the roof surface temperature can be reduced by the green roof.

4. Simulation-Based Management of a Green Roof System

As mentioned in Section 2, a green roof is one of the most important ways to make an area environmentally friendly. The goal of this study is to develop a simulation model for the management of a green roof system. Figure 3 represents a conceptual model of the proposed green roof system involving two water sources such as HVAC condensate water and tap water. In addition, the electricity is supplied by photovoltaic (PV) solar panels to run an irrigation system. In fact, this approach has been adopted in the agro-photovoltaic (APV) system, which utilizes solar energy for crop production [42]. The role of sensors is to collect real-time temperature and electricity consumption data of a building. As a result, the green roof system is expected to reduce GHG emission and energy use of a building.

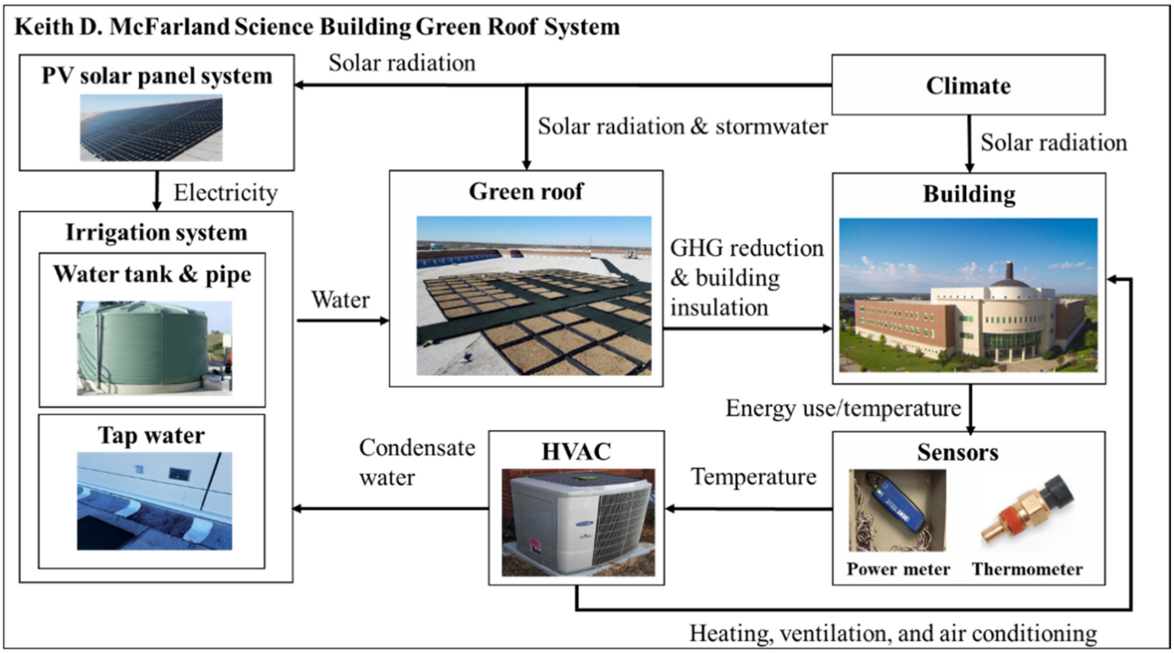


Figure 3. Proposed sustainable green roof system.

In this study, in order to develop the simulation model, the field experiment data mentioned in Section 2 is utilized. Figure 4 reveals an overview of the simulation model of the proposed green roof system. The simulation is developed via AnyLogic® University 8.6.0 simulation software, Chicago, IL, USA. The model has three agents such as solar panel agent, irrigation system agent, and HVAC system agent. These agents have two states in their state charts to mimic the behavior of each system. To be more specific, if there is no need of water, Irrigation system agent is in the idle state. Otherwise, the system is in busy state to water the plants. Similarly, solar panel agent is only in busy state when the solar radiation is available. HVAC system agent consumes electricity when it needs to maintain the indoor temperate in building. While the simulation run, performance measures (e.g., energy consumption, water use, surface temperature, etc.) are computed via numerical models shown in the following sections in detail.

