Title
Electrical Energy Storage and Energy Management System for the Sustainable City in Dubai

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Electrical Energy Storage and Energy Management System for the Sustainable City in Dubai

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Prepared for:

Diamond Developers

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1. Executive Summary

This report, prepared for Diamond Developers, details the efforts by collaborative research teams to investigate the electricity consumption patterns and social behaviors of residents at The Sustainable City (TSC) of Dubai, and to design a battery energy storage system for TSC to perform peak shaving, load leveling, and off-grid functionality. Three research groups contributed to the analysis and findings contained within this report: the social study team, the design/engineering team, and the economic/environmental team.

The social study team sought to understand residential energy consumption patterns that would inform the creation of an electric load profile model. A social study was developed through three data collection methods: in-depth household interviews, an online survey, and field observations, all reviewed by the University of California, Davis Institutional Review Board to ensure compliance with UC Davis' ethical research requirements. The team also conducted informal data collection through communication and collaboration with Dr. Meier and Dr. Circella's teams as well as with Diamond Developers during the team's field work efforts in Dubai. The team finalized the survey preparation, data collection, and data analysis. Their report was submitted to the sponsor program in September of 2017.

The design/engineering team considered the results of the social study along with additional documentation from Diamond Developers to develop a residential load profile and peak energy demand of TSC. NREL's System Advisor Model (SAM) program was used to project solar energy generation from currently-installed photovoltaic solar panel systems and modeled battery storage systems of various sizes and configurations. The energy storage requirements for the residential sector were evaluated based on two general scenarios. The first scenario focused on peak shaving and load reduction and includes three sub-simulations. The second scenario focused on making TSC grid-independent microgrid and includes two sub-simulations. The scenarios compared system costs and projected revenue (based on energy savings) for both Lithium-ion and Vanadium flow battery storage systems. These technologies were also compared based on technical and environmental advantages/disadvantages. The design/engineering team finalized their modeling and analysis in October of 2018 and as of December 2018, is in communication with Diamond Developers to finalize the research.

The economic/environmental team developed the methodology and formula for calculating the economic and environmental benefits of energy storage based on various scenarios, including levelized cost of electricity (LCOE) and net present value (NPV) calculations as well as initial lifecycle analyses (LCA). These methodologies were used by the design/engineering team to evaluate each simulation and optimize the design parameters. A holistic analysis of the economic benefits of a battery storage system requires a detailed understanding the of the Dubai electric grid, Dubai Electricity and Water Authority's (DEWA) resource plans (e.g., energy storage, feed-in tariffs, etc.), and DEWA's electricity rate structures (e.g., time-of-use rates) for end-users in Dubai. To understand each of these parameters, the study team interviewed a Director at Navigant Consulting in Dubai, given that company works closely with DEWA on related matters. This team worked closely with the design/engineering team to formulate recommendations for installation and further study (Section 4.6). The economic/environmental team finalized their research in mid-2018 and continued to support the design/engineering team through December 2018.

2. Introduction

Three research groups performed the collaborative research for this project. The UC Davis social study group visited Dubai and conducted interviews with residents and Diamond Development staff. Based on the insights gained from the interview responses, the social and behavioral survey instruments were designed and implemented through an online platform. The output of the survey data was used as an input on the load demand forecast for the technical group. The UC Davis technical group developed the microgrid model and analyzed various grid integration and energy management scenarios. The economic/environmental group, American University of Cairo (AUC), performed the lifecycle analysis and environmental impact of the lithium ion batteries for energy storage.

The simulation is based on data provided by the Diamond Developers and from data acquired based on interview responses with residents at TSC during the social survey. This means that the results of the simulation are specific to TSC. Any suggestions relating to the amount of PV generation and energy storage required for various goals apply directly to TSC. The results will provide DD with the information needed to make decisions regarding the installation of energy storage along with the existing PV generation, and how much energy storage would be needed.

2.1 Project Task flow

The project task flow and teams are shown in the following figures.

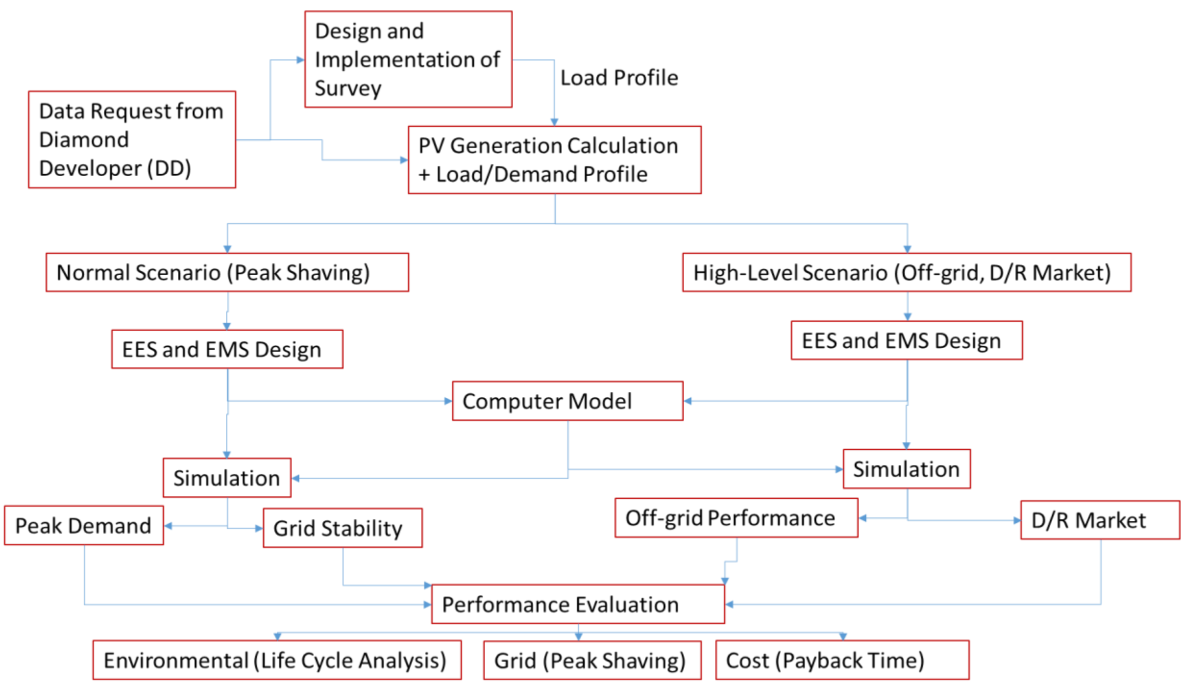

Figure 2-1 The project task flow

The teams that worked on the tasks are shown in the following figure.

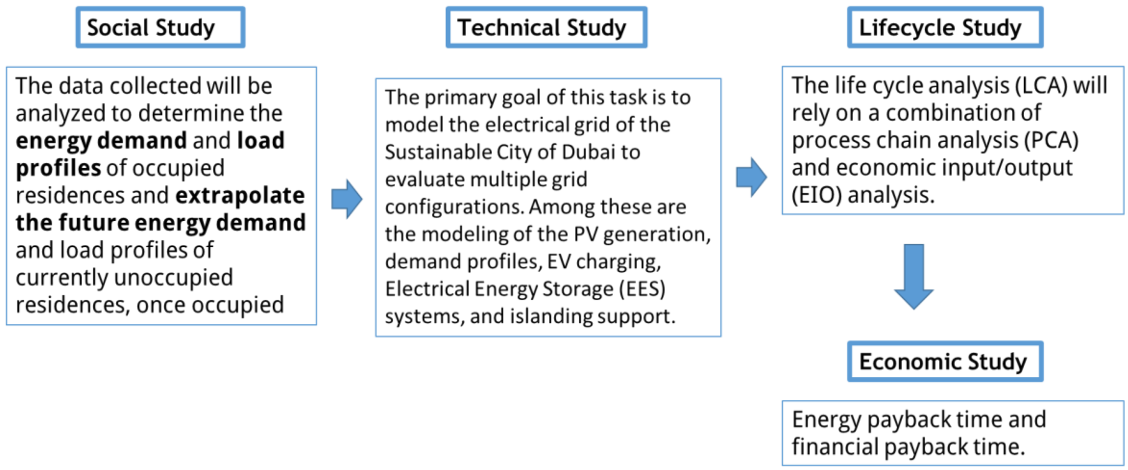

Figure 2-2 The research team collaboration

3. Social Study Team

3.1 Objectives

The objective of the social study was to inform the modeling of The Sustainable City's micro-grid, performed under this contract. In particular, we sought data concerning residential energy consumption patterns to create the electricity load profile model described in Chapter 3. A secondary objective was to develop an understanding of the context in which the energy storage system would operate in order to inform assumptions made in the modeling work.

3.2 Methodology

Three data collection methods were used to develop the social study: in-depth household interviews, an online survey, and field observations. These methods were reviewed by the UC Davis Institutional Review Board to ensure protection of the human subjects and their data in accordance with UC Davis' ethical research requirements. Each method is described in detail below.

Less formal data collection efforts were also conducted. Specifically, Dr. Outcault exchanged information with the research teams led by Dr. Meier and Dr. Circella via email and in-person communications during field work in Dubai and throughout the course of the project. The Meier team in particular, which spent weeks conducting field research and knows the community well, provided valuable insights that informed the social study. Diamond Developers also greatly supported the research by providing important community data (e.g., maps, project plans, and information about residents).

3.2.1 Resident interviews and field observation

Dr. Outcault conducted in-depth, in-person interviews with residents of TSC to explore how residents use energy in their homes. The purpose was twofold: 1) to gather preliminary data to inform the household survey design, and 2) to probe more deeply than would be possible with the subsequent survey.

Interview subjects were recruited through a post on the community portal on TSC's website, and scheduling was handled by the Diamond staff member responsible for resident engagement. Recruitment was conducted in cooperation with the Meier team's interview research, i.e., some participants were referred from one study to the other. No incentive was offered for participation in interviews.

Although the precise number of households at TSC that have live-in domestic staff (i.e., nannies and maids) is not known, it is thought to be significant. The typical duties and habits of domestic staff have an impact on household energy use, therefore the study sought to collect data from domestic staff as well as householders. To respect the privacy of TSC residents, only one key informant was approached - the domestic staff of a Diamond employee who lived in TSC.

An interview protocol was used to ensure thorough but flexible data collection through semi-structured interviews. Interviews were conducted in residents' homes or in a villa provided by TSC, according to each participant's preference. Interviews lasted between 21 and 80 minutes. The interviews were audio recorded using a Livescribe digital recording device, with the permission of the interview subjects, to facilitate accurate data collection. Through the interviews, information was collected on household composition, occupancy, AC use, appliance use, and electric vehicle interest.

Dr. Outcault lodged at TSC during her field visit, affording the opportunity to observe the community and talk informally with residents and Diamond staff. Many field notes were taken to provide context for the interview and survey data.

3.2.1.1 Interview Participants

Twenty-two residents from 17 households were interviewed. These included two residents who are also members of Diamond staff, one domestic staff for a TSC family, and five couples that participated in the interview together. A majority of respondents were female (N=14); 8 were male. Interview participants were diverse in their nationalities. Eleven respondents had European nationalities, 5 were from North America, 2 from Asia, 2 from Africa and 1 from Australia. Notably, none were from the Middle East. Most interview subjects rented their TSC home, and the length of residence in TSC ranged from 2 weeks to 15 months.

3.2.2 Resident survey

A resident survey was implemented to assess the prevalence of various factors that relate to the community's energy storage needs. An online survey was designed to gather data on residents' knowledge, attitudes and practices related to household energy use and electric vehicles. As with the interviews, the research team and Diamond staff agreed that collecting data from domestic staff would be important, so the survey was designed to target both TSC householders and domestic staff.

3.2.2.1 Survey Instrument

In an effort to minimize the burden on survey participants and Diamond staff charged with facilitating implementation, a joint survey was created to gather data for three studies, namely those led by Dr. Park, Dr. Meier, and to a lesser extent, Dr. Circella. Researchers on the Park team led the development of questions on household energy use, home characteristics, and household demographics, and provided advice to the Meier team on their questions on sustainability and community engagement. The

Park team programmed the survey in an online survey software called Qualtrics, and the Meier team aided with survey testing and refinement.

The drawback of combining survey efforts is that it resulted in a rather long survey. Researchers were concerned that a long survey would exacerbate response bias whereby only the more energy- or sustainability-minded residents would be inclined to participate. It was important to gather data from residents with relatively less energy-conservative attitudes and behaviors in order to inform the energy storage modeling, therefore it was important to shorten the survey to no more than 10 minutes. The two teams developed a solution by creating a core survey that was estimated to take 10 minutes to complete, with additional survey modules presented as optional at the end. Respondents were offered an additional incentive if they agreed to complete extra questions.

Topics covered in the core survey for residents included:

- Household characteristics and participant demographics
- Attitudes and behaviors related to household energy use (e.g., lights, laundry), with particular focus on air conditioning
- Knowledge, attitudes, and behaviors related to household water use
- Community engagement

Optional survey modules included questions on knowledge, attitudes, and behaviors related to transportation, waste, food, and landscaping. Domestic staff were presented with a subset of the core questions, excluding several questions related to energy or water bills and metering, and community engagement.

3.2.2.2 Survey Procedure

The survey was deployed from May 28, 2017 to June 20, 2017. Diamond staff conducted survey recruitment, posting a survey invitation message on TSC's community website every other day and on TSC's Facebook page. Householders were asked to complete the online survey on a computer or mobile device. Domestic staff were invited to complete the survey on a computer in the community management office, which was made available from 9am to 3pm Saturday through Thursday for the duration of the data collection period.


Innovation Center (Management)

Subject: Online Survey linked to "Developing a Culture of Sustainability" Research Project

Dear Residents,

Researchers at the University of California at Davis and the American University of Cairo are conducting a study to understand the attitudes, habits and needs for various resources such as energy and water in The Sustainable City. As part of this study, researchers are conducting an online survey with TSC residents and domestic staff. The research is sponsored by Diamond Innovation Center.

The survey will take approximately 10 minutes to complete on a computer or mobile phone. Here's the link: http://bit.ly/TSC_survey

Your input is vitally important to the outcome of the study. To encourage participation, Diamond is offering generous thank you gifts to those who complete the survey.

Residents will be entered into a drawing in which one lucky participant will receive 5 FREE riding classes in The Sustainable City Equestrian Center (valued at AED800 for kids or AED900 for adults), and 10 other winners will each receive a Nol card for RTA services valued at AED 50.

Domestic staff (nannies and maids) can take the survey on a computer made available at the community management office from 9am to 3pm Saturday – Thursday (Cluster 3 Garden Villa 6). Staff will be available to provide help if needed. Domestic staff who complete the survey will receive a AED 50 phone card as a thank you.

We thank you in advance for your participation.

Kind regards,
Diamond Innovation Center

Figure 3-1 Survey invitation on TSC resident portal

The introductory page of the online survey contained language to allow participants to make an informed decision about participating in the survey (e.g., expected time to completion, contact information for the research team, and details about the incentive). To grant consent, they were asked to check a box before proceeding to the first set of questions.

A minimal amount of identifying information (e.g., householder vs. staff, unit address) was requested of survey respondents so researchers could discern when there was more than one respondent in the same household and to facilitate comparisons across characteristics. In the consent language respondents were promised anonymity, i.e., that identifying information would only be accessible to the researchers and not shared. Anonymity was considered particularly important for domestic staff, to assure them their responses would not be shared with their employers.

In order to encourage participation, an incentive was offered for survey completion. Completion of the core survey and the additional modules earned householders entry into a raffle for prizes (one entry for the core survey and another for the additional modules); first prize was 5 free riding classes at TSC Equestrian Center (valued at AED 800-900), and 10 other winners received a Nol card for RTA services (valued at AED 50). The latter was intended to boost ridership on a busline recently extended to TSC. A different incentive scheme was implemented for domestic staff; each staff participant received an AED 50 phone card immediately upon completion of the survey. Diamond Developers selected and distributed the incentives.

3.2.2.3 Survey Participants

One hundred twenty-eight TSC residents answered the first core survey question and 116 answered the last core survey question; total sample size varies because respondents were allowed to skip questions.

Of the 128 respondents, 113 reported their household unit number, and 15 declined to answer. There were multiple respondents from eleven different households, resulting in 98 unique households identified in the data and up to 15 more unique households (corresponding to the 15 participants who did not report their unit number). This represents a participation rate of 27-31% of all TSC households.[1]

A majority of respondents were female (61.5%); 38.5% were male. Their ages ranged from 21 to 61 years, with a mean of 40 years (standard deviation = 7 years). Respondents' nationalities (n = 113) varied widely and included British/Irish/Scottish/UK (8), Filipino (7), Australian (4), French (3), and many more countries represented by one or two respondents; categorized by continent of origin, Europe was by far most common (58%), followed by Asia (22%), Australasia (6%), North America (5%), Middle East/North Africa (4%), and Africa (4%).

Only 14% of the sample reported that their household owns their TSC unit; 70% were renters and 16% were staff. A majority of respondents lived in villas (88%); 11% lived in apartments; and one participant was a renter of a commercial space. Respondents' length of residence in TSC ranged from less than 1 month to 18 months, with a mean of 8 months (standard deviation = 5 months). Length of residence in Dubai ranged from less than 1 year to 24 years, with a mean of 5 years.