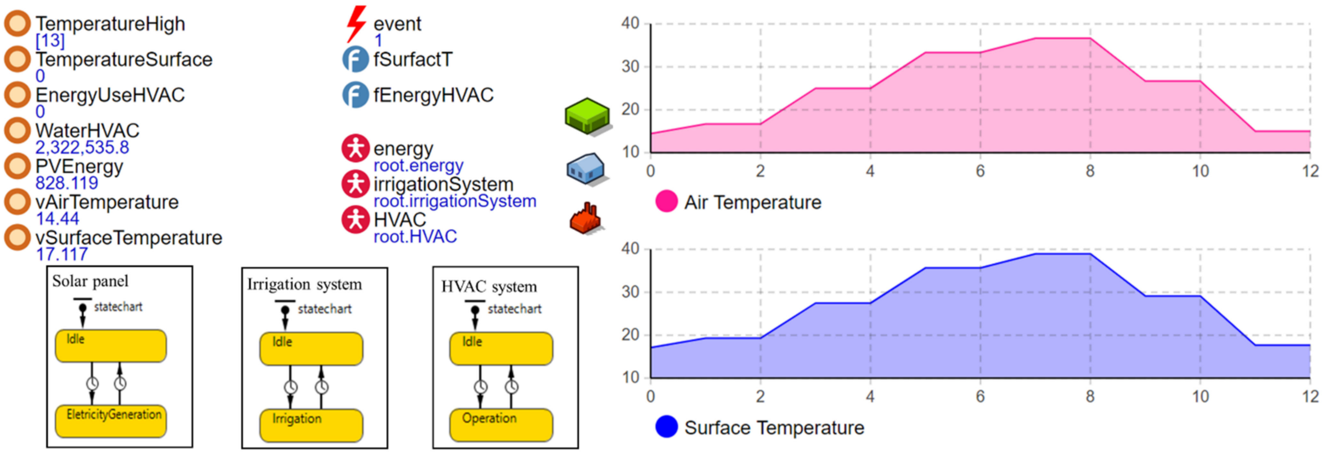


Figure 4. Overview of the proposed simulation model.

4.1. Surface Temperature Estimation Model

Based on the experiment addressed in Section 3.1, a surface temperature estimation model under green roof is developed via regression model.

$$T_{\text{surface}} = 24.5979 + 0.9826T_{air} - 21.67x_1 \quad (1)$$

where T_{surface} is the surface temperature; T_{air} is the atmosphere temperature (or air temperature) in Celsius; and x_1 is presence of a green roof (1: green roof and 0: non-green roof). p-values of five coefficients in the model are 0.0210, 0.0020, and 0.0000, respectively. Thus, we can conclude that these three coefficients are significant at $\alpha = 0.05$. R^2 of the polynomial regression model is 0.7194 so that it can capture 71.94% of variability within the observed data set.

4.2. Energy Consumption Model of a Building

Table 2 represents energy consumption data of the Keith D. McFarland Science Building at the Texas A&M University-Commerce, Commerce, TX. Size of the subject building is 10,169.45 m^2, and its annual energy consumption (i.e., measured consumption) is 2,917,799.83 kWh. In other words, annual energy cost is approximately $291,779.98 when the unit price is $0.1 per kWh. Monthly energy consumption is 243,149.99 kWh in average. The minimum energy use (i.e., 197,482.49 kWh) in April is due to the minimum use of HVAC so that we use it as a reference point to estimate the variable electricity use associated with HVAC. To be more specific, the energy use of 197,482.49 kWh is mainly used to maintain the subject building under 25 °C (i.e., reference indoor temperature), and additional energy use of 59,661.93 kWh in August is required to cool down the building to 25 °C from air temperature of 36.67 °C. Average energy use per meter of the subject building is 263.92 kWh/m^2.

Table 2. Energy consumption data of the subject building in Texas.

Month	Energy Consumption (KWh)	Energy Cost ($)	HVAC (KWh)	Air Temperature High (°C) [1]	Surface Temperature High (°C) [2]
Jan.	338,347.93	33,834.79	140,865.43	14.44	38.79
Feb.	248,121.81	24,812.18	50,639.32	16.67	40.97
Mar.	236,843.55	23,684.35	39,361.06	20.56	44.80
Apr.	197,482.49	19,748.25	0.00	25.00	49.16
May	200,753.10	20,075.31	3270.61	29.44	53.53
Jun.	225,565.28	22,556.53	28,082.79	33.33	57.35
Jul.	248,121.81	24,812.18	50,639.32	35.56	59.53
Aug.	257,144.42	25,714.44	59,661.93	36.67	60.63
Sep.	250,377.47	25,037.75	52,894.97	32.78	56.81
Oct.	230,076.59	23,007.66	32,594.10	26.67	50.80
Nov.	214,287.02	21,428.70	16,804.53	20.56	44.80
Dec.	270,678.34	27,067.83	73,195.85	15.00	39.34

[1] The highest air temperature; [2] the highest surface temperature under the green roof.