3.3 Results

Results are presented as follows. First, we describe interviewee and survey respondents' air conditioning usage patterns, and self-reported household energy practices, including energy curtailment behaviors. We then describe respondents' knowledge and attitudes about energy usage, assessment of home energy technologies, and interest in electric vehicles. Finally, we triangulate these findings to assess the potential for changing household behavior to enable further energy savings.

3.3.1 Household air conditioning practices

Air conditioning accounts for a significant portion of household electricity use at TSC. It also contributes substantially to peak energy demand, as therefore is an important factor in designing an energy storage system.

3.3.1.1 Interviews

The interviews included in-depth discussions of how respondents and their family members use the air conditioners in their homes. There was a range of control strategies. Some had routines, like turning the ACs off in the morning as they head downstairs for breakfast. Others operated it on demand for spot cooling like when, for instance, "somebody gets angry from being too hot".

Some families use ACs to cool the home regardless of current occupancy, while others only use ACs when rooms are occupied. Some respondents routinely turn units off as they leave a room. Others do it only as they leave the house for a portion of the day. Several reported leaving the AC running while away on vacation. In some cases this was to provide cooling for pets, while in others it was due to concerns that excess heat would damage furniture and other contents when summer temperatures soared.

[1] The actual participation rates fall somewhere within this range, depending on how many survey respondents who did not report their unit number lived in the same household.

Reported temperature settings ranged from 20 to 28℃. Some respondents had the habit of adjusting the temperature while others maintained fixed settings. Most respondents reported operating the thermostats manually, although a few had learned how to program them or set timers to anticipate their cooling needs. Many expressed strong preferences related to conditioning their home which impacted their AC use. They mentioned opinions about using fans, opening windows for "fresh air", and temperature, wind speed, and noise from air conditioners.

Although some interview subjects reported retaining their typical AC practices from other regions, others noted that their behavior had adjusted to the local environment and norms. For example, one noted that in Africa they had mostly relied on ceiling fans and used AC only sparingly, but had no fans in their TSC home and found they used AC a lot. To an extent, as this respondent acknowledged, behavior is shaped by the environment. Similarly, several interview subjects noted that the default AC setting of 18℃ in buildings and vehicles in Dubai serves as an anchor, as this quote illustrates:

> *That figure [18℃] stays in your head unless you're consciously thinking about it, and you say, oh, I need to raise it up. [Adjusting the setpoint to save energy is] not really there on your radar all the time.*

Interviews also probed respondents about challenges they face in minimizing AC use. Respondents mentioned a range of factor that influence their AC use:

- Preferences
    - Differences (and conflicts) among family members, as theses quotes illustrate
        - *My husband and I are always quarreling. He wants 26℃ and I want 27℃.*
        - *There's a bit of an inter-family war.*
    - Desire to replicate or escape from home-country climate (*"I like warm, coming from [Europe], but not 50℃"*.)
- Physiological characteristics
    - *"My husband is a large man, a radiator. He just sweats a lot."*
    - Menopause among some women
- Concerns about the health of children (e.g., vulnerability to heat stroke), themselves (e.g., asthma), and/or pets
- Clothing levels
- Activity (e.g., yoga, sleeping, working, cooking)
- Solar heat gain through the windows

Interview respondents were also asked about their willingness to change AC use patterns. This is addressed in a later section.

3.3.1.2 Survey

The household survey was designed to measure the prevalence of several key aspects of AC use that were explored in the interviews. For example, we asked survey respondents how many air conditioning units are typically running in their households on the hottest days of summer, and what the typical temperature setpoints are for different times of day. Seventy-nine percent of households reported typically having at least one AC unit running twenty-four hours a day; 87% of households reported at least one AC unit running in each mornings and afternoons and 96% reported at least one unit running during each evenings and nights; more detailed results are presented in Table 1.

Table 3-1 Number of AC units running on hottest days, per household survey

Time of Day	0 units	1 unit	2 units	3 units	4 units	5 units
Morning (6am-12pm)	13%	37%	33%	9%	6%	4%
Afternoon (12-5pm)	13%	40%	30%	4%	5%	6%
Evening (5-10pm)	4%	30%	31%	15%	10%	11%
Night (10pm-6am)	4%	27%	28%	30%	5%	5%

Temperature setpoints were reported by 49 respondents. This lower sample size compared to the overall survey sample size was due to two factors: (1) there was an error in survey programming such that the early participants were not asked to input temperature setpoint values, and (2) yet other participants chose to skip those questions.

The survey asked about temperature setpoints ranging from 18 to 28℃. The median and mode value for each time of day was 24℃. Mean setpoint at night was the lowest [*M(SD)* = 23.60℃(2.53)], followed by evenings [*M(SD)* = 23.87℃(2.16)], then mornings [*M(SD)* = 23.93℃(2.31)], and afternoons [*M(SD)* = 24.22℃(1.72)].

Figure 1 shows the distribution of temperatures throughout the day. In general, more households maintain lower temperatures at night (10pm-6am). Setpoints during the afternoon (12-5pm) were the most clustered around the median, with fewer extreme temperatures.

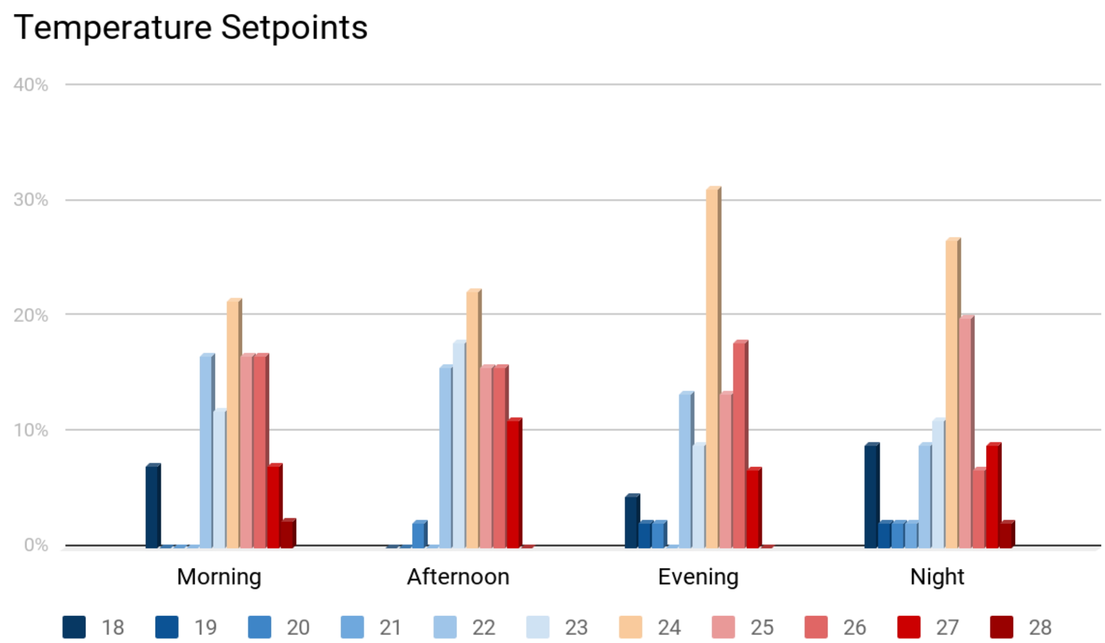

Figure 3-2 Percent of households that maintain a given setpoint, by time of day

Sixty-nine percent of respondents who reported temperature setpoints gave different setpoints for different times of day. For these respondents, the range in setpoints varied from 1 to 7℃, with a mean of 2.4℃ (standard deviation = 1.8). Forty-five percent reported at least one setpoint below 24℃ and of those, 69% also reported a setpoint of 24℃ or higher.

Based on comments from interview participants we wanted to test whether there were significant differences in temperature setpoints across cultural groups. There were only enough Europeans and Asians in the sample to run comparisons between those groups, and temperature setpoints were not significantly different for any time of day.

Temperature setpoints did not differ significantly between villa versus apartment dwellers, nor between owners and renters. Setpoints did not correlate significantly with length of residence at TSC, but they did correlate negatively with length of residence in Dubai; that is, the longer survey respondents had lived in Dubai the lower their morning and afternoon thermostat setpoints, on average (morning: r = -.44, p = .004; afternoon r = -.42, p = .004). Length of residence in Dubai explained 19% of the variance in morning setpoints and 18% of the variance in afternoon setpoints. This suggests that over time, individuals who move to Dubai from other nations gradually adopt lower setpoints. Anecdotally, lower setpoints are the norm in Dubai, so this may suggest adaptation to local practices.

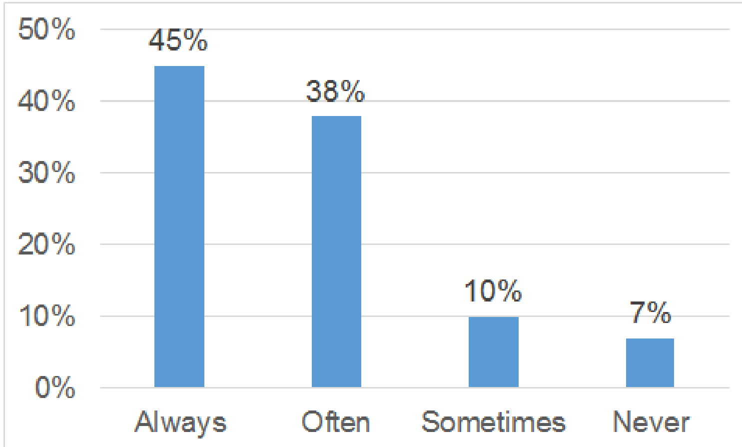

Figure 3-3 Percent of respondents who shut off AC when leaving a room

3.3.2 Household energy practices

In both the interviews and household survey, we also asked about other energy-related behaviors (e.g., use of electric dryers and heaters, turning off lights when leaving a room) to estimate the prevalence of energy-conserving habits.

3.3.2.1 Interviews

Interview subjects were asked about using clothes dryers. Only one subject reported doing so, the rest noted that with the heat in Dubai, clothing dried quickly when hung, and using a dryer would be a waste of energy.

The interview also covered questions related to cooking (e.g., use of the cooktop, oven, range hood). Although according to the interviews dinner preparation in many households corresponds with the estimated system peak, respondents reported little willingness to modify their cooking behaviors. For this reason, these questions were excluded from the subsequent household survey.

Dishwasher use was very common among interview subjects. Most used the dishwasher numerous times per week, mostly in the evening. The majority said they would be willing to shift the time they use the dishwasher to outside of the peak time. Several noted that this would be easy and convenient to do if the dishwashers had timers (and did not make a loud noise when the cycle finished). We noted that some dishwashers installed had a timer and others did not.

Respondents noted several miscellaneous appliances in their households that may have notable electricity consumption. These include the heater in the maid's room, an extra fridge, an electric cooker, and an additional dryer. However, these were owned and/or used by very few households, so we did not include questions about extra household appliances in the household survey.

3.3.2.2 Survey

In the survey, we focused on energy curtailment behaviors. A majority of respondents reported 'always' turning off the lights when leaving a room and running loads in clothes washers and dishwashers only when full. About one-third reported taking relatively short showers. Detailed results presented in Table 2.

Table 3-2Frequency of energy-curtailment behaviors, per household survey

	Always	**Often**	**Some-times**	**Never**	**N/A**
Turn off lights when leaving room	65%	29%	4%	2%	--
Run dishwasher only when full	68%	13%	4%	4%	11%
Run clothes washer only when full	72%	17%	6%	4%	1%
Take short (~5 min) showers	34%	40%	20%	7%	--

There was a positive correlation between the frequency of several of these energy-saving behaviors and thermostat setpoints, meaning people who engage in such activities have, on average, higher setpoints. Specifically, afternoon setpoints correlated positively with turning the lights off when leaving a room (r = .36, p = .016) and running full dishwasher loads (r = .35, p = .026); and evening setpoints correlated positively with checking one's energy meter (r = .39, p = .039). One interpretation of the fact that there were no significant correlations between energy curtailment behaviors and setpoints during the morning and nighttime is that residents may be less amenable to changing their setpoints during those periods.

Only 11% of survey respondents reported that electric heaters are used in their household during the winter. As in the interviews, electric dryer use was relatively rare; only 11% reported that their household's laundry is typically dried in an electric dryer.

Survey respondents were also asked whether they check their energy meters to monitor consumption. Forty percent reported checking their energy meter; of these, only 7% (or 2.8% of all respondents) reported checking it at least once per week.

Interview and survey respondents volunteered other activities they undertake to save energy. Actions specifically related to AC use included closing curtains/shades to reduce heat gain, using fans (floor or ceiling) to reduce sensible temperature, closing bedroom doors at night to contain cold air, and leaving AC units on auto rather than adjusting the setpoints up and down. Other energy-saving measured included turning off electric backup water heaters during the summer, using solar chargers for phone charging, not using electric buggies, unplugging kitchen appliances when not in use, rewearing clothes, limiting washing to one load per week, boiling only as much water as needed, boiling water from kettle instead of cold tap, only running dishwasher and washing machine during the day, and installing an instant hot water heater and "table dishwasher".

3.3.3 Knowledge, attitudes and motivations related to energy use

Interviews were particularly useful to understand residents' level of knowledge about energy use at TSC, as well as their attitudes and motivations related to energy use and conservation. The survey also included several questions about energy attitudes and motivations.

3.3.3.1 Knowledge

There appeared to be a wide range in general knowledge regarding energy and sustainability among interviewees. Some interviewees expressed embarrassment over their ignorance about sustainability, energy, and related topics, while others had a sophisticated understanding of solar generation and household energy consumption, among other things. Several residents expressed their sense that TSC residents in general were quite energy-savvy.

Since TSC is a unique community and residents have diverse backgrounds, many residents do not have prior experience that fully prepares them to manage their homes. For example, very few had lived in a solar-powered home before. Some interviewees reported that they had never previously lived in a home with AC. Several interviewees and one survey respondent expressed that they are looking for guidance on how to use their thermostats (e.g., programming, temperature setting, fan speed). One particular question that emerged numerous times is whether it's more sustainable to turn the AC on and off or maintain a single temperature, either while home or when leaving the house for a period. Several expressed interest in receiving advice from Diamond Developers on this question.

3.3.3.2 Attitudes and motivations

The interviews included some discussion of attitudes and motivations related to household energy use. Some respondents made reference to trying to avoid wasting energy, while others made comments that suggested frugality or environmental consciousness, as the following quote illustrates.

> *We've been conscious of these growing 'carbon boots' when living here in Dubai, and we're probably now living in a more environmentally sustainable/conservative way than many people in the world because of this development. Don't feel like such a hypocrite anymore.*

However, with respect to AC in particular, comfort was an important behavioral driver. Some respondents specifically noted their desire to be comfortable, without consideration of the energy costs:

> *If it's hot-hot, I would turn [the AC] down. There's no point to live like this.*

The survey also included questions about attitudes and motivations related to energy use. Specifically, the survey gauged respondents' moral and financial motivations for energy conservation (see Table 3). In general, respondents conveyed relatively high moral and financial motivation to conserve.

Table 3-3 Energy attitudes, per household survey

		Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I feel morally obligated to use	Householders	3%	1%	4%	33%	59%

energy efficiently	Staff	10%	10%	0%	15%	65%
I try to minimize energy use to decrease the household energy bill	Householders	2%	0%	3%	33%	62%
	Staff	14%	0%	5%	5%	76%

We were curious to explore relationships between these attitudes and reported behaviors. There was no correlation between the responses to these attitudinal questions and thermostat setpoints. This is likely due to the fact that so few respondents disagreed with the statements (a ceiling effect), making it difficult to detect any significant patterns.

Open-ended survey responses and interview data yielded richer insights into the interactions among reported behaviors and financial, environmental and social motivations for saving energy. For example, although 82% of residents who responded to the survey think their electric bill is lower than it would be elsewhere in Dubai, some doubted whether the solar generation is actually lowering their bills. At the extreme, several households reportedly noticed no appreciable difference in their electricity bill before and after their solar panels were connected. Even in the absence of such extreme problems, solar panels can weaken the motivation to conserve energy. One survey respondent noted:

> *I think having solar panels [makes me] slightly less conservative about my power use than before.*

On a related note, many residents do not trust their electricity bills. Some households reported having higher use months (e.g., when family members visited), and lower use months (e.g., when they tried to conserve energy), but detecting no difference on their bill. The research team validated residents' skepticism when we observed an arithmetic error on an interviewee's energy bill. However, although residents want fair billing, many are resigned to the lack of transparency, as this quote illustrates:

> *There's so little faith in DEWA [energy utility], that you just think there's no point finding out [what the problem is].*

Interviewees also attributed their energy-related attitudes (and behaviors) to cultural norms and values associated with one's nationality. Some Europeans proudly described importing their sustainable practices to Dubai, and perceived the attitudes and practices of local residents and workers of TSC to be less oriented toward sustainability. For example, a few interviewees claimed that Middle Eastern residents, Diamond's "office boys", and construction workers at TSC set thermostats to 18℃. Several respondents expressed a resignation to the local norm that borders on fatalism, as in this quote:

> *If I were in Europe, I would think the environment [would motivate me to conserve energy], but here, I would be the only one to do it in Dubai.*

Finally, several residents remarked that their motivation and ability to adopt and maintain sustainable practices (related to energy, water and waste) are influenced by Diamond Developers itself, through the activities of commercial entities and workers operating within, and under contract with, TSC. Residents noted irresponsible watering practices by the gardening crew, copious use of plastic bags by the checkers at Zoom, and use of conventional (instead of environmentally friendly) building materials. Residents who noted these examples reflected that it undercuts their motivation and ability o adopt and maintain sustainable practices.