Based on the energy consumption data shown in Table 2, Equation (2) is developed via polynomial regression proposed by [43] for the estimation of energy consumption of the subject building.

$$E_{\text{HVAC}} = 6225.9 - 1133.4(T_{air} - T_{\text{reference}}) + 1052.6(T_{air} - T_{\text{reference}})^2 \quad (2)$$

where T_{air} is air temperature, and $T_{\text{reference}}$ is reference indoor temperature. R^2 of Equation (2) is 0.8284 so that it can accurately estimate the energy load of HVAC. Figure 5 reveals non-linear relationship between energy consumption and temperature difference. The temperature difference refers to difference between outdoor temperature and reference indoor temperature of 25 °C.

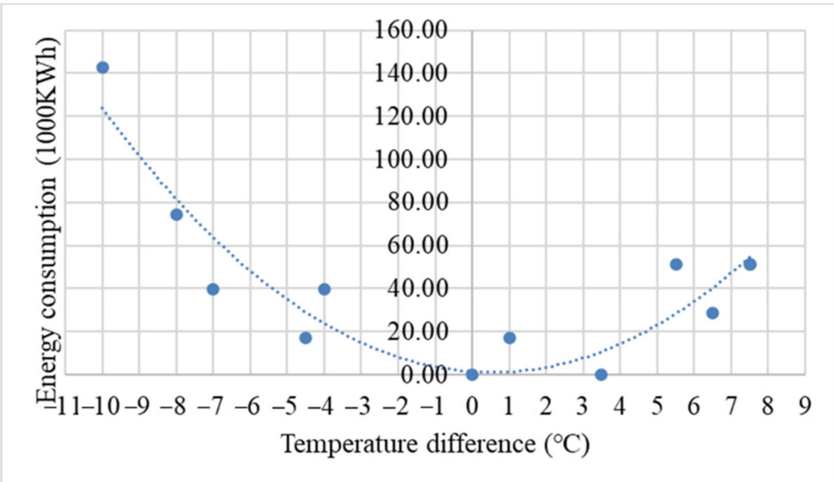


Figure 5. Energy consumption of HVAC under various temperature.

4.3. Irrigation System Model of a Building

The proposed irrigation system utilizes two different water types such as HVAC condensate water and tap water. Utilization of the HVAC condensate to water plant has been considered as one of the best irrigation approaches because the condensate water is clean, energy-efficient, and cost-effective [35]. As mentioned in Section 2, Guz [36] showed that the production rate of condensate water at a building is approximately 0.0244 LMH (Liters per square Meter per Hour) in Texas. Thus, the condensate water quantity can be estimated via Equation (3).

$$W_{\mathrm{HVAC}} = 0.0244 x_2 \tag{3}$$

where W_{HVAC} is production rate of HVAC condensate water (L/h) and x_2 is size of building. Regarding the area of the subject building is 10,169.45 m^2, production rate of the generated condensate water is approximately 248 L/h. Since each extensive green roof grid (i.e., 0.61 m × 0.61 m × 0.11 m) requires 12.28 L/day in summer (30% of the grid volume), the condensate water of 5955.22 L/day can supply about 485 green roof grids (i.e., 13.43 m × 13.43 cm × 0.11 m). Although this number of grids can only cover 7.3% of a roof with 2471.87 m^2, it can be used with the stormwater. Monthly precipitation of the subject area is between 0.0478 m and 0.1402 m, and its average is 0.0948 m. In other words, daily precipitation is 0.0032 m in average. This amount (7909.98 L/day) is 9.70% of the required water amount (81,576.36 L/day) of the subject extensive green roof. 83% of the required water amount should be filled by tap water. Regarding that, the tap water cost is $1.72 per 1000 L in Commerce, TX [44], the water cost is approximately $166.62 per month.