3.3.4 Assessment of household appliances

During the interview and survey, numerous respondents volunteered comments about the performance of the air conditioning system and water heater. These are summarized here.

3.3.4.1 AC Performance

In the course of interviewing subjects, AC performance came up numerous times. Some respondents suspected there were problems with the AC equipment, installation and/or controls. The interviewer observed, and heard reports of, thermostat readings that are clearly wrong; for example, 27-28℃ felt freezing to some residents. Some attributed this to the AC being "too good". It gets very cold, but is not consistent, as illustrated by this interviewee quote:

> *There's never a happy medium. The temperature's always up, down, up, down.*

To address this, some families reported switching the AC on and off, since maintaining a consistent temperature tends to overcool the space. Others complained of the fan speed or noise.

3.3.4.2 Water heating

Both the interviews and surveys collected data on water heating. Several interviewees reported it taking up to 4 minutes to get hot water to the kitchen. Others reported hot water temperatures that far exceed their needs (and which result in high electricity bills). The research team wondered if the heat pump might be coming on too early in some cases and too late in others, relative to the solar water heaters. Some respondents were not aware that TSC provided solar water heating.

Additionally, several survey respondents expressed the need for more efficient hot water heaters to save water and energy.

> *We do believe that the water that is run waiting for hot water is a major downside to the villa. We would not be able to store all of the water that is wasted and feel a better solution is needed.*
>
> *They should seriously consider putting in a pump for the hot water so you don't waste so much water waiting for it to get hot.*

3.3.5 Electric vehicles

Several interview questions elicited information from subjects about electric vehicle use and interest. These data were collected to inform the energy storage modeling and sustainability study, and to share with the UCD research team led by Dr. Circella looking at transportation in TSC.

According to the resident interviews, there is:

- Some limited interest in electric vehicles if free charging were available at TSC;
- Limited knowledge of how charging works among some residents; and
- Many barriers to adoption.

Interview respondents noted the following barriers to adoption:

- High cost of vehicles
- Lack of desirable vehicles: There are reportedly only small vehicles available, which respondents considered unsafe. Some respondents preferred larger vehicles more resembling a "tank". In some cases this was related to Dubai's "chaotic" roads, and in other the winds and sand were cited as hazards.
- Limited availability of *any* electric vehicles: A few respondents who had looked had trouble finding any for sale
- Concerns about availability of service and parts for repairs
- Need for long range batteries required for long commutes (to Abu Dhabi, for example)
- Concerns about parking in the city if designated charging points were not adequately enforced
- Concerns about the ability to resell after purchase: Vehicles can be difficult to sell and ex-patriots face uncertainty about how long they will be in Dubai, making electric vehicles a risky purchase

Results from the transportation module of the household survey will be presented in the report submitted by Dr. Meier's team.

3.3.6 Scope for increasing energy savings

Results from the interviews and survey suggest there is potential for saving energy through behavior change among TSC residents, particularly with regard to AC usage. To support the energy storage modeling effort, we estimated the proportion of households that might be willing to raise their AC setpoints by 1 degree. In the interviews, we asked this directly, and 13 out of 17 households expressed a willingness to turn up the thermostat 1 degree. Of the few who were unwilling to increase their setpoint, several already maintained relatively high temperatures (i.e., 26-28℃), and another had health problems that were triggered by high temperatures. Given that individuals willing to grant an interview on energy use are likely to be among the more energy-conscious in the community, we expect that a smaller portion of the community as a whole would agree to adjust their setpoints to save energy.

We employed a different method to estimate behavioral plasticity from the survey data. Specifically, we developed a predictive model for estimating the proportion of survey respondents that might be induced to raise their typical thermostat setpoints by 1℃ by leveraging data on reported setpoints and correlated energy conservation behaviors. The model proceeds as follows.

We first excluded survey participants who reported conservative setpoints, defined setpoints at the 75th percentile or higher for each time of day. The 75th percentile was 26℃ for morning, afternoon, and evening, and 25℃ for nighttime. We assume no potential for change in these households, as they are already at the upper end of the setpoint range. Eight of the forty-nine participants who reported at least one setpoint value were excluded based on these criteria.

We then applied the following inclusion criteria to the remaining 41 households. We considered respondents likely to be amenable to raising temperature setpoints by 1℃ if they met any of one of these conditions

- Reported different setpoints for different times of day, indicating some flexibility or dynamism in preference or tolerance
- Comment in open-ended responses implied lack of efficacy using the thermostat, indicating potential to save via knowledge gains (i.e., instructions on how to use the system)
- Reported "Always" turning off lights when leaving a room, a curtailment behavior that was correlated with higher setpoints
- Reported "Always" running the dishwasher only when full, a curtailment behavior that was correlated with higher setpoints
- Reported checking their energy meter (with any frequency), as this behavior was correlated with higher setpoints

Applying these criteria resulted in a predicted 49% of TSC households that might be persuaded to increase their temperature setpoint by 1℃. The means and standard deviations of setpoints for this group at various times of day are as follows: Morning: 23.95℃ (2.20); Afternoon: 23.90℃ (1.61); Evening: 23.62℃ (2.09); Night: 23.48℃ (2.50).

To use this estimate in the energy storage model, it is important to understand the extent to which this finding is generalizable to the entire population of TSC residents. While we do not have data on those that did not participate in the survey, we do have data from the first wave of respondents who participated in the survey but did not provide setpoint data, for the reasons explained above. We hypothesized that those most eager to take the survey (first wave responders) might be more energy-conservative compared to later responders and the general population. Comparisons of the two sub-samples (first versus second wave responders) determined that there were no statistically significant differences between the two groups in terms of the variables used for the behavioral plasticity predictive model.

Certainly, caution should be exercised when projecting energy savings based on behavior change. Although we found evidence of behavioral plasticity, and interest in learning how to use the air conditioning more efficiently, we also found that longer tenure in Dubai was associated with lower thermostat setpoints, so as time goes on, all else equal, TSC residents may tend towards lower setpoints. That said, TSC has many opportunities it can leverage to encourage more conservative AC use in order to achieve its sustainability goals and minimize its energy storage needs.

3.4 Discussion

At a macro level, the data collected from the social study of energy use at TSC indicates that energy behaviors (especially with respect to AC use) are not especially conservative, though residents generally agree that minimizing energy use is somewhat important. Whether these findings suggest a dissonance between thoughts and actions is a matter of interpretation. Regardless, there appears to be some scope for containing energy consumption from AC use, which contributes significantly to energy demand and peak load in TSC.

3.4.1 Potential to reduce energy use from AC

3.4.1.1 Technical change

From the interviews and surveys it is clear that few residents use their thermostats as an effective means of controlling their AC use and minimizing energy waste. Very few reported having programmed their thermostats. Several noted that their thermostats continually revert to the 18 degree default. We recommend two efforts to reduce energy use through improved controls:

1. Diamond staff could adopt the policy of programming thermostats each time a unit becomes vacant. We suggest setting 24 degrees as the default, building in setbacks for nighttime (and workdays for the apartments), and short override periods.
2. Diamond staff could run a campaign to program existing residents' thermostats, starting with the template outlined above, and modifying as dictated by residents' needs.

There is also a notable lack of alternative (and less energy-intensive) cooling solutions in TSC homes. We recommend Diamond consider encouraging the use of fans. This could be as simple as providing information on the resident portal, or as involved as creating a program that handles purchasing and delivery/installation of fans (either floor fans or ceiling fans, where possible).

There are also opportunities to improve efficiency by incorporating more sophisticated alternative cooling technologies and strategies, e.g., subterranean precooling, indirect evaporative cooling, and condenser pre-cooling. The evaporative cooling technique used in the domes could be used as an ambassador technology to raise awareness about the potential for more innovative strategies to deliver cooling, either to the residences or to commercial buildings.

3.4.1.2 Behavior change

There also appears to be some appetite for behavior change among TSC residents. Many expressed an interest in developing a more optimal usage strategy for AC in their home. Many also value sustainability, at least in theory.

There are many ways to encourage behavior change with respect to AC use. Perhaps the first option to consider would be to provide comprehensive instructions on how to program thermostats. These would:

- State the recommended temperatures (we suggest, at a minimum, 24 degrees when occupied, and higher when not)
- Instructions on how to program the thermostat, set the temperatures for occupied and unoccupied periods, how to override it, and how to adjust it for extended absences
- Advise on when to turn the unit(s) off and when to leave them running [e.g., when leaving a room; going out for the day; departing on holiday (with or without pets)]
- Advise on how to operate multiple thermostats most efficiently (e.g., determine which thermostats to utilize during the day and at night to cool the occupied areas)

Diamond could also provide tips on reducing the need for AC by taking actions like the following:

- Closing bedroom doors at night to retain cooling;
- Closing curtains to reduce heat gain;
- Using fans (or increasing HVAC fan speed) to reduce sensible temperature; and
- Providing reassurance that desired comfort can still be achieved when using these strategies that also reduce energy use

Other sustainable communities have had some success with running experiments to reduce AC use.[2] Diamond Developers could run a program to offer free fans to residents willing to turn their ACs up 1 degree, and monitor electricity consumption for a month. Participating residents could be encouraged to share their experiences with others on the portal and at community events.

In pursuing any of the above options, we recommend utilizing effective levers to encourage behavior change. These include, but are not limited to:

- Social norms
- Financial savings
- Information on environmental benefit

One resident shared an innovative idea for encouraging reduced AC use: use the money saved by reducing AC use to provide heating to a poor family in a cold region. Similar programs that offer charitable contributions as an incentive, leveraging prosocial values as a motivator, have proven successful in other contexts.

Finally, Diamond should not overlook their role in influencing the behavior of TSC residents, both directly and indirectly. Residents look to Diamond staff and the organization to demonstrate the values they espouse. When Diamond's message and actions (or those of their contractors) do not align, residents begin to question the commitment to sustainability. Given that, any campaign to urge sustainable activities (such as prudent AC strategies) should be adopted and modeled within the Diamond offices. Doing so would help to establish social norms of conservation.

3.4.2 Barriers, limitations and challenges

Of course, there are many challenges to maintaining a culture of sustainable energy use. As mentioned, there are technical barriers to containing energy use, including issues with controls, metering and billing. In addition, some residents feel disempowered to save energy, lacking confidence that their actions will significantly impact their consumption, with the concomitant financial and environmental reward. When residents doubt their efforts to conserve energy will be effective (or appropriately credited), their motivation to make sustainable choices can start to erode.

Finally, this study relies on self-report to describe residents' current practices. Behavioral plasticity, or willingness to change, was measured by self-report and extrapolated from current behaviors. These methods have limitations in predicting future behavior. For this reason, we have exercised an abundance of caution in using these results as inputs to the energy storage model, as described in Chapter 3.

[2] Outcault, S. Pritoni, M., Heinemeier, K., and A. Mikami. (2016). "Can you take the heat? A cross-national comparison of thermal comfort strategies and energy-saving field experiments." Conference Proceeding Paper. 2016 ACEEE Summer Study on Energy Efficiency in Buildings.

4. Design/Engineering Team

4.1 Introduction and Project Scope

The goal of this technical study is to assess the viability of installing a battery energy storage system (BESS) or systems coupled with an energy management system to further develop TSC's microgrid. Lithium ion batteries are primarily analyzed with secondary analysis comparing the advantages and disadvantages of Vanadium flow batteries. This study will outline various combinations of solar PV and energy storage systems to compare metrics such as cost, net present value, payback period, and levelized cost of electricity. This study will also discuss how battery storage, although a nascent technology, is a key step in advancing the renewable energy utilization efforts of TSC and Diamond Developers.

TSC has already installed photovoltaic (PV) solar panels capable of producing up to 10 MW, including solar panels on commercial buildings, carparks, and residential rooftops. Solar panels provide shading for parked cars and produce up to 3 MW across all TSC residential carparks. However, a BESS is a desirable addition to current renewable TSC technology. The main functions of a BESS include shaving electric load during peak hours, decreasing ramping effects at sundown, allowing for islanding capabilities during a blackout, and supplying the necessary amount of energy for city-wide EV charging. The following topics will be studied and discussed:

- The necessary sizes and recommended models for inverter and PV modules
- Other necessary equipment for proper BESS installation
- Various storage and PV size configurations for different residential cluster sizes
- Advantages and disadvantages of Lithium-ion BESS compared to Vanadium Flow BESS and PV-only systems

Various simulation programs have been utilized for this study including the National Renewable Energy Laboratory's (NREL) System Advisor Model (SAM) and the Electric Power Research Institute's (EPRI) StorageVET. SAM allows for detailed modeling of combined PV-storage technology including thorough lifetime and economic analyses. StorageVET analyzes the economic benefits and revenue streams of grid-tied and off-grid PV-storage technology. Detailed descriptions of the parameters used in SAM and StorageVET may be found further in this report. Various residential groupings, or cluster sizes, have been analyzed with these programs to identify the most cost-effective BESS design.

4.2 PV Panel and Inverter Overview

The residential PV is installed at a 5 degrees tilt angle, and a 50 degrees azimuth angle towards the south east.

Table 4-1. Residential PV design data for each TSC villa type

Villa Type	Designed per day (kWp)
3-bedroom	5.2
4-bedroom	5.75
Semi-attached	8.19
Stand-alone	9.83

Table 4-2. Solar cell PV modules currently installed at TSC

Type	Brand	Model	Size (mm x mm)	Output power (W)	Efficiency
60 Cells (MULTICRYSTALLINE MODULE)	DUOMAX Series (TrinaSolar)	Dual Glass Module	992x1658	260	15.8 %
72 Cells (MULTICRYSTALLINE MODULE)	DUOMAX Series (TrinaSolar)	Dual Glass Module	992x1978	315	16.1 %

Table 4-3: Inverter models currently installed at TSC

Cluster	Villa type	Brand	Model	Efficiency
C1 & C2	Town house	ABB	PVI-5000-TL-OUTD-S	97%
	Semi-attached		TRIO-7.5-TL-OUTD-S	98%
	Stand-alone		TRIO-8.5-TL-OUTD-S	98%
C3, C4 & C5	Not Installed yet (Fronius Inverters in C3 town houses & ABB in the rest)			

4.3 Residential Storage Solutions

TSC is comprised of 500 villas grouped into five residential clusters. Each villa is allocated two parking spaces shaded with solar panels, which provide energy for street lighting, electric vehicle charging, grey water treatment, and the urban farm. Commercial buildings include the Hotel Indigo, Rehabilitation Hospital, Equestrian Center, Fairgreen International School, See Nexus Headquarters, and the Sustainable Plaza. A variety of sizing scenarios for energy storage are analyzed, including residential and commercial options; smaller BESS solutions (less than 200 kWh) and larger BESS solutions (greater than 200 kWh) are also considered. Grouping options are tabulated below. Due to limited information about the load and size of TSC's commercial buildings, energy storage has been analyzed for an overall estimated demand. A more thorough analysis of commercial energy storage options may be conducted with detailed commercial demand information.

Five simulations were run to test different configurations of solar PV systems coupled with battery energy storage. Simulations 1, 2, and 3 have assumed existing (previously-installed) PV capacity while Simulations 4 and 5 have added additional PV capacity to achieve off-grid and zero net energy functionality; these simulations will essentially mix residential and communal PV and centralized battery storage. The simulations were also run with PV only (battery storage disabled), to compare the costs and payback periods of installing a PV-plus-storage with a PV-only system. In all cases except simulation 1, both Lithium-ion Cobalt (LCO) and flow batteries were tested. This is because flow batteries are a much newer and more expensive technology and are not yet available for small-scale residential installation like Lithium-ion battery systems. Simulations are described in detail below; see Table 4-4 for a brief overview.

All simulations were run with SAM's peak -shaving functionality enabled, which is designed to minimize electricity purchases from the grid as much as possible. All load was purchased and sold at DEWA rates outlined in Table 4-6; these rates and subsequent energy costs were the basis of savings calculated in SAM. The only yearly costs were assumed to be from operation and maintenance (O&M) since detailed information about debt and other cost parameters was not available. The real discount rate of 1% was provided by Diamond Developers and an approximate 4% inflation rate for Dubai was assumed[3], resulting in a calculated nominal discount rate of 5% -- real discount rate takes year-over-year inflation into account while nominal discount rate does not.

Table 4-4. Residential Sector Simulations Overview

Simulation	Description	Storage Capacity (kWh)	Storage Power (kW)	Solar PV (kW)
1	Four-bedroom villa	20	10	5.75
2	One villa cluster (100 villas)	2,000	1,000	575
3	Entire residential area (500 villas)	10,000	5,000	2,875
4	Entire residential area, entirely off-grid case	38,500	6,200	22,760
5	Entire residential area, zero-net bill case	10,000	6,000	14,110 – 14,225

Simulation 1: A single four-bedroom villa at TSC was modeled with a 5.75 kW PV system coupled with a 20 kWh / 10 kW Lithium-ion battery storage system. A storage system of this size is typically sold for residential applications with typically high loads during peak hours (due to the necessity of running the air conditioner) and is analogous to a system sold by a popular electric car manufacturer. Because solar panels are installed on villa rooftops, it is not currently feasible to increase the size of the residential PV arrays which range between 5.2 – 9.8 kWp. However, degraded panels might be replaced with higher-efficiency panels in the future which could theoretically yield approximately 25% more capacity while maintaining the same rooftop area.