4.4. PV Solar Panel Model

The PV solar panel is needed to run the proposed green roof system involving the irrigation system addressed in Section 4.3. Regarding that the green roof grids with plants could run without electricity (see Section 3.1), the irrigation system is the major component consumes electricity. If the irrigation system uses 100 kW centrifugal pump two times for 10 min each in a day, it requires 37.02 kWh. This implies that the monthly consumption of the system can be approximately 1110.7 kWh, and annual consumption is 4442.8 kWh. Note that the condensate water is only generated from June to September. According to the study conducted in Texas [45], the PV solar panel system consisting of 20 panels (7.38 m × 4.25 m) can annually generate 60,994 kWh. Its initial investment cost involving modules, inverter, pipe, foundation, material, and labor is $145,357. Based on this information, we can develop a simple energy generation model of the PV solar panel as follows.

$$E_{solar} = 0.3481 x_4 \tag{4}$$

where x_4 is the number of PV panels; and E_{solar} is generated energy by solar panel for an hour (kWh). Equation (4) gives that the required PV solar panel system should have two panels with annual capacity of 6099.4 kWh. The estimated investment cost is $14,535.7, and required space is 3.3 m by 0.95 m. The return on investment (ROI) is approximately 41 years with an interest rate of 1% when the price of 1 kWh is $0.1. Although this has low profitability, this cleaner energy source meets the goal of green roof system which tends to make an urban area eco-friendly. Note that the scope of this study is about a green roof system operating with solar energy (i.e., not a green building which can be fully operated by solar energy). Thus, we assume that there is an external power source for the building maintenance (e.g., HVAC).

4.5. Simulation Results

The developed simulation model is used to understand the impact of the proposed green roof system. The air temperature data shown in Table 2 is used as input data in the simulation model so that Equations (1) and (2) in the simulation model enables to compute surface temperature of the subject building and energy consumption of the HAVC, respectively. Table 3 shows the performance of green roof and non-green roof. Average surface temperature of the subject building in green roof and non-green roof cases is 28.04 °C and 49.71 °C, respectively. The temperature difference between the surface temperature and indoor temperature (25 °C) is 3.04 °C under the green roof and 24.71 °C under the non-green roof. The temperature gap causes electricity use of HVAC so that HVAC in the green roof scenario annually uses 85,091.21 kWh, the HVAC of the non-green roof scenario annually uses 825,416.65 kWh. The green roof scenario can reduce 89.69% of energy use of HVAC in the non-green roof. If we consider the annual energy consumption for maintenance of the subject building (i.e., 2,917,799.83 kWh), the green roof can contribute to reduce 25.37% of the annual energy consumption. In other words, the energy saving cost is $74,032.54. Particularly, in summer (from June to September), 36,649.17 kWh of energy use can be saved from 378,780.61 kWh. Estimated saving cost in summer is $37,878,06.

Table 3. Performance comparison of a green roof.

Category	Air Temperature High (°C) [1]	Green Roof		Non-Green Roof	
		Surface Temperature High (°C) [2]	Energy Consumption (kWh) [3]	Surface Temperature High (°C) [2]	Energy Consumption (kWh) [3]
Jan.	14.44	17.12	14,914.69	38.79	135,470.00
Feb.	16.67	19.81	9647.28	40.97	88,768.12
Mar.	20.56	23.13	3403.96	44.80	32,055.33
Apr.	25.00	27.50	643.31	49.16	6225.90
May	29.44	31.86	2207.90	53.53	21,980.67
Jun.	33.33	35.68	6841.89	57.35	69,878.12
Jul.	35.56	37.87	10,759.00	59.53	111,542.67
Aug.	36.67	38.96	13,045.03	60.63	136,273.46
Sep.	32.78	35.14	6003.25	56.81	61,086.37
Oct.	26.67	29.13	742.42	50.80	7260.79
Nov.	20.56	23.13	3403.96	44.80	32,055.33
Dec.	15.00	17.67	13,478.53	39.34	122,819.90

[1] The highest air temperature; [2] the highest air temperature estimated by Equation (1); [3] the energy consumption of HVAC estimated by Equation (2).

Table 4 reveals cost estimate of the green roof system. The initial investment on a roof (2378.97 m^2) of the subject building requires $444,766.31 with 6394 extensive green roof grids. In other words, the installation cost of $186.96/$m^2$ is in the range from $107.64/$m^2$ to $215.28/$m^2$ suggested by [31]. As mentioned in Section 3, the PV solar panel system and irrigation system requires $145,357 (31.54%) and $ 10,242.81 (2.22%), respectively. 66.24% of the initial investment cost is used to purchase plants, green roof grid, and planting medium.

As mentioned earlier, energy savings of HAVC is approximately $74,032.54 per year. Regarding the maintenance cost (e.g., fertilizer, soil, and plant replacement and water bill) of a green roof is from $8.07/$m^2$ to $16.15/$m^2$ [31], the maintenance cost can be approximately from $19,198.29 to $38,420.37. Under the annual profit range from $35,612.17 to $54,834.25, the return on investment (ROI) at an interest rate of 0.01 is between 9 to 14 years. In addition, the green roof system can contribute to the elimination of GHG emission. According to Othman and Kasim [46], carbon sequestration rate (CSR) with 300 Lantana plants is 0.03 per tCO_2e. CSR of the subject green roof system is approximately 2.56 per tCO_2e because it has 25,576 plants. Regarding that a general building annually generates 1.60 t CO_2e/m^2 [47], the subject green roof can remove 4.10 t CO2e/m^2. As a result, the green roof can annually remove 9,744.26 t CO2e. Regarding that, the U.S. is planning to impose GHG emission tax (i.e., $25 per t CO2e) [48], the subject green roof system can save $ 243,606.5. In this situation, the ROI can be up to 2 years.

Table 4. Cost analysis of the green roof system.

Category	Item	Quantity	Unit Cost ($)	Cost ($)
Green roof	Extensive grid (grid) [1]	6394	5	31,970.00
	Planting medium (ton) [2]	261.73	68	17,797.49
	New Gold Lantana (plant) [3]	6394	9.99	63,876.06
	Purple Trailing Lantana (plant) [3]	6394	9.99	63,876.06
	Hardy Ice (plant) [3]	6394	9.99	63,876.06
	White Trailing Lantana (plant) [3]	6394	9.99	63,876.06
Irrigation	HVAC irrigation system (m^2) [4]	2378.97	4.31	10,242.81
	PV solar panel system (m^2) [5]	2378.97	61.10	145,357

[1] Size of an extensive grid is 0.61 m × 0.61 m × 0.11 m; [2] composition (volume): 1/3 coarse horticultural vermiculite, 1/3 peat moss, and 1/3 blended compost; [3] four plants are needed for each extensive grid; [4] detail information is addressed in Section 4.3; [5] detail information is addressed in Section 4.4.

5. Conclusions

The goal of this study is to propose a modeling and simulation approach for a green roof system which can reduce energy cost of a building exposed to high temperatures throughout the summer season. The study consists of two parts: (1) the field-based study to understand thermal impact of a green roof system on a building surface in Commerce, Texas, U.S. and (2) the simulation study with agent-based simulation developed via AnyLogic® University 8.6.0 simulation software to accurately estimate the energy cost and monetary benefits of the green roof system. An extensive green roof system with four plants (i.e., New Gold Lantana, Purple Trailing Lantana, Hardy Ice Plant, and White Trailing Lantana) were used in the study. Thermal impact of the green roof system on surface temperature of a building was evaluated under the four different plants. The results from the field experiment showed that plant types were not the significant factor to reduce the temperature, but presence of the green roof can significantly reduce the surface temperature. In average, surface temperature of non-green roof building and green roof building is 57.77 °C and 36.21 °C, respectively. Based on the collected field data and literatures, estimation models of surface temperature, energy consumption, and water use involving HVAC condensate water are developed in the proposed simulation. The proposed approach was applied to estimate energy reduction cost of the Keith D. McFarland Science Building at Texas A&M University, Commerce, Texas (33.2410° N, 95.9104° W). The subject building with a roof area of 2378.97 m^2 requires 6394 green roof grids with the installation cost of $444,766.31. Energy savings of the subject green roof is approximately $74,032.54 per year, and it can annually save the GHG emission tax of $243,606.5 when the emission tax rate of $25 per tCO2e. ROI of the subject green roof system can be up to 2 years in this situation. As a result, the proposed green roof system is cost-effective, and simulation-based study showed how to estimate potential cost and benefits of a green roof. The proposed approach will contribute to implementation of a sustainable building and urban agriculture.