Simulation 2: One grouping of 100 villas, referred to as a villa cluster, was modeled with a 575 kW PV system (the combined PV contribution from those 100 villas) coupled with a 2 MWh / 1 MW energy storage system. The energy storage system was sized by scaling up the system size for a single villa. Simulations were run to test the results from both Lithium-ion and flow batteries. For this simulation, only rooftop PV arrays were used to contribute to the overall system size. Villa landlords also own portions of a 3 MW PV system installed on shaded parking structures, and TSC has a special net metering agreement with DEWA that allows excess generation to be sold back to the grid at purchase rates. However, it is unknown how much carpark PV is used to meet which loads and how much is sold back to the grid, so it is excluded from the overall PV array size.

[3] https://tradingeconomics.com/united-arab-emirates/inflation-cpi

Simulation 3: The entire residential area of TSC with a total of 500 villas, was modeled with a 2.875 MW PV system (the combined PV contribution from all 500 villas) combined with a 10 MWh / 5 MW energy storage system. Like Simulation 2, the energy storage system size was scaled up from the system size for one villa cluster (one-fifth of the entire residential area). The simulation was also run to observe results from both Lithium-ion and flow battery systems.

Simulation 4: The entire residential area of TSC was modeled with a system adequate to achieve off-grid functionality or become zero-net energy (ZNE) capable. To achieve this case, it was necessary to size the PV and storage systems large enough to accommodate the day of highest electricity load such that no electricity would be needed from the DEWA grid. Additionally, the PV-plus-LCO storage system and PV-plus-Flow storage system required slightly different sizing combinations because of discrepancies between yearly system energy production. With these constraints in mind, the simulation was modeled with a 14.225 MW PV system combined with a 10 MWh / 6 MW energy storage Lithium-ion system, and again with a 14.11 MW PV system combined with a 10 MW / 6 MW energy storage Flow battery system. To generate an estimate for PV array size, the following formula was used:

$$Array\ Size = \frac{Peak\ load, highest\ day\ sum\ (kWh)}{24\ hours * CF}$$

Where CF represents a capacity factor of 16%[4], the ratio of actual generation and maximum potential generation based on nameplate capacity, and peak load for the simulation was approximately 87.4 MWh. PV system size and energy storage size/capacity were iterated within SAM until a combination was identified that eliminated draw from the DEWA grid for all hours across one year.

Simulation 5: The entire residential area of TSC was modeled again with a system adequate to achieve zero-net billing, meaning TSC's net energy bill for an entire calendar year would be approximately $0. Because TSC can sell back electricity at the same rates at which electricity is purchased through a net-metering agreement with DEWA, a system can be designed such that all electricity consumption is eventually sold back to the grid within one year. Comparing SAM's outputs for electricity drawn from grid (kWh) to electricity sent to grid (kWh), it was possible to iterate PV and storage sizes to a point where electricity drawn from grid was equivalent to electricity sent to grid over one year. This resulted in a 14.35 MW PV system coupled with an 18.825 MWh / 6.8 MW energy storage system, run with both Lithium-ion and flow batteries.

Table 4-5. Overview of results, Simulations 1-5

Simulation	Land Area (acres)	System Cost, range ($/Wdc)	Recommended for installation?
1	0	4.22	No
2	2.3	4.12 – 6.82	No
3	11.3	6.34 - 11.27	No
4	82.1	2.55 - 3.60	Yes*
5	55.6	2.01 – 2.61	Yes*

**With further analysis of impact on DEWA distribution grid from selling back high volumes of electricity*

[4] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf

4.3.1 General Parameters and Assumptions

It was necessary to make some generalizing assumptions to complete each Residential analysis. First, it was assumed that villa load was adequately represented by the GreenTech Energy Model Report for three- and four-bedroom villas. This report generalizes villa consumption into five main systems: HVAC, lighting, water heating, pumps and fans, and home appliances. Monthly electric consumption for all villa types are pulled from GreenTech's energy efficient model results and are tabulated in the Appendix. Since consumption data was only provided per month, a model was created to extrapolate hourly consumption profiles – this model is detailed in the section below.

Further assumptions were made to run each simulation in SAM. This program from NREL is designed to estimate performance and cost specifications for grid-connected power projects based on a variety of inputs. Although some inputs are automatically populated based on certain default settings, it was necessary to review these assumptions as well as input other project-specific parameters into the program to obtain an accurate analysis. SAM-generated performance models gave hourly results for each designed system's electricity production, as well as detailed data tables, charts, and annual system output values. These results were essential for the system optimization process.

Typical meteorological year (TMY) data was also required for the simulation. The team was not able to find a TMY dataset for Dubai as the city is not adequately represented among online meteorological databases. However, a TMY dataset for Abu Dhabi could be used as a suitable substitution because the two cities are located relatively close to one another (approximately 140 km) and are both classified as hot desert climates (BWh) according to the Köppen Climate Classification.[5]

All simulations assume a constant 23°C indoor setpoint and that HVAC systems are constantly running.

Simulations in SAM were run using PV modules from TrinaSolar (Duomax Dual Glass Module, 60 Cell Multicrystalline). A single-phase string inverter from ABB (PVI-5000-TL-OUTD) was used for larger cluster simulations but was oversized for single residential unit applications, so a smaller ABB single phase string inverter was used (PVI-3.6 OUTD-S-US-Z-M-A). For a detailed description of SAM and the parameters used by the team, please see the System Advisor Model (SAM) Assumptions and Parameters section in the Appendix.

Dubai's electric utility DEWA charges customers for electricity using a slab tariff.[6] Owners of residential or commercial PV systems who are participating in the SHAMs Dubai initiative, a net-metering structure, can sell surplus electricity back to DEWA at the same prices tabulated below. These slab tariff prices were integrated into SAM to calculate the value of electricity savings for each simulation.

Table 4-6. DEWA's Slab Tariff for Electricity

Sector	Consumption (kWh/month)	Slab Tariff (USD $/kWh)
Residential/Commercial	0-2000	0.063
	2001-4000	0.076
	4001-6000	0.087
	6001 and above	0.10

[5] http://www.thesustainabilitycouncil.org/desert-biome.html
[6] https://www.dewa.gov.ae/en/customer/services/consumption-services/tariff

Without detailed financial information about the project, it was difficult to estimate the inputs necessary to calculate debt forecasts, therefore the team neglected these inputs and calculations. However, a levelized cost of electricity (nominal and real) could be calculated based on assumptions that TSC has net-metering and can sell excess electricity back to the grid at purchase rates, and that Operation & Maintenance (O&M) costs represented approximately 1% of the project's capital expenditure (CAPEX) across the analysis lifetime of 25 years.

The Levelized Cost of Energy (LCOE) was calculated for each simulation in order to compare the costs of renewable technologies across different investment parameters by taking inflation and discount rate into account. SAM calculates (LCOE) according to the following formula[7]:

$$LCOE = \frac{C_{lifetime}}{\sum_{n=1}^{N} E_n \div (1+d)^n}$$

Where:

LCOE = Levelized cost of energy
$C_{lifetime}$ = Total cost over lifecycle
E_n = Energy output in one year
d = Discount rate (nominal or real)
N = Analysis period, years

Using provided parameters and output results from SAM, LCOE values were calculated for the various PV-storage system configurations, as well as for PV-only system configurations.

Net present value (NPV) was also calculated for each simulation. NPV measures a project's economic feasibility and incorporates both revenue (or savings) and cost. It is the present value of the after-tax cash flow discounted to year one using the nominal discount rate. Generally, positive NPVs indicate that a project is economically feasible while negative NPVs indicate that a project is not economically feasible. Because NPV represents a present value and does not need to account for inflation, the nominal discount is used. The number of years until revenue is earned is considered the payback period and occurs when cumulative cash flow becomes positive. Payback period is an important metric when considering investing in a new system; generally, a lower payback period is desirable but is ultimately up to the project investors to determine an appropriate payback period and whether they are willing to make the financial investment for the project.

$$NPV = \sum_{n=1}^{N} \frac{C_n}{(1+d_{nominal})^n}$$

Where:

C_n = After-tax cash flow in year *n* for residential and commercial projects (not based on cash flows after interest)
N = Analysis period, years

[7] http://www.nrel.gov/docs/legosti/old/5173.pdf

$d_{nominal}$ = Nominal discount rate

4.3.2 Load Profile Modeling

To properly design the BESS, it was important to consider and meet both the power and energy requirements of the community. The electricity consumption of each home was modeled and summed in combinations corresponding to the different energy storage configuration options tabulated above. To some degree, this data is provided by the GreenTech report, which gives the expected monthly and annual consumption of each type of home. However, the monthly estimates do not provide an adequately high resolution to properly size the BESS.

The behavioral data given by an Oman Time Use Survey (TUS) report conducted by the Oman government was incorporated to add variability to the load that is more characteristic of a Middle Eastern residential community. The appliance load, or miscellaneous equipment load, was generated using the results to model occupant activity for a full community. For the TUS, the activity of 2,500 Omani and non-Omani families were categorized and recorded from May 2007 to May 2008. Residents recorded which of several activities they were participating in at every hour, e.g. sleeping, cooking, relaxing, etc. This was then summarized to convey the percentage of people who participated in each activity for each hour of the day. This was further broken down into weekdays and weekends. In this case, the data for the non-Omani were used, who were assumed to have behavior similar enough to that of the residents projected to live at The Sustainable City.

For each resident, the model randomly generates an array of probabilities for each activity for each hour of the year and compares it to the TUS percentages and determines what activity (or activities) the resident is doing at every hour, creating a Boolean matrix. Each activity is assigned an average hourly load value and is multiplied to the matrix and summed by the hour to produce an hourly load for the resident.

The GreenTech baseline case results were used as a foundation for an hourly demand model, because GreenTech's estimates include information that would be accounted for in more advanced building modeling, e.g. heat loss through the walls or light loss factors. Assumption were made to extrapolate the monthly estimates which would create an hourly model. HVAC load was assumed to be linearly dependent on the size of the home and the temperature difference between the outdoor temperature and indoor setpoint temperature. Like the GreenTech report, the indoor setpoint was assumed to be a constant 23°C. The hourly HVAC values were then calculated using a monthly constant derived from GreenTech's projected load:

$$C_{HVAC,n} = \frac{L_{GT,n}}{24d_n(T_{avg,n} - T_{set})}$$

Where:
n = month
$L_{GT,n}$ = projected GreenTech load
d_n = number of days in the month
T_{avg} = average outside temperature based on hourly weather data

The hot water and external usage loads were assumed to be only be dependent on occupancy and that each bedroom held a maximum of two residents. Because estimates were given for the 3- and 4-

bedroom villas, the 3-bedroom data was scaled proportionally to the number of bedrooms to generate profiles for the studio and 2-bedroom apartments.

4.3.3 Simulation Results: Load Reduction/Peak Shaving

4.3.3.1 Simulation 1: Four-bedroom villa

This simulation utilizes the currently-installed PV array size of 5.75 kWdc on a four-bedroom villa. Various villa types (e.g. three-bedroom, courtyard villa) will have slightly different PV array sizes ranging between 5.2 kWdc and 5.75 kWdc. Installation of more rooftop capacity is not currently possible as developers are restricted by limited rooftop area, however new higher-efficiency panels may be installed in the future. The battery storage system for this simulation was sized at 20 kWh/10 kW after performing initial market research and performing comparisons of commercially-available residential energy storage solutions. From there, the size and capacity values were iterated slightly to maximize peak shaving functionality. As reported by Diamond Developers, operation and maintenance costs (O&M) represent 1% of the total capital expenditure (CAPEX) and the real discount rate has a value of 1%. Based on current Dubai economic parameters, a nominal discount rate of 5% could be determined. The simulation was run to model costs with a PV-plus-storage system and a PV-only system.

Table 4-7. Simulation 1 input parameters

Parameter	***Input***
PV Module	TrinaSolar TSM-260PEG5
Inverter	ABB: PVI 4.2 OUTD-S-US-Z-M-A
Array size	5.75 kWdc
Battery type	Lithium Cobalt Oxide (LCO)
Storage capacity	20 kWhdc
Storage power	10 kWdc
CAPEX, PV + Storage	$24,000
O&M (% of CAPEX)	1%
Analysis period (years)	25
Real discount rate	1%
Nominal discount rate	5%

The combined PV-plus-storage system is not a cost-effective choice for this simulation (negative NPV and high payback period) and would require more installed PV and a larger battery, which is not currently feasible. Although this system would not allow for off-grid functionality for the single villa, it would be able to perform peak shaving and reduce the overall draw from the grid, as illustrated below with the graph of modified load versus electricity load for the four-bedroom villa. The PV-only model is much more cost-effective, with a payback period of 16.85 years and a positive NPV, indicating payback within the 25-year analysis period. This simulation is simply meant to be an illustrative, granular example for what is happening at the villa level once the system is scaled up to size; TSC has already installed rooftop PV on most, if not all, villas and will likely prefer to invest in a larger grid-scale system instead of retrofitting and upgrading each individual villa.

Table 4-8. Simulation 1 results

Output	***PV + LCO Storage***	***PV only***
LCOE (nominal, $/kWh)	0.34	0.149
LCOE (real, $/kWh)	0.13	0.131
Net present value	-$4,000	$19,000
Payback period (yrs)	26.70	14.97

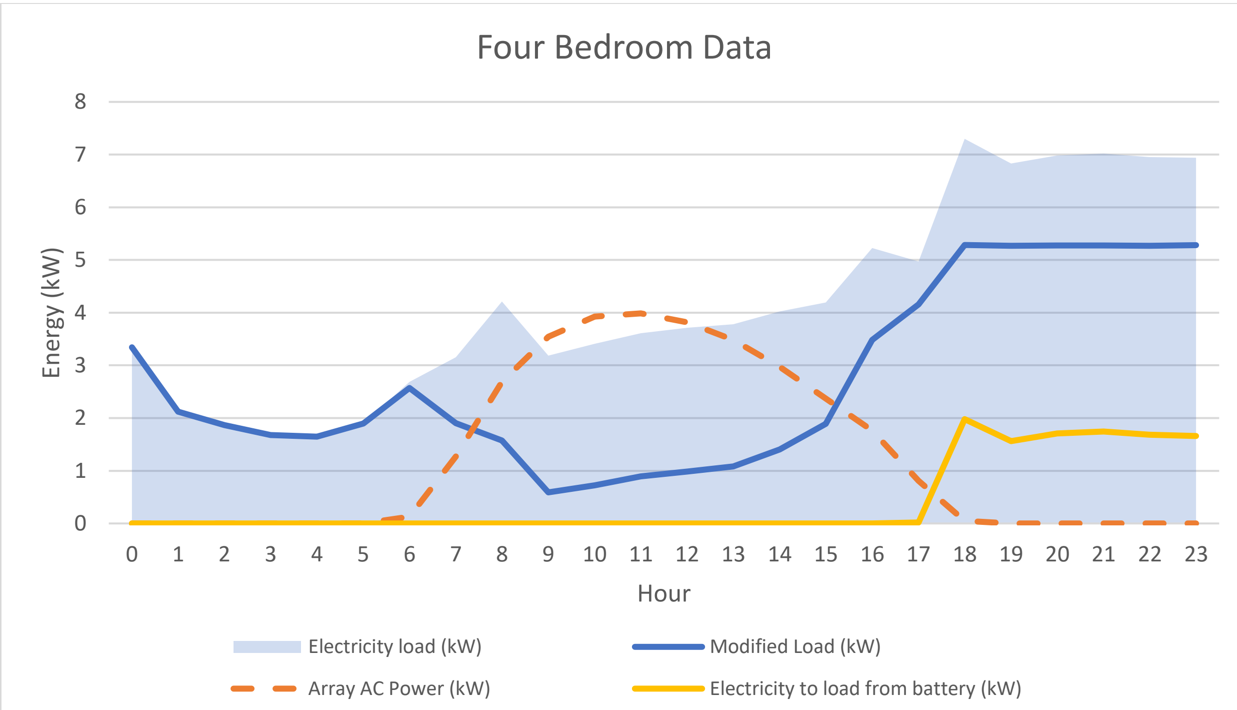

Figure 4-1. Four-Bedroom villa load plotted against modified load (after system contributions) and array AC power from a 97% inverter efficiency. This snapshot represents the averaged-hourly values for one year with a Lithium-ion system.

4.3.3.2 Simulation 2: One villa cluster (100 villas)

Simulation 2 models a single grouping of 100 villas, referred to as a villa cluster, with the combined PV contributions from each villa within the cluster and battery storage sized scaled up by a factor of 100 from the single residential storage solution. The simulation was run twice with a PV-plus-storage system, with a 575 kW PV array and a 2 MWh/1 MW battery storage system, for both Lithium-ion and Vanadium Flow battery storage units, and once with PV only. As discussed above in Simulation 1, the O&M percentage of CAPEX costs as well as real and nominal discount rates apply to this simulation and are constant throughout the analysis.

Table 4-9. Simulation 2 input parameters

Parameter	Input
PV Module	TrinaSolar TSM-260PEG5
Inverter	ABB: PVI 4.2 OUTD-S-US-Z-M-A
Array size	575 kWdc
Battery type	Lithium Cobalt Oxide (LCO) or Vanadium Flow
Storage capacity	2 MWhdc
Storage power	1 MWdc
CAPEX, PV + Storage	$2,364,000
O&M (% of CAPEX)	1%
Analysis period (years)	25
Real discount rate	1%
Nominal discount rate	5%

Like with Simulation 1, the monthly load for one villa cluster is too high to pay off both LCO and Flow systems within the analysis period of 25 years, resulting in negative NPVs with high payoffs. At an estimated cost of $900/kWh for Flow batteries, the Flow storage system is significantly more expensive than the LCO system which costs approximately $450/kWh based on initial market research. In addition, the system is not large enough to support the villa cluster in off-grid mode, requiring more PV installation and likely a larger storage system to achieve off-grid functionality. However, peak shaving functionality can be achieved with systems of this size, as illustrated on the graph of original electricity load and modified load, post-system installation, below. Simply utilizing 575 kW of PV to meet the villa cluster load is much more cost-effective and will meet a significant portion of daytime load, however the villa cluster will have to draw from the grid during hours of darkness to meet load.