Although the proposed approach successfully showed the performance of the green roof system, further studies are needed. First of all, the impact of other green roof types (i.e., an intensive green roof) on building temperature should be also analyzed for the reliable investment on a green roof system. In addition, for the estimation accuracy of the proposed simulation model, investment and maintenance costs of buildings with various types of HVACs should be considered in future.

Author Contributions: Conceptualization, S.K. (Sojung Kim), B.A.; methodology, S.K. (Sojung Kim), S.K. (Sumin Kim), B.A.; software, S.K. (Sojung Kim); validation, S.K. (Sojung Kim), S.K. (Sumin Kim); resources, S.K. (Sojung Kim), B.A.; writing—original draft preparation, S.K. (Sojung Kim), S.K. (Sumin Kim), B.A.; writing—review and editing, S.K. (Sojung Kim), S.K. (Sumin Kim), B.A.; visualization, S.K. (Sojung Kim), S.K. (Sumin Kim); project administration, S.K. (Sojung Kim); funding acquisition, S.K. (Sumin Kim). All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2021R1F1A1045855).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Niachou, A.; Papakonstantinou, K.; Santamouris, M.; Tsangrassoulis, A.; Mihalakakou, G. Analysis of the green roof thermal properties and investigation of its energy performance. *Energy Build.* **2001**, *33*, 719–729. [CrossRef]
2. Szlivka, D.F.; Rajnai, Z. Examination of Temperature Change of Green Roof and Flat Roof in Frequency Range. *Ann. Fac. Eng. Hunedoara* **2016**, *14*, 221.
3. Dimitrijevic, D.; Tomic, M.; Zivkovic, P.; Stojiljkovic, M.; Dobrnjac, M. Thermal characteristics and potential for retrofit by using green vegetated roofs. *Ann. Fac. Eng. Hunedoara* **2016**, *14*, 41.
4. Park, G.; Hawkins, T.W. An Examination of the Effect of Building Compactness and Green Roofs on Indoor Temperature through the Use of Physical Models. *Geogr. Bull.* **2015**, *56*, 93–101.
5. He, Y.; Lin, E.S.; Tan, C.L.; Tan, P.Y.; Wong, N.H. Quantitative evaluation of plant evapotranspiration effect for green roof in tropical area: A case study in Singapore. *Energy Build.* **2021**, *241*, 110973. [CrossRef]
6. Chagolla-Aranda, M.A.; Simá, E.; Xamán, J.; Álvarez, G.; Hernández-Pérez, I.; Téllez-Velázquez, E. Effect of irrigation on the experimental thermal performance of a green roof in a semi-warm climate in Mexico. *Energy Build.* **2017**, *154*, 232–243. [CrossRef]
7. Schade, J.; Lidelöw, S.; Lönnqvist, J. The thermal performance of a green roof on a highly insulated building in a sub-arctic climate. *Energy Build.* **2021**, *241*, 110961. [CrossRef]
8. VanWoert, N.D.; Rowe, D.B.; Andresen, J.A.; Rugh, C.L.; Fernandez, R.T.; Xiao, L. Green roof stormwater retention: Effects of roof surface, slope, and media depth. *J. Environ. Qual.* **2005**, *34*, 1036–1044. [CrossRef]