Table 4-10. Simulation 2 results

Output	PV + LCO Storage	PV + Flow Storage	PV only
LCOE (nominal, $/kWh)	0.37	0.61	0.12
LCOE (real, $/kWh)	0.14	0.24	0.05
Net present value	-$561,000	-$2,140,000	$1,039,000
Payback period (yrs)	28.31	39.76	13.12

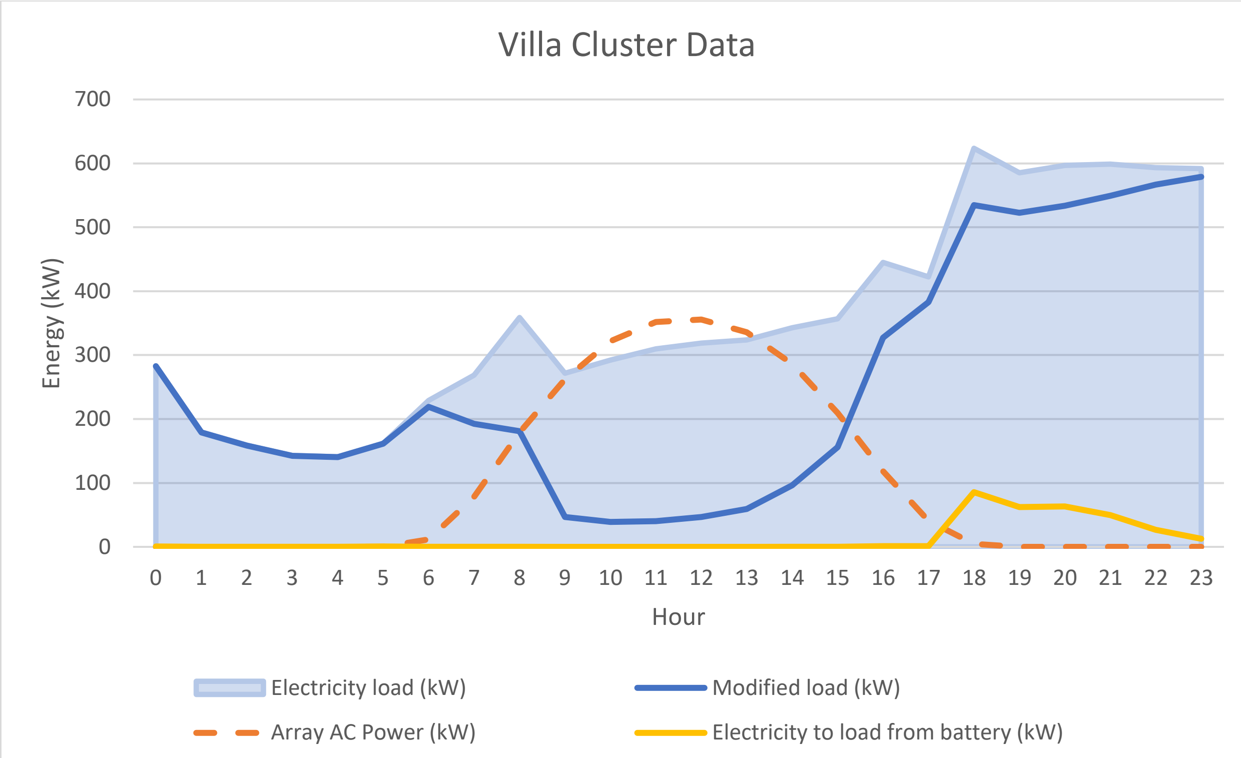

Figure 4-2. Villa cluster load plotted against modified load (after system contributions) and array AC power from a 96% inverter efficiency. This snapshot represents the averaged-hourly values for one year with a Lithium-ion system.

4.3.3.3 Simulation 3: Entire residential area (500 villas)

This simulation models the entire residential area of TSC with a total of 500 villas, or five villa clusters. The PV array and battery storage system used in this simulation are scaled up by a factor of 5 from Simulation 2 to give a PV array size of 2.875 MW and a battery storage system of 10 MWh/5 MW. This simulation was run three times, with a PV-plus-LCO storage system, a PV-plus-Flow storage system, and a PV-only system to compare technology types and costs.

Table 4-11. Simulation 3 input parameters

Parameter	***Input***
PV Module	TrinaSolar TSM-260PEG5
Inverter	ABB: PVI 4.2 OUTD-S-US-Z-M-A
Array size	2.875 MWdc
Battery type	Lithium Cobalt Oxide (LCO) or Vanadium Flow
Storage capacity	10 MWhdc
Storage power	5 MWdc
CAPEX, PV + Storage	$11,830,000
O&M (% of CAPEX)	1%
Analysis period (years)	25
Real discount rate	1%
Nominal discount rate	5%

Simply scaling up the system size does not provide an effective solution to manage the entire residential area's load, although some peak shaving/load leveling functionality is possible and reduces overall strain on the distribution grid. As with the other simulations, Flow storage is significantly more expensive. It is worth noting that Flow storage systems across all simulations produce slightly less lifetime electricity than LCO systems, leading to higher LCOE values when coupled with the fact that Flow systems are more expensive on a $/kWh basis. The PV-only system will pay off quickly with a positive NPV and low payback period, however it will only be able to mitigate residential load during daylight hours.

Table 4-12. Simulation 3 results

Output	***PV + LCO Storage***	***PV + Flow Storage***	***PV only***
LCOE (nominal, $/kWh)	0.36	0.60	0.13
LCOE (real, $/kWh)	0.14	0.23	0.05
Net present value	-$2,725,000	-$10,597,000	$5,190,000
Payback period (yrs)	28.14	39.45	13.14

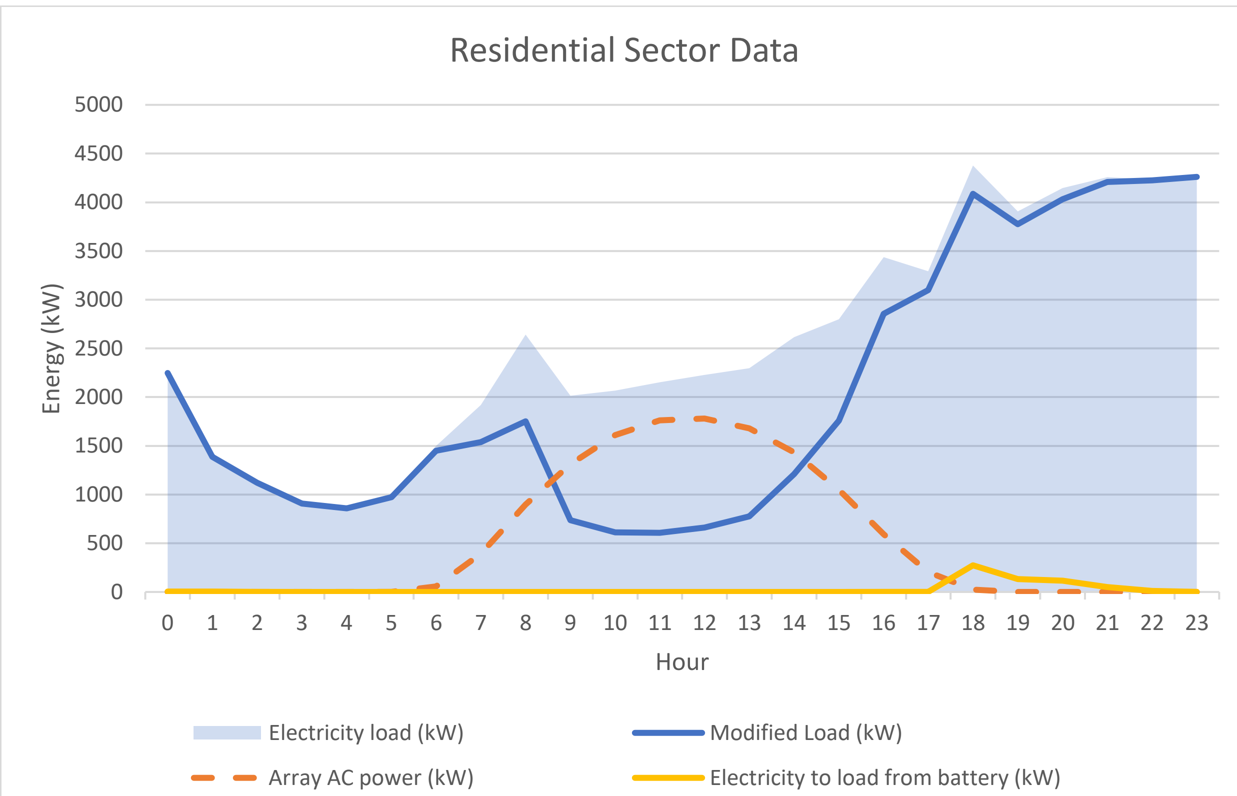

Figure 4-3. Residential load plotted against modified load (after system contributions) and array AC power from a 96% inverter efficiency. This snapshot represents the averaged-hourly values for one year with a Lithium-ion system.

4.3.4 Simulation Results: Minimizing/Eliminating Grid Reliance

4.3.4.1 Simulation 4: Entire residential area (500 villas), entirely off-grid case

The entire residential area of TSC (500 villas) was modeled again with a system sized for off-grid, zero net energy (ZNE) functionality. In order to size for off-grid, it was necessary to consider the day of peak load which occurs on August 25th and design the system such that all load on this day is met with a PV-plus-storage system with no draw from the grid. If the system is designed to meet the day of highest load then it will be adequately sized to perform off-grid functionality for the rest of the year, however the system will overproduce at many times throughout the year to accommodate for the electricity requirements on August 25th. The peak load for the residential area is approximately 6.04 MW and the day's consumption is approximately 87.4 MWh. To generate an estimate for PV array size, the following formula was used:

$$Array\ Size = \frac{Peak\ load, highest\ day\ sum\ (kWh)}{24\ hours * CF}$$

Where CF represents a capacity factor of 16%, the ratio of actual generation and maximum potential generation based on nameplate capacity. This yielded an array size of 22.76 MW which will theoretically generate enough energy to meet the entire day's load after accounting for losses due to the capacity factor. The battery system was then sized to store enough energy to adequately meet residential load during the non-daylight hours of 6 PM to 7 AM.

It is important to note that the modeling tool used for these simulations, SAM, is not technically designed to model grid-independent systems. Some paid software tools exist but were not utilized by this team who opted instead to use open-source software tools. Developers and investors may rely on these figures as reliable preliminary estimates when planning to install new technology and infrastructure at TSC.

Table 4-13. Simulation 4 input parameters

Parameter	***Input***
PV Module	TrinaSolar TSM-260PEG5
Inverter	ABB: PVI 4.2 OUTD-S-US-Z-M-A
Array size	22.76 MWdc
Battery type	Lithium Cobalt Oxide (LCO) or Vanadium Flow
Storage capacity	39 MWhdc
Storage power	6.2 MWdc
CAPEX, PV + Storage	$54,757,000
O&M (% of CAPEX)	1%
Analysis period (years)	25
Real discount rate	1%
Nominal discount rate	5%

During daylight hours when PV is producing energy (7 AM – 6 PM), the PV array will meet the residential daytime load of 48.4 MWh and produce enough excess energy to meet load during non-daylight hours. To avoid oversizing, this excess energy should be approximately equivalent to the load during non-daylight hours, which is approximately 39 MWh. Therefore, the battery storage system was sized at 39 MWh with a bank power value of 6.2 MW to ensure the system would meet peak load. Although theoretically sized for off-grid functionality, the resulting load shapes graphed below do not adequately resemble an off-grid system due to various limitations with SAM's modeling abilities. Theoretically, the graph below should show a modified load profile of 0 kW for all hours of the day.

Despite this limitation, cost data can be extracted to analyze system payback and value. The PV-plus-LCO storage system will be paid back in a little over 19 years and has a low real LCOE value while the PV-plus-Flow storage system will take over 25 years to pay back and is not cost-effective, as indicated by its negative NPV. With both the PV-plus-storage and PV-only simulations, it will be necessary to study how a large PV system will impact the local distribution grid if excess generation is sold back to DEWA through a net-metering scheme. The presence of battery storage will help mitigate ramping effects during sundown when PV production decreases while residential load increases, however these ramping effects will become more pronounced with a PV-only system of this magnitude. Further studies and discussions with DEWA are necessary for a system of this size.

An important consideration that is missing from this analysis is the presence of additional generation sources. Many partial or full off-grid systems of this scale have a diverse renewable portfolio including solar PV, wind, and/or hydroelectric power coupled with various types of storage, plus a natural gas or diesel generator to increase reliability. The system for Simulation 4 is sized such that all load is met with solar PV production and battery storage for the day of highest consumption which means the system will overproduce for most months of the year and will send a high volume of electricity back to the grid or curtail solar production, increasing payback period and reducing the value of the investment. Adding a natural gas or diesel generator to the system would ensure there is enough backup power to meet residential load during high-demand days like August 25th and would stay powered off during times when load can be adequately met with PV-plus-storage.

Table 4-14. Simulation 4 results

Output	***PV + LCO Storage***	***PV + Flow Storage***	***PV only***
LCOE (nominal, $/kWh)	0.21	0.31	0.125
LCOE (real, $/kWh)	0.08	0.12	0.049
Net present value	$18,767,000	-$7,212,000	$41,098,000
Payback period (yrs)	19.29	25.26	13.14

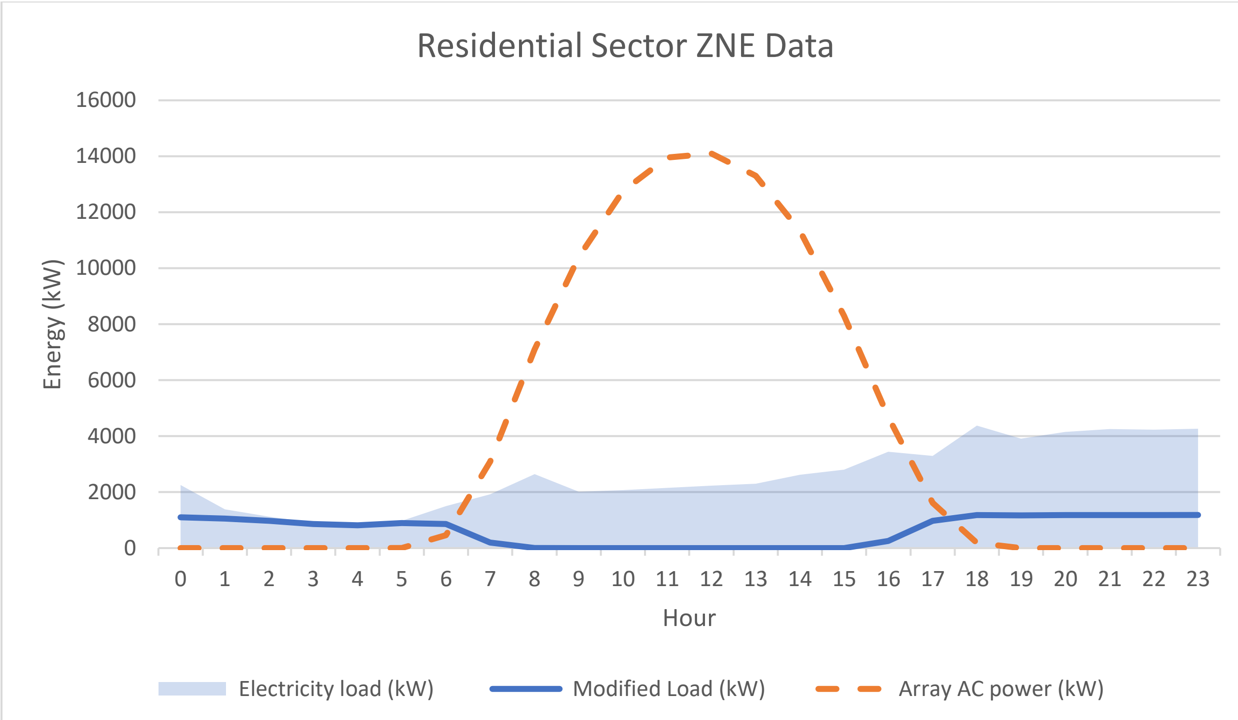

Figure 4-4. Residential load plotted against modified load (after system contributions) and array AC power from a 96% inverter efficiency, ZNE case. This snapshot represents the averaged-hourly values for one year with a Lithium-ion system.

4.3.4.2 Simulation 5: Entire residential area (500 villas), zero-net bill case

Simulation 5 takes a different approach to the concept zero net by considering the case where net energy charges are $0 over one year. As previously discussed, TSC has a unique net-metering arrangement with DEWA by which excess PV generation is sold back to the grid at purchase rates via a credit on the next month's bill. In this way, a zero-net yearly bill could be achieved by producing as much energy as was consumed throughout one year. This simulation does not support off-grid functionality for the residential area, although it is possible that some days are inadvertently off-grid due to a combination of low demand and high PV production for that day. To achieve a zero-net bill, the system was iterated using parametric simulations in SAM until a satisfactory array size, 14.35 MW, and battery storage size, 18.825 MWh/6.8 MW, were identified.