9. Mentens, J.; Raes, D.; Hermy, M. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landsc. Urban Plan.* **2006**, *77*, 217–226. [CrossRef]
10. Cavanaugh, L.M. Redefining the green roof. *J. Archit. Eng.* **2008**, *14*, 4–6. [CrossRef]
11. Ellingwood, B.R.; Culver, C.G. Analysis of live loads in office buildings. *J. Struct. Div.* **1977**, *103*, 1551–1560. [CrossRef]
12. Luckett, K. *Green Roof Construction and Maintenance*; McGraw-Hill Education: New York, NY, USA, 2009.
13. Liu, K.; Minor, J. Performance evaluation of an extensive green roof. In Proceedings of the Green Rooftops for Sustainable Communities, Washington, DC, USA, 4–6 May 2005; pp. 1–11.
14. Speak, A.F.; Rothwell, J.J.; Lindley, S.J.; Smith, C.L. Reduction of the urban cooling effects of an intensive green roof due to vegetation damage. *Urban Clim.* **2013**, *3*, 40–55. [CrossRef]
15. He, Y.; Lin, E.S.; Tan, C.L.; Yu, Z.; Tan, P.Y.; Wong, N.H. Model development of Roof Thermal Transfer Value (RTTV) for green roof in tropical area: A case study in Singapore. *Build. Environ.* **2021**, *203*, 108101. [CrossRef]
16. Nurmi, V.; Votsis, A.; Perrels, A.; Lehvävirta, S. Green roof cost-benefit analysis: Special emphasis on scenic benefits. *J. Benefit-Cost Anal.* **2016**, *7*, 488–522. [CrossRef]
17. Aydin, B.; Kim, S.; Harp, D. Designing an Automated Sustainable Green Roof System. In *Proceedings of the IISE Annual Conference, Orlando, FL, USA, 19–22 May 2018*; Institute of Electrical and Electronics Engineers (IISE): Piscataway, NJ, USA, 2018.
18. Ávila-Hernández, A.; Simá, E.; Xamán, J.; Hernández-Pérez, I.; Téllez-Velázquez, E.; Chagolla-Aranda, M.A. Test box experiment and simulations of a green-roof: Thermal and energy performance of a residential building standard for Mexico. *Energy Build.* **2020**, *209*, 109709. [CrossRef]
19. Woltmann, S.; Zarte, M.; Kittel, J.; Pechmann, A. Agent based simulation model of virtual power plants for greener manufacturing. *Procedia CIRP* **2018**, *69*, 377–382. [CrossRef]
20. Delamare, J.; Bitachon, B.; Peng, Z.; Wang, Y.; Haverkort, B.R.; Jongerden, M.R. Development of a smart grid simulation environment. *Electron. Notes Theor. Comput. Sci.* **2015**, *318*, 19–29. [CrossRef]
21. Morvaj, B.; Lugaric, L.; Krajcar, S. Demonstrating smart buildings and smart grid features in a smart energy city. In Proceedings of the 3rd International Youth Conference on Energetics (IYCE), Leiria, Portugal, 7–9 July 2011; pp. 1–8.
22. Kim, S.; Kim, S.; Yoon, C. An Efficient Structure of an Agrophotovoltaic System in a Temperate Climate Region. *Agronomy* **2021**, *11*, 1584. [CrossRef]
23. Department of Economic and Social Affairs Population Dynamic. *World Urbanization Projects 2018*; United Nations: New York, NY, USA, 2018.