Table 4-15. Simulation 5 input parameters

Parameter	***Input***
PV Module	TrinaSolar TSM-260PEG5
Inverter	ABB: PVI 4.2 OUTD-S-US-Z-M-A
Array size (LCO)	14.225 MWdc
Array size (Flow)	14.11 MWdc
Battery type	Lithium Cobalt Oxide (LCO) or Vanadium Flow
Storage capacity	10 MWhdc
Storage power	6 MWdc

CAPEX (LCO)	$ 28,551,000
CAPEX (Flow)	$ 36,922,000
O&M (% of CAPEX)	1%
Analysis period (years)	25
Real discount rate	1%
Nominal discount rate	5%

To determine when zero-net billing was achieved, the team found when hourly outputs for electricity to/from grid (kW) summed to zero over one year. Electricity draw from the grid has a negative sign convention while electricity sent back to the grid has a positive sign convention and should net to zero for all revenue to offset electricity purchases. SAM's iteration capabilities are not granular enough to set system sizes so the sum of electricity to/from grid is exactly zero, and the actual sum fluctuated significantly between small PV array step sizes of 2 kW. It was necessary to size LCO and flow battery systems differently, since each system will produce different amounts of annual energy. For the LCO system sized at 10 MWh/6 MW with a 14.11 MW PV array, a slight yearly overproduction of approximately 1,800 kWh will be observed, resulting in a net revenue of $106. For the Flow system sized at 10 MWh/6 MW with a 14.225 MW PV array, a yearly overproduction of approximately 2,500 kWh will be observed with an associated net revenue of $148.

Table 4-16. Simulation 5 results

Output	***PV + LCO Storage***	***PV + Flow Storage***	***PV only (14.225 MW)***	***PV only (14.11 MW)***
LCOE (nominal, $/kWh)	0.18	0.23	0.125	0.125
LCOE (real, $/kWh)	0.07	0.09	0.048	0.049
Net present value	$16,606,000	$5,582,000	$14,457,000	$25,287,000
Payback period (yrs)	17.16	20.71	14.71	13.23

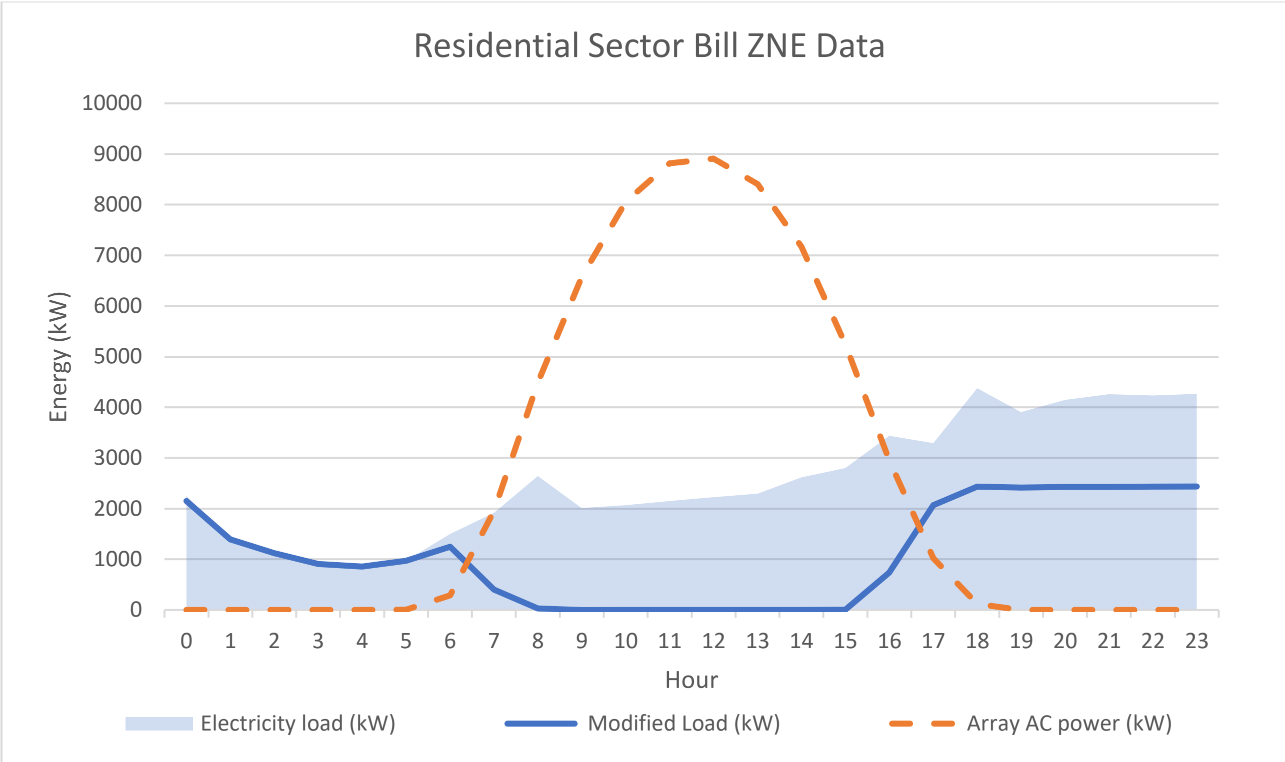

Figure 4-5. Residential load plotted against modified load (after system contributions) and array AC power from a 96% inverter efficiency, zero-net bill case. This snapshot represents the averaged-hourly values for one year with a Lithium-ion system.

4.4 Advantages of Battery and Demand Response

To better determine the advantages and disadvantages of a grid-tied and off-grid energy infrastructure, electricity costs for four different scenarios were simulated using StorageVET. These four scenarios pertain to a TSC four-bedroom villa and provide an illustrative representation of the benefits of demand response.[8]

- Electricity cost with no PV or battery, and no demand response
- Electricity cost with installed PV, but no battery and no demand response
- Electricity cost with no PV, an installed battery, and demand response enabled
- Electricity cost with installed PV and battery, and demand response enabled

To generate this data, numerous assumptions were made for the input parameters. These assumptions are listed below. The limitations of these assumptions are also discussed. The basis for demand response data is provided by the California Independent System Operator (CAISO); this organization independently facilitates the transmission of wholesale electricity in California, USA and also runs an

[8] Demand response (DR) gives customers an opportunity to reduce or offset their electricity consumption during periods of peak demand in response to time-based rates or other financial incentives, thus reducing strain on the grid and ensuring grid reliability. Some electric system operators and utilities have manual (customer-controlled) or automated DR programs for which residential, commercial, and industrial customers may sign up. DR is considered a valuable resource that can ensure grid longevity, thereby avoiding costly transmission and distribution system upgrades.

electricity market to allow participants to sell and purchase electricity on this distribution- and transmission-scale.

- The battery technology was chosen to be Lithium-ion, as this technology is more mature and installation-ready than other technologies like flow. StorageVET does not allow for the input of specific Lithium-ion battery chemistries.
- A battery storage capacity of 40 kWh was modeled with 100% capacity available. The energy usage for a 3600 ft^2 apartment, the approximate size of a four-bedroom villa, is estimated to be 36 kWh/day from an online modeling tool provided by a well-known electric vehicle and battery storage manufacturer based in California.
- Hourly CAISO electricity prices were used instead of DEWA prices as StorageVET is designed to perform economic analysis solely for energy storage systems in California and DEWA does not offer demand response. However, California has several tariffs that are similar in form to the DEWA slab tariff.
- Hourly solar generation data was generated by inputting Abu Dhabi weather data into SAM. The only available TMY weather data for Abu Dhabi is comprised of data ranging from 1997-1999, making it approximately 20 years old.
- Hourly load data for a four-bedroom villa was interpolated from monthly values provided by Greentech (same method used to model load in the simulations), however this load data showcases a scenario in which the AC is on year-round to maintain a constant indoor setpoint. Because of this, residential load will be much higher than what is expected if residents turn off the AC when they are not home.
- The retail PG&E tariff, Time-of-Use (TOU) A6 was used to represent a commonly-used, small/residential time-of-use schedule.

DEWA does not yet allow for two-way grid connection between energy providers and large commercial energy storage facilities, although net-metering agreements are possible through their SHAMs initiative and special agreement with TSC. Because DEWA does not yet have demand response programs or grid-connected storage systems, this analysis was performed to present the mutual benefits if these services were to be incorporated into Dubai's energy infrastructure. In reality, ancillary services such as demand response are only available to energy storage systems of considerable size (MW-scale). Furthermore, CAISO values were used for a majority of the StorageVET inputs. Because of these factors, this analysis is merely to represent possible economic and utilitarian benefits from implementing storage and reforming energy prices rather than provide an accurate estimation. Below, the tabulated data for the four cases can be seen, summarized with net revenue. Monthly values for each scenario may be found in the appendix, section 4.6.1.

Table 4-17. Revenue comparison with various combinations of solar PV, battery storage, and demand response

Scenario	Net Revenue, 1 Year ($ USD)
Four-bedroom villa; no PV or battery, no demand response	-$1,480
Four-bedroom villa; installed PV, no battery, no demand response	-$1,075
Four-bedroom villa; no PV, installed battery, demand response enabled	-$480

Four-bedroom villa; installed PV and battery, demand response enabled	$985

In the first scenario, electricity was charged from the grid in the amount of the hourly load. As such, electricity was purchased from the grid regardless of its cost. With no solar being present, the entirety of the load must be satisfied through grid purchases. Thus, demand response cannot be enacted and no energy savings are seen.

The second scenario represents the current situation at TSC, with each residential unit generating its own PV. This scenario has no demand response since the PV generation is uncontrolled and the there is no storage to buffer energy demand, so that any load not met by PV is met by the grid. The cost is lower than not having PV due to a reduced overall demand on the grid, but it is not the most efficient use of this newly generated power since the generation does not necessarily match when the consumption is occurring.

The third scenario installs only a battery without installing PV. Due to the ability of the battery to participate in demand response, the cost of electricity is one-third the value with no PV and no BESS simply due to optimizing the time at which energy is used. No additional energy is generated in this scenario, yet significant savings compared to the previous two scenarios were found. This is not currently possible in Dubai due to the lack of demand response and the inability to participate in the energy market. It does however show the value that energy storage can bring to the consumer. It also benefits the utility since it increases the predictability and stability of the demand, which is reflected in the time of use pricing.

The fourth and final scenario modeled in storage vet is similar to the system modeled in SAM and is closest to the system that would be installed in TSC since PV already exists. Thus, this scenario shows the value that could be extracted from the installation of PV and BESS if time of use billing were implemented by DEWA or TSC was able to participate in demand response. This system generates a profit of $985 compared to the losses incurred by all other systems. This is made possible by the increased self-consumption of energy generated by the PV thanks to the BESS, and to demand response services sold back to the utility.

This is clearly beneficial for the customer, since they can now profit from their energy use. It must also be beneficial to the utility, presumably the services provided by the customer to the utility must be worth more than $985 to the utility if they are willing to pay this to the customer. Thus, we see that this situation is good for both the consumers and the utilities, but it requires that demand response and time of use be implemented which is not the current state of the energy market in Dubai. This section has shown what the possible benefits of installing PV and BEES can be when the utility makes a large commitment to renewable energy and demand response and allows third-parties to participate in the energy market. The sections regarding the SAM model compare the cost of BESS in Dubai.

4.5 Comparison of Lithium-Ion and Flow Batteries

Although lithium ion batteries have been the preferred choice of technology for battery energy storage, redox flow batteries (RFBs) are an emerging and promising new technology for energy storage applications. Like a polymer electrolyte membrane fuel cell, an RFB is an electrochemical energy conversion device that initiates redox reactions in external fluid tanks and draws electrons through a polymeric membrane to store or discharge energy when required. Because the redox reaction occurs in external tanks, there is potential for adding near-unlimited storage capacity simply by adding more tanks. In addition to their high capacity and scalability, RFBs have high round-trip efficiency and deep depth of charge.[9] Unlike traditional lead-acid or lithium-ion batteries, RFBs have separate power and energy system capacities; power capacity is determined by electrode size and number of cells in a stack, while energy storage capacity is determined by the concentration and amount of electrolyte solution in the external tanks.[10] Small RFB systems can successfully integrate with renewable generation technologies to serve end-use customer load while large RFB systems can provide grid-scale services like spinning reserves, frequency control, or load levelling (Redox for energy conversion).

TSC storage models have been analyzed primarily using lithium-ion battery technology because of its prevalence in the energy storage industry. However, analysis has been conducted considering redox flow batteries because of the technology's promising application in large-scale, low impact energy storage. The International Renewable Energy Agency reports that vanadium RFBs may have cycle lives of over 12,000 full cycles with estimated installation costs of approximately $350 USD/kWh. Average costs for Lithium-ion (any chemistry) battery packs was $280/kWh in 2016 and is forecast to be as low as $190/kWh by 2020 and $74/kWh by 2030 according to Bloomberg.[11] However, this does not account for the *installed* cost of energy storage, which can add a significant cost. In 2018, the installed cost of residential energy storage was as high as $1,000/kWh based on Tesla Power Walls and LG Chem's RESU10H.[12] Conversely, large grid-scale energy storage installed costs are between $500/kWh[13] for a 129 MWh system and $700/kWh[14] for a 100 kWh system. Redox flow technologies are promising for future applications but are not as widely used and manufactured as lithium-ion technologies and their cost is not coming down as quickly, which is why lithium-ion technology has been recommended for use at TSC.

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[9] https://ac.els-cdn.com/S1364032113005418/1-s2.0-S1364032113005418-main.pdf?_tid=458b9d74-22b3-4e5e-a351-4ce684e4e695&acdnat=1526916483_c19209e6ed802dce26c97a92dbaf8b97
[10] https://ac.els-cdn.com/S037877530600437X/1-s2.0-S037877530600437X-main.pdf?_tid=a4602d5a-247e-4dbc-9e45-63ec56151dd7&acdnat=1526929412_3469af98df9725c77aa07af9c7ddc58a
[11] https://data.bloomberglp.com/bnef/sites/14/2017/07/BNEF-Lithium-ion-battery-costs-and-market.pdf
[12] https://www.greentechmedia.com/articles/read/tesla-hikes-powerwall-prices
[13] https://electrek.co/2018/09/24/tesla-powerpack-battery-australia-cost-revenue/
[14] https://electrek.co/2018/01/10/tesla-powerpack-system-france/

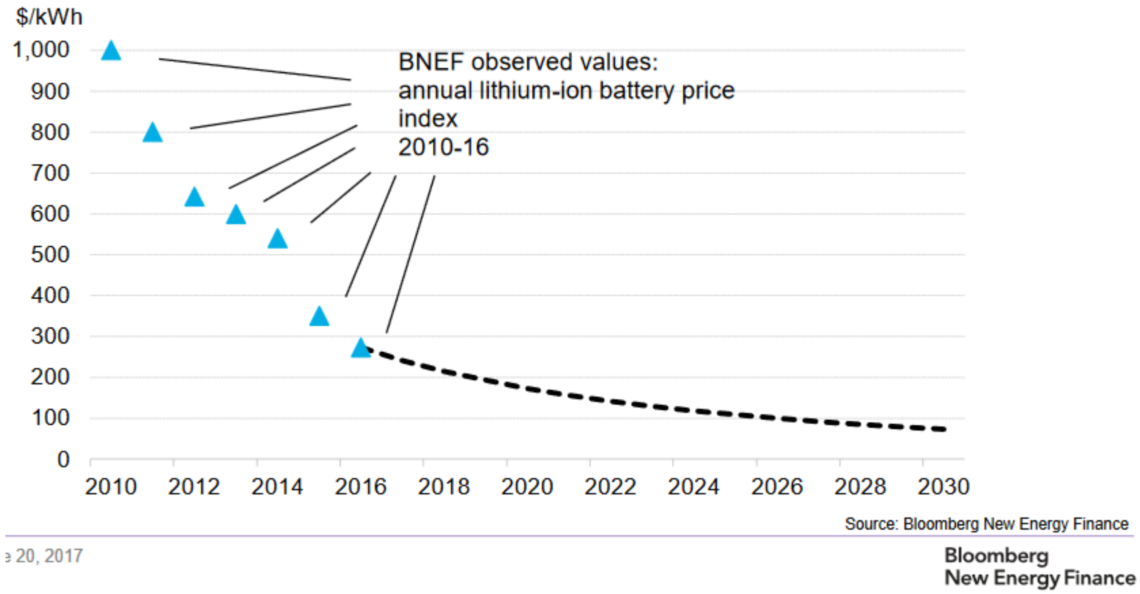

Figure 6: Historical and predicted costs of lithium-ion battery packs for electric vehicles from Bloomberg.[15]

4.6 Recommendations for Installation and Further Study

The team's recommendations should be prefaced with a realistic accounting of the energy market and landscape in Dubai as of this study's publishing in late 2018. In a country filled with opportunities for growth in the renewable energy sector, Dubai has begun to facilitate the installation of both rooftop residential and commercial/grid-scale solar PV systems through their SHAMs PV initiative and the development of net metering schemes. However, the country's energy sector must undergo significant growth to pave the way for an advanced energy infrastructure like California, the region with which the team is most familiar. Unlike Dubai, California has a variety of net metering schemes, demand response programs, and time-of-use tariffs that make PV-plus-storage and/or PV-only systems affordable and cost-effective. California also has regulatory bodies, utilities, and an independent grid operator that all function in tandem to both maintain grid stability/safety and drive new innovations in the renewable energy sector. Large-scale storage installations to enhance reliability and phase out nonrenewable generators are not only encouraged, but mandated.