24. Yau, K.; Muller, M.P.; Lin, M.; Siddiqui, N.; Neskovic, S.; Shokar, G.; Fattouh, R.; Mutakas, L.; Beaubien-Souligny, W.; Thomas, A.; et al. COVID-19 outbreak in an urban hemodialysis unit. *Am. J. Kidney Dis.* **2020**, *76*, 690–695. [CrossRef] [PubMed]
25. Dhakal, S. GHG emissions from urbanization and opportunities for urban carbon mitigation. *Curr. Opin. Environ. Sustain.* **2010**, *2*, 277–283. [CrossRef]
26. Pearson, L.J.; Pearson, L.; Pearson, C.J. Sustainable urban agriculture: Stocktake and opportunities. *Int. J. Agric. Sustain.* **2010**, *8*, 7–19. [CrossRef]
27. Hui, S.C.; Chan, S.C. Integration of green roof and solar photovoltaic systems. In Proceedings of the Joint Symposium 2011: Integrated Building Design in the New Era of Sustainability, Kowloon, Hong Kong, China, 22 November 2011; pp. 1–12.
28. Shafique, M.; Kim, R.; Rafiq, M. Green roof benefits, opportunities and challenges—A review. *Renew. Sustain. Energy Rev.* **2018**, *90*, 757–773. [CrossRef]
29. Peck, S.W.; Callaghan, C.; Kuhn, M.E.; Bass, B. *Greenbacks from Green Roofs: Forging a New Industry in Canada*; Canada Mortgage & Housing Corporation: Ottawa, ON, Canada, 1999.
30. MacIvor, J.S.; Lundholm, J. Performance evaluation of native plants suited to extensive green roof conditions in a maritime climate. *Ecol. Eng.* **2011**, *37*, 407–417. [CrossRef]
31. HomeAdvisor. Green Roof Cost. 2021. Available online: https://www.homeadvisor.com/cost/roofing/green-roof/#avg (accessed on 1 May 2021).
32. Dixon, R.; Bray, S. Appendix P4 Preliminary Texas Evaporation Trends Report. 2010. Available online: https://gato-docs.its.txstate.edu/jcr:d97dab4e-67fe-45e5-8303-1cf064adcfca/Preliminary_Texas_Evaporation_Trends_Report.pdf (accessed on 5 May 2021).
33. Charalambous, K.; Bruggeman, A.; Eliades, M.; Camera, C.; Vassiliou, L. Stormwater retention and reuse at the residential plot level—Green roof experiment and water balance computations for long-term use in Cyprus. *Water* **2019**, *11*, 1055. [CrossRef]
34. Heritage Water Tanks. The Ultimate Guide to Water Tank Prices. 2021. Available online: https://heritagetanks.com.au/water-tank-prices/ (accessed on 8 May 2021).
35. Algarni, S.; Saleel, C.A.; Mujeebu, M.A. Air-conditioning condensate recovery and applications—Current developments and challenges ahead. *Sustain. Cities Soc.* **2018**, *37*, 263–274. [CrossRef]
36. Guz, K. Condensate water recovery. *ASHRAE J.* **2005**, *47*, 54–56.
37. Bryant, J.A.; Ahmed, T. *Condensate Water Collection for An Institutional Building in Doha, Qatar: An Opportunity for Water Sustainability*; Texas A&M University: College Station, TX, USA, 2008.
38. Van Mechelen, C.; Dutoit, T.; Hermy, M. Adapting green roof irrigation practices for a sustainable future: A review. *Sustain. Cities Soc.* **2015**, *19*, 74–90. [CrossRef]
39. Wang, Y.; Singh, R.P.; Fu, D.; Zhang, J.; Zhou, F. Thermal Study on Extensive Green Roof Integrated Irrigation in Northwestern Arid Regions of China. *Water* **2017**, *9*, 810. [CrossRef]
40. Scherer, T.F. *Irrigation Water Pumps. NDSU Extension Service.* 2017. Available online: https://www.ag.ndsu.edu/publications/crops/irrigation-water-pumps (accessed on 8 May 2021).
41. Schindler, A.K.; Ruiz, J.M.; Rasmussen, R.O.; Chang, G.K.; Wathne, L.G. Concrete pavement temperature prediction and case studies with the FHWA HIPERPAV models. *Cem. Concr. Compos.* **2004**, *26*, 463–471. [CrossRef]
42. Moreda, G.P.; Muñoz-García, M.A.; Alonso-García, M.C.; Hernández-Callejo, L. Techno-Economic Viability of Agro-Photovoltaic Irrigated Arable Lands in the EU-Med Region: A Case-Study in Southwestern Spain. *Agronomy* **2021**, *11*, 593. [CrossRef]
43. Kim, S.; Jeong, J.; Kahara, S.N.; Kiniry, J.R. APEX simulation: Water quality of Sacramento Valley wetlands impacted by waterfowl droppings. *J. Soil Water Conserv.* **2020**, *75*, 713–726. [CrossRef]
44. City of Commerce. Utility Services. 2020. Available online: https://commercetx.org/departments/department-of-finance/152-2/ (accessed on 15 May 2021).
45. Chang, B.; Starcher, K. Evaluation of wind and solar energy investments in Texas. *Renew. Energy* **2019**, *132*, 1348–1359. [CrossRef]
46. Othman, R.; Kasim, S.Z.A. Assessment of plant materials carbon sequestration rate for horizontal and vertical landscape design. *Int. J. Environ. Sci. Dev.* **2016**, *7*, 410. [CrossRef]
47. Yim, S.Y.; Ng, S.T.; Hossain, M.U.; Wong, J.M. Comprehensive evaluation of carbon emissions for the development of high-rise residential building. *Buildings* **2018**, *8*, 147. [CrossRef]
48. Congressional Budget Office. Impose a Tax on Emissions of Greenhous Gases. 2018. Available online: https://www.cbo.gov/budget-options/54821 (accessed on 15 May 2021).