Without this complex framework of policy, incentives, and opportunities, there is not much opportunity for energy storage to provide benefits to system owners in Dubai. This is unlikely to change unless a large amount of renewable generation is added to the grid, which will give the utility an incentive to install storage or have customers install storage.

The team believes that the listed items below, if implemented in Dubai with DEWA's support, would make energy storage a competitive and cost-effective technology in Dubai:

- Time-of-Use (TOU) rate structures
- Demand Response programs offered by utility or grid operator

[15] https://data.bloomberglp.com/bnef/sites/14/2017/07/BNEF-Lithium-ion-battery-costs-and-market.pdf

- Ancillary services offered by grid operator (e.g. energy arbitrage, reserve capacity, transmission/distribution upgrade deferrals, black start/spin/non-spin capacity)
- Government incentives and/or mandates for renewable technology
- Market competition between large brands to drive $/kWh prices down in the region

4.6.1 Technical System Recommendations

In TSC's specific case, there is little benefit in installing energy storage especially since the landlords have a special net metering agreement with DEWA by which all excess generation is sold back to the grid at purchase rates. Because there is no difference in price from buying or selling, there is no reason to store electricity rather than purchasing directly from the grid from TSC's perspective. DEWA would benefit from TSC's installation of storage and the associated peak shaving scenarios which would relieve strain on the local distribution grid (but in this case, smaller remote storage systems could be installed behind-the-meter at the grid tie point). From a cost perspective, it is cheaper and more efficient to purchase electricity directly from the grid and perhaps add new or expand current PV installations to meet load during daylight hours or over generate to take advantage of the net-metering agreement. This effectively uses DEWA's grid as a battery by "storing" extra energy in terms of credits that can be used to buy it back when it is needed. However, from an environmental perspective, installing battery storage allows for excess daytime PV energy to be stored and discharged during non-daylight hours, increasing the renewable fraction of TSC's energy. This also reduces reliance on the grid, therefore reducing TSC's overall carbon footprint. This not only has an environmental benefit, but also increases the "perceived greenness" of TSC and may be of interest to show TSC's commitment to clean energy to potential investors and residents. It will be up to TSC and Diamond Developers to identify the driving factor behind installing energy storage, whether it be cost-driven, environmentally-driven, or marketing-driving.

4.6.1.1 Simulation 1

Simulation 1, a single four-bedroom villa with a small Lithium-ion battery system, shows that energy storage is not a cost-effective solution at that scale. Despite high consumption (primarily due to the air conditioning unit and interior/exterior lighting), the current amount of installed rooftop PV can offset about 25% of the average villa's daily consumption during daytime hours. However, because the PV will never produce more than the unit's load requirements, there is no opportunity to charge the battery from renewable generation enough to make a significant difference.

The battery could charge from the grid during the day to meet load at night but because DEWA does not currently have a time-based rate structure, there is no financial incentive to storing energy during the day/consuming stored energy at night instead of just consuming directly from the grid. In fact, this may be more inefficient due to various losses associated with charging and discharging a battery. Since most of the grid electricity is sources from fossil fuels at all times of day, these losses amount to increasing TSC's carbon footprint.

If DEWA were to implement time-based rates, a battery at each villa may be a financially beneficial installation but currently is not recommended by the team. Alternatively, if DEWA were to generate a significant fraction of their daytime energy from solar PV, installing a battery and charging it during the day from the grid and discharging at night could reduce TSC's carbon footprint. Each unit could also increase their individual amount of PV generation by between 400% - 600%, at which point PV could generate enough energy to power the villa during the day while charging the battery for discharge at night. However, this option increases costs and is not feasible due to the limited rooftop area on each villa.

4.6.1.2 Simulations 2 and 3

The results from Simulations 2 and 3, which are based on scaled energy storage capacity/power values from Simulation 1, again show that energy storage is not a cost-effective solution at this scale. As was the case with the single four-bedroom villa, there is simply not enough currently-installed PV to generate enough energy to power the villa cluster (100 villas) or entire residential area (500 villas) such that the units are not reliant on DEWA grid power. However, at this scale, properly-sized battery storage systems coupled with the PV that is currently installed may be able to provide services like peak shaving or load leveling.

Peak shaving is a desirable application because it decreases the amount of load spikes, increasing grid stability, helping mitigate reductions in power quality, and increasing distribution efficiency. Although this does not apply under DEWA's tariff, some utilities (especially in California) implement high demand charges when large residential areas have spikes/peakiness in their load profile. A demand charge is a billing mechanism used by utilities that charges users for their highest power draw in terms of kW rather than kWh, typically $12-$18/kW. Demand charges make battery storage especially beneficial because it can level out these spikes and decrease expensive demand charges.

Battery storage can also be useful at TSC for load leveling, where load is kept at a relatively constant target value. In this way, stability and reliability are ensured and TSC is able to accurately predict energy bill charges on a month-to-month basis since demand stays essentially constant. There may also be opportunities for other special arrangements (e.g. bill reduction or credits for avoidance of load spikes) with DEWA in this case, since this will be beneficial for the health of the distribution grid and help to avoid costly equipment upgrades or audits. However, the amount of currently-installed PV coupled with appropriately-sized battery storage for both Lithium-ion and Vanadium flow technologies does not currently support off-grid functionality; this may be achieved with the installation of additional PV generation, discussed below.

4.6.1.3 Simulations 4 and 5

With the goal of off-grid functionality in mind, the team recommends Simulations 4 and 5 for review by Diamond Developers. Generally, both modeled systems are advantageous because they are centralized instead of distributed (Simulation 3's system is also centralized but is not feasible based on the points outlined above). This means that additional PV panels/components and battery storage units will be marketed towards the commercial & industrial sectors and can be purchased in bulk, driving down costs and eliminating retail markups. Annual operation and maintenance costs are also likely to be lower since maintenance personnel can service equipment in one centralized area instead of travelling between residences; a few large shipping containers' worth of battery storage units are more efficient to service than hundreds of battery storage units distributed throughout TSC.

Simulation 4 presents the required system size for the entire residential area of TSC, 500 villas, to operate entirely without dependence on the DEWA distribution grid. To ensure true off-grid functionality for any point during the year, the minimum required PV array size would need to generate enough energy to meet 100% of residential load on the day of highest demand on an average weather day. This array size was calculated to be 22.76 MW, taking into account the highest day's total load and the estimated capacity factor of 16%. It was found that the required battery storage would need to store 39 MWh of electricity at 6.2 MW power to ensure off-grid functionality on this day of highest load. Implementation of this system would require engagement with DEWA to discuss the legal and logistical implications of disconnecting from grid service.

In addition to purchasing and installing new battery storage units, TSC would need to install additional PV to ensure off-grid functionality is met. Assuming all existing residential and parking structure PV contributed to making the residential portion of TSC off-grid, an additional 16.89 MW of PV would need to be installed. The SAM simulations were run assuming *all* PV and battery storage would be purchased and installed without any contribution from existing PV; SAM modeling tools are not granular enough to differentiate between these specifics. However, based on previous conversations with Diamond Developers, the 3 MW of parking structure PV is already used to meet commercial/lighting and electric vehicle charging load, therefore 22.76 MW of PV is only a slight overestimation and will provide an upper estimation of expected costs.

This system configuration has a high expected capital expenditure ranging between $54 million for Lithium-ion batteries and $75.8 million for Vanadium flow batteries, resulting in a cost-per-watt value of $2.55/W and $3.60/W for each technology respectively. Because Lithium-ion battery technology is more mature and readily-available for large installations than flow battery technology, the team recommends Lithium-ion battery technology. In addition, the payback period for the Lithium-ion system is much shorter than for the flow system at 19.3 years, compared to 25.3 years. Payback period is based on year-over-year operation & maintenance costs and system revenue, where system revenue is simply the avoided cost by producing energy from PV instead of consuming from the grid. It is important to clarify that, due to the current DEWA rate structure and tariff, TSC will actually be saving less money by installing the battery system and will only be avoiding the cost of consuming energy directly from the grid after paying the capital expenditure required to install the system, which is relatively high. To examine the differences in cost and payback period, the team also ran this simulation without battery storage but with the 22.76 MW of PV. In this case, payback will be reduced to 13.1 years but there will be issues with significant overgeneration and end-of-day ramping as the sun sets. It is not recommended to install this much PV without having some sort of storage technology to avoid overgeneration, curtailment, and the ramping effects that could damage the local distribution grid (assuming there was some remaining connection to the DEWA grid).

Simulation 5's configuration will not achieve true island/off-grid functionality but will enable TSC to become "zero-net energy" (ZNE) and lower capital expenditures for system installation. Instead of autonomously producing enough energy using PV, the system will produce energy during the day to meet load in addition to charging the battery and selling energy back to the grid; at night, the battery will discharge to meet load in addition to drawing grid power. At the end of one year, the amount of energy sold back to DEWA will equal the amount of energy drawn from the grid, resulting in a net consumption of approximately 0 kWh and a net electricity bill of approximately $0. The actual system sizes for Lithium-ion batteries and flow batteries will result in slight kWh overproduction and net positive revenue but can be considered approximate ZNE systems.

Because Lithium-ion and flow battery systems produce slightly different amounts of lifetime energy, PV sizing varied slightly between technologies. For a Lithium-ion battery system, 14.225 MW of PV coupled with a 10 MWh/6 MW storage system was required for ZNE capability; for a flow battery system, 14.11

MW of PV coupled with a 10 MWh/6 MW storage system was necessary. Like with Simulation 4, this configuration does not take into account the already-installed parking structure PV and therefore provides a slight overestimate of the additional PV required and the costs associated with that additional PV.

The capital costs for this simulation range from $28.6 million for Lithium-ion batteries and $36.9 for Vanadium flow batteries, yielding a cost-per-watt value of $2.01/W and $2.61/W respectively. Again, Lithium-ion battery technology is recommended over flow battery technology due to Lithium-ion's lower costs and commercial availability. The payback period for a Lithium-ion system is 17.16 years compared to the payback period for a flow battery system of 20.7 years. Again, the only revenue from the system consists of avoided energy costs (not purchasing energy from DEWA) due to the tariff and rate structures currently in place. It will be cheaper to simply install PV, resulting in a payback period ranging from 13.2 – 14.7 years for the Lithium-ion and flow configuration respectively. However, TSC may experience dangerous ramping effects and overgeneration/curtailment by installing large amounts of PV without any storage component. Further discussions with DEWA will be required to see if this large amount of PV can be integrated into the distribution grid without requiring grid upgrades.

It is also important to account for the required surface area for both systems in Simulations 4 and 5. For energy storage, a good estimation is that every 1 MWh of BESS requires one ISO 20-foot shipping container, or about 2 parking spots. Considering 39 MWh of BEES for Simulation 5, the equivalent of about 80 parking spaces is required. The area required for the PV is also large, at 332,000 m^2, or about 70% of the surface area of TSC for Simulation 4's 22.7 MW of PV. Simulation 4's area is slightly more reasonable (but likely still impractical) at 225,000 m^2 or about 48% of the area of TSC. When we consider that this PV is required in addition to the currently installed parking lot PV that is powering the commercial sector, more land may be required to install sufficient PV to implement Simulations 4 or 5.

4.6.2 Areas for Further Study

As previously mentioned, the implementations of Simulations 4 and 5 will require further study and discussion with DEWA. The area of main concern is the large volume of electricity that will be produced by installing megawatt-scale PV systems that may over-generate during many times throughout the year (especially for Simulation 4's system). When PV systems are at risk of over-generation, i.e. producing more electricity than can be consumed, the PV system will shut off and curtail the production of excess electricity. This is advantageous because it protects electrical equipment from surges and high-volume transmission, extending the life of the distribution grid and avoiding outages. The addition of battery storage can also avoid curtailment; however the storage needs to be sized to store the largest amount of overgeneration possible, typically during the day of highest insolation.

However, TSC has a net-metering agreement with DEWA enabling the sale of excess electricity back to the grid which means PV systems do not have to curtail when production exceeds demand. For both Simulations 4 and 5, there will be large amounts of over-generation at various times throughout the year when demand is low and insolation is high, meaning large volumes of electricity would be sold back to DEWA. Because net-metering and solar installation is a relatively new phenomenon in Dubai, there may not be regulations or mandates surrounding the bulk sale of electricity back to the grid. For example, when a large generation plant (on the scale of the PV systems required for Simulations 4 and

5) wants to connect to the distribution or transmission grid to sell electricity back to the grid, they are required to complete a technical study that models the effect of the generator on the local grid. By completing such a study, it is possible to see if the bulk transmission of electricity from the generator will have adverse effects on the grid equipment. A study like this may be required for DEWA to authorize the installation of these systems. Additionally, the net-metering agreement may be restricted to a certain amount of electricity (e.g. electricity will be purchased back at sell-rates up to a maximum amount of 5 MWh per month). Further discussion with DEWA will be required to ensure the success of an off-grid or ZNE system at TSC.

5. Economic/Environmental Team

The economic/environmental team developed the methodology and formula for calculating the economic factors which some of them have already been presented in the previous section.

5.1 Formulation and Methodology

This section describes the methodology used for calculating various economic parameters that are used for modeling the cost effectiveness of the various system designs.

5.1.1 Energy Pay-back Time (EPBT)

Energy payback time is defined as the period required for a renewable energy system to generate the same amount of energy (in terms of primary energy equivalent) that was used to produce the system itself. Following the energy payback time formula by Fthenakis et al., (2011) for the report of the International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS Task 12) for Life cycle inventories and life cycle assessment of photovoltaic systems:

$$EPBT = \frac{Emat + Emanuf + Etrans + Einst + EEOL}{\left(\left\{\frac{Eagen}{\eta G}\right\} - EO\&M\right)}$$

Applying it on the EES:

- *Emat* = Primary energy demand to produce materials of the energy storage system
- *Emanuf* = Primary energy demand to manufacture the storage system
- *Etrans* = Primary energy demand to transport all materials used in the storage system during the life cycle
- *Einst* = Primary energy demand to install the system
- *EEOL* = Primary energy demand for end of life treatment
- *Eagen* = Annual generated electricity
- *EO&M* = Annual primary energy demand for operation and maintenance
- *ηG* = Grid efficiency, the average primary to electricity conversion efficiency at the demand side.

According to Fthenakis et al., (2011) there are two conceptual approaches to calculate the EPBT of PV power systems:

1. PV as replacement of the energy resources used in the power grid mix. This approach calculates the time needed to compensate for the total renewable and non-renewable primary energy required during the life cycle of a PV system (except for the direct solar radiation input during the operation phase, which is not accounted for as part of EO&M). Hence, the annual electricity generation (Eagen) is converted into its equivalent primary energy, based on the efficiency of electricity conversion at the demand side, using the current average (in attributional LCAs) or the long-term marginal (in decisional/consequential LCAs) grid mix where the PV plant is installed.

2. PV as replacement of the non-renewable energy resources used in the power grid mix. This approach calculates the EPBT by using the non-renewable primary energy only; whereas the renewable primary energy is not accounted for, neither on the demand side, nor during the operation phase. This approach calculates the time needed to compensate for the non-renewable energy required during the life cycle of a PV system. The annual electricity generation (Eagen) is likewise converted to primary energy equivalent considering the non-renewable primary energy to electricity conversion efficiency of the average (in

attributional LCAs) or the long-term marginal (in decisional/consequential LCAs) grid mix where the PV plant is installed. The result of using this approach must be identified as Non-Renewable Energy Payback Time (NREPBT) to clearly distinguish it from the EPBT derived from the 1st approach. The formula of NREPBT is identical to that of EPBT except for replacing primary energy with nonrenewable primary energy.

5.1.2 Energy Return on Investment (EROI)

As noted by Fthenakis et al., (2011) EROI can be calculated as follows:

EROI = lifetime / EPBT =

$$\frac{T * \left(\left\{\frac{Eagen}{\eta G}\right\} - EO\&M\right)}{(Emat + Emanuf + Etrans + Einst + EEOL)}$$

As suggested by Camilo et al. (2017) the NPV,IRR, PI, DPP, and LCOE can be used to conduct an economic assessment as follows:

5.1.3 The Net Present Value (NPV):

The NPV can be defined as the sum of present values of incoming (benefits) and outgoing (costs) cash flows, over the period of time considered for the project. NPV can be computed by:

$$NPV = \sum_{j=1}^{n} \frac{RL_j}{(1+a)^j} - \sum_{j=0}^{n-1} \frac{I_j}{(1+a)^j} + \frac{V_r}{(1+a)^n}$$

Where

- ❖ n is the project life time
- ❖ a the discount rate
- ❖ V_r salvage value of the installation at the end of the lifetime
- ❖ I_j the investment in year J
- ❖ RL_j the net revenue obtained in year j calculated from the difference between gross investment R_j and maintenance and operation costs $d_{O\&Mj}$ as a percentage of total investment I_j such that RL_j= Rj- $d_{O\&Mj}$ I_t

The project is accepted at NPV > 0

5.1.4 Internal Rate of Return (IRR)

Is the rate of return for which NPV is null, it is used to measure and compare the profitability of the investment.

$$\sum_{j=1}^{n} \frac{RL_j}{(1+IRR)^j} - \sum_{j=0}^{n-1} \frac{I_j}{(1+IRR)^j} + \frac{V_r}{(1+IRR)^n} = 0$$

Where

- ❖ n is the project life time
- ❖ V_r salvage value of the installation at the end of the lifetime

- I_j the investment in year J
- RL_j the net revenue obtained in year j calculated from the difference between gross investment R_j and maintenance and operation costs $d_{O\&Mj}$ as a percentage of total investment I_j such that $RL_j = Rj - d_{O\&Mj} I_t$

The project is economically profitable If the IRR > a (the discount rate).

5.1.5 The Profitability Index (PI) (Benefit-Cost Ratio)

It is the ratio of the present value of the estimated cash inflows of the investment to the present value of the estimated cash outflows of the investment.

$$PI = \frac{\sum_{j=1}^{n} \frac{RL_j}{(1+a)^J} + \frac{V_r}{(1+a)^n}}{\sum_{j=0}^{n-1} \frac{I_j}{(1+a)^j}}$$

Where:

- n is the project life time
- a is the discount rate
- V_r is the salvage value of the installation at the end of the lifetime
- I_j is the investment in year J
- RL_j is the net revenue obtained in year j calculated from the difference between gross investment R_j and maintenance and operation costs $d_{O\&Mj}$ as a percentage of total investment I_j such that $RL_j = Rj - d_{O\&Mj} I_t$

The project is accepted at PI > 1

5.1.6 Discounted Payback Period (DPP)

It is the time required to recover the initial investment from the present value of the expected future cash flows.

$$\sum_{J=1}^{DPP} \frac{RL_j}{(1+a)^J} + \frac{V_r}{(1+a)^n} = \sum_{j=0}^{n-1} \frac{I_j}{(1+a)^j}$$

Where

- n is the project life time
- a the discount rate
- V_r salvage value of the installation at the end of the lifetime
- I_j the investment in year J
- RL_j the net revenue obtained in year j calculated from the difference between gross investment R_j and maintenance and operation costs $d_{O\&Mj}$ as a percentage of total investment I_j such that $RL_j = Rj - d_{O\&Mj} I_t$

The project is accepted at DPP < n

5.1.7 Levelized Cost of Electricity (LCOE)

Is the discounted production cost of installing and operating a project, expressed in $/kWh of electricity, over its lifetime.

$$LCOE = \frac{\sum_{j=1}^{n} \frac{I_j + d_{O\&Mj}}{(1+a)^j} - \frac{V_r}{(1+a)^n}}{\sum_{j=1}^{n} \frac{E_j}{(1+a)^j}}$$

Where

- ❖ n is the project life time
- ❖ a the discount rate
- ❖ V_r salvage value of the installation at the end of the lifetime
- ❖ I_j the investment in year J
- ❖ $d_{O\&Mj}$ maintenance and operation costs
- ❖ RL_j the net revenue obtained in year j calculated from the difference between gross investment R_j and maintenance and operation costs $d_{O\&Mj}$ as a percentage of total investment I_j such that RL_j= Rj- $d_{O\&Mj}$ I_t
- ❖ Ej is the electrical energy generated in year j

A low LCOE means that electricity is being produced at a low price, with higher expected returns for the investor. Additionally, there are equations to evaluate the cost of batteries and the cost of the storage system as a whole.

5.1.8 Life Cycle Cost Analysis (LCCA)

A life cycle cost analysis (LCCA) can be used to estimate the costs added to store electricity. Poonpun (2006) suggested that LCCA can be calculated as follows:

The total energy discharged annually by an energy storage system which is referred to as annual energy production (AEP) is equal to:

$$AEP=P*n*H_o*D$$

where

- ❖ P is rated power output (kW).
- ❖ n is number of charge/discharge cycles per day.
- ❖ H_o is the length of each discharge cycle (h).
- ❖ D is the number of days the storage is operated each year.

The annual cost of a storage system consists of annualized capital cost (AC), annualized replacement cost (ARC), and annual operation and maintenance cost (OMC).

The annual fixed operation and maintenance cost (*OMC*) in US$ per year is:

$$OMC = OM_f * P$$

- ❖ Where OM_f is the fixed operation and maintenance cost per rated kW of storage (US$/kW).

The total capital cost (TCC) for the energy storage plant comprises three components: the total cost of the power electronic inverters (PCS), the total cost for storage units (SUC), and the total cost for the balance of plant (BOP).

The total cost for the power electronic inverter (PCS) in US$ is

PCS = PCSU* P

- where PCSU is the unit cost for the power electronic system in US$/kW.

The total cost for storage units (SUC) in US$ is:

$$\mathrm{SUC} = \frac{\mathrm{SUCU} * \mathrm{P} * \mathrm{H_o}}{\mathrm{eff}}$$

- where SUCU is the unit cost for the storage units (US$/kWh) and *eff* is the efficiency of the system calculated as:

$$\mathrm{eff} = \frac{\text{energy (kWh)out during discharge}}{\text{energy (kWh)in during charge}}$$

The total cost for the balance of plant (BOP) in US$ is

BOP = BOPU * P

- Where BOPU is the unit cost for the balance of plant (US$/kWh).

Hence, the total capital cost (TCC) is the sum of the total costs for the power conversion system, storage units, and balance of plant:

TCC = PCS + SUC + BOP

The annualized capital cost (AC) is:

AC = TCC * CRF

- Where CRF is the capital recovery factor, calculated as follows:

$$CRF = \frac{(i_r(1+i_r)^y)}{((1+i_r)^y - 1)}$$

where i_r is the annual interest rate to finance the storage plant, and y is the life of the plant in years.

In case of battery replacement during the life of the project, the cost of replacement is annualized (US$/kWh):

The annual replacement cost of battery is:

$$\mathrm{ARC} = \frac{\mathrm{A} * \mathrm{P} * \mathrm{H_o}}{\mathrm{eff}}$$

- Where A is:

$$\mathrm{A} = \mathrm{F}\,\{\left((1+\mathrm{i_r})\right)^{-\mathrm{r}} + (1+\mathrm{i_r})^{-2\mathrm{r}} + \cdots\}\mathrm{CRF}$$

- Where F is future battery replacement cost (US$/kWh) and r is the replacement period. The number of terms in the factor of the equation is equal to the number of replacements during the life of the project.

The replacement period r is calculated as:

$$r = \frac{C}{n * D}$$

- where C is number of charge/discharge cycles in the battery life.

Finally, the cost added to a unit (in kilowatt hour) of electricity stored is the total annual cost divided by the total energy discharged annually from a storage system:

$$COE = \frac{(AC + OMC + ARC)}{(P * n * H_o * D)}$$

N.B This cost is independent of the cost of electricity used to charge the storage.

5.1.9 References:

- Camilo, F. M., Castro R., Almeida, M.E., and Pires V. F. (2017). Economic assessment of residential PV systems with self-consumption and storage in Portugal. *Solar Energy*. 150. pp. 353–362.
- Fthenakis, V., Frischknecht, R., Raugei, M. Kim, H. C., Alsema, E., Held, M. and Wild-Scholten, M. D. (2011). *Methodology Guidelines on Life-Cycle Assessment of Photovoltaic Electricity*. International Energy Agency Photovoltaic Power Systems Programme IEA PVPS Task 12, Subtask 20, LCA Report IEA-PVPS T12-03:2011.
- Poonpun, P. (2006). *Economic Analysis of Electric Energy Storage*. (Unpublished Master's Thesis). The Department of Electrical and Computer Engineering and the faculty of the Graduate School of Wichita State University.

5.2 Lifecycle Analysis Methodology

The ISO (the International Organization for Standardization)[16] created standards for life cycle assessment (LCA) as a technique used to measure the environmental impact. LCA is a collection and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle, it addresses the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (cradle-to-grave). LCA usually does not address the economic or social aspects of a product. The ISO produced standard number ISO 14044 which set the requirements for conducting an LCA. It identified four phases in an LCA study: the goal and scope definition phase, the inventory analysis phase, the impact assessment phase, and the interpretation phase.

The first phase, the definition and scope include system boundaries whereas the level of detail of an LCA depends on the subject and the intended use of the study. Hence, the depth and the breadth of LCA differ

[16] ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework, Available at: https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en

considerably depending on the goal of a particular LCA. The second phase the life cycle inventory analysis phase (LCI phase) is an inventory of input/output data with regard to the system being studied. It entails collecting necessary data to meet the goals of the defined study. The third phase the life cycle impact assessment phase (LCIA) aims at providing additional information to help evaluate a product system's LCI results to better understand their environmental importance. The fourth phase the life cycle interpretation is the stage which the results of an LCI or an LCIA, or both, are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition. In some cases the goal of an LCA can be satisfied by performing only an inventory analysis and an interpretation. This is usually referred to as an LCI study; LCI studies are similar to LCA studies but exclude the LCIA phase however they differ than the LCI phase of an LCA study. The ISO standards provide detailed definitions, several requirements and recommendations to ensure transparency of these studies.

5.2.1 Greenhouse Gas Emissions and their Calculations

A greenhouse gas (GHG) is any gas in the atmosphere which absorbs and re-emits heat which keeps the planet's atmosphere warmer than it otherwise would be. The main GHGs in the earth's atmosphere are water vapor, carbon dioxide (CO_2), methane (CH4), nitrous oxide (N2O) and ozone. Although GHGs occur naturally in the earth's atmosphere human activities such as the burning of fossil fuels lead to increasing the levels of GHG's in the atmosphere, causing global warming and climate change.[17]

Different GHGs last in the atmosphere for different lengths of time and absorb different amounts of heat. Thus, the "global warming potential" (or "GWP") index of a GHG is calculated, it indicates the amount of warming a gas causes over a given period of time (normally 100 years)is, with CO_2 having the index value of 1, and the GWP for all other GHGs is the number of times more warming they cause compared to CO_2. Carbon dioxide (CO_2) is considered the most important and common GHG. However, other GHG's are still important, so Carbon dioxide equivalent (CO_2 e/CO_2 eq/CO_2 equivalent/ CDE) is used to describe different greenhouse gases in a common unit. For any quantity and type of greenhouse gas, CO_2e indicates the amount of CO_2 which would have the equivalent global warming impact. [18]

5.2.2 Life Cycle Analysis of Solar Photovoltaic Systems:

The authors noted that electricity generation is a source of global emissions of greenhouse gases (GHG), which requires measurement to identify the environmental impacts. Hence, they study the photovoltaic technology (PV) used for the production of electricity from renewable sources to reduce the energy consumption from traditional sources and decrease air pollution. During its operation PV technology is free from fossil energy consumption and greenhouse gases (GHG) emission. Nevertheless, when looking at its life cycle, it consumes a large amount of energy and emits some GHG during its different stages.[19]

The authors relied on various studies to appraise the four types of solar PV systems currently employed - Mono Crystalline, Multi Crystalline, Si PV System, and CdTe /CIS PV system- according to their LCA where they estimated the energy requirement, and energy payback time and GHG emissions. They compared between the different types according to the primary energy used and their efficiency and concluded with

[17] Brander, M. (2012). Greenhouse Gases, CO2, CO2e, and Carbon: What do all these terms mean?. Ecometrica
[18] Oprea D., (2010), Calculation of emission factor. Technical University of Moldova, pp.48-51.
[19] Baharwani, V., Meena, N., Dubey, A., Brighu, U. and Mathur, J., (2014). Life Cycle Analysis of Solar PV System: A Review, International Journal of Environmental Research and Development, 4 (2), pp. 183-190.

identifying a set of parameters that are responsible for the performance variability of different technologies

The Planov paper[20] aimed at conducting an internal Life cycle assessment for Gaia Solar- a company in Copenhagen established in 1996 which produces several solar panels- on its Design Line 145 (DL 145) to identify and highlight the stages in the production chain with the highest environmental impact to be improved.

They concluded that solar cells production accounted for the largest impacts in almost all categories because solar cell production is a very energy intensive process. In terms of resource consumption The two most resource demanding parts were roof installation and inverters, concerning the cumulative energy demand for the production of solar cells which reflects on the energy intensity of the production process, it was found that approximately 73% of the total CED is used in the solar cell production processes. The environmental impact related to showed that solar cell production contributes the most to GWP based on the results of the CED and especially non-renewable energy.

The IEA report[21] developed guidelines that were approved by PV LCA experts in North America, Europe, and Asia for assumptions made on PV performance, process input and emissions allocation, methods of analysis, and reporting of the results. The report guidelines were categorized into four main areas: recommendations on technical characteristics related to photovoltaic systems, aspects of modeling approaches in life-cycle-inventory analysis, and life-cycle impact assessment, interpretation, and reporting and communication.

The first category discussed photovoltaic specific aspects including life expectancy of different parts, irradiation, performance ratio, degradation, and backup systems. The second category discussed LCI/LCA modeling aspects including system modeling: static /prospective (attributional / consequential), electricity mix in background data, small versus large scale explained that the appropriate system model relies on the goal of the LCA; where it considered three types of LCA -retrospective LCA which reports environmental impacts of PV currently installed in a utility's network, short-term prospective LCA which focuses on the choice of a PV electricity-supplier, comparisons of PV systems, or of electricity generating technologies, and long-term prospective LCA which are long-term energy policy which compares between future PV systems or of future electricity generating technologies- and made recommendations for them.

5.2.3 Life Cycle Assessment of Electricity Generation Technologies, Energy Storage Systems, and Batteries.

5.2.3.1 Energy Storage Systems

The Stenberg paper[22] using life cycle assessment offered a systematic environmental comparison of energy storage systems providing different products such as reconversion to power, mobility, heat, fuels

[20] Palanov N. (2014).Life-cycle assessment of Photovaltaic systems- Analysis of environmental impact from the production of PV system including solar panels produced by Gaia Solar. Lund.

[21] Fthenakis, V., Frischknecht, R., Raugei, M. Kim, H. C., Alsema, E., Held, M. and Wild-Scholten, M. D. (2011). Methodology Guidelines on Life-Cycle Assessment of Photovoltaic Electricity. International Energy Agency Photovoltaic Power Systems Programme IEA PVPS Task 12, Subtask 20, LCA Report IEA-PVPS T12-03:2011.

[22] Sternberg A.and Bardow, A. (2015). Power-to-What? – Environmental assessment of energy storage systems. Energy and Environmental Science. Royal Society of Chemistry. 8. pp. 389–400.

and chemical feedstock, through evaluating the environmental impacts avoided by using 1 MW h of surplus electricity in the energy storage systems instead of producing the same product in a conventional process using data for United States, Brazil, Japan, Germany and the United Kingdom. The paper presented a general method to compare energy storage systems with different products with respect to their environmental impacts based on the life cycle assessment (LCA) principle through answering the question: which energy storage system has the greatest environmental benefit given 1 MWh of surplus electricity from renewable energies?

The energy storage systems were compared through focusing on two environmental impact categories: global warming (GW) and fossil depletion (FD). The results for fossil depletion and global warming impact were presented in oil-equivalents and CO2-equivalents, respectively. Also, impact categories of eutrophication (freshwater and marine), human toxicity, ionizing radiation, mineral resource depletion, photochemical oxidant formation, ozone depletion, particulate matter and terrestrial acidification were analyzed. The paper analyzed four different types of energy storage systems: Power-to-Power storage systems which convert electricity to chemical or mechanical energy, Power-to-Mobility storage systems which store input electricity in battery electric vehicles (BEV), Power-to-Heat storage systems which convert power directly to heat, and Power-to-Fuel storage systems which produce hydrogen by electrolysis. To find out the environmental impacts, the energy storage systems were modeled in GaBi 6.3

The paper concluded that the highest global warming and fossil depletion impact reductions were achieved by using surplus power in heat pumps (Power-to-Heat) and battery electric vehicles (Power-to-Mobility), while the third highest environmental impact reductions were achieved by the Power-to-Power systems. In addition, environmental impact reductions were achieved through the direct utilization of hydrogen but these impact reductions were lower than for the Power-to-Heat, Power-to-Mobility and Power-to-Power systems. Moreover, the lowest CO2 mitigation costs were achieved by compressed air energy storage and pumped hydro storage while the battery electric vehicle and the Power-to-Heat storage systems also have the potential for low CO2 mitigation costs they required a more frequent surplus power supply (e.g. once a day) and more hours with surplus power supply.

The Hoppman paper[23] claimed three important barriers face the widespread use of solar PV. First, electricity generation from this source is limited to daytimes, second, it depends on local weather conditions, third, it fluctuates strongly. Thus, storage technologies are employed to reduce the mismatches between electricity demand and electricity supply by irregular energy sources. Storage solutions based on battery technologies became popular yet adding storage technologies to a PV system also raises the overall investment cost. Hence, the paper conducted a simulation model to examine the economic viability of battery storage for residential PV in Germany for eight different electricity price scenarios from 2013 to 2022 based on a review of previous studies that examined the economics of integrated PV-battery systems.

The results of the model showed that battery storage is economically viable for small PV systems under all electricity price scenarios, especially the scenarios that were in line with trends in Germany. In addition, if households have limited access to the wholesale market in the future, this would not weaken and may boost the storage profitability. Concerning environmental pollution, the studied lead-acid batteries

[23] Hoppmann J., Volland J., Schmidt T.S., Hoffmann V.H. (2014). "The Economic Viability of Battery Storage for Residential Solar Photovoltaic Systems - A Review and a Simulation Model", Renewable and Sustainable Energy Reviews. 39. pp. 1101–1118.

contained sulfuric acid as well as toxic lead and generated carbon emissions particularly during lead mining and polypropylene production, the environmental impact of these batteries can be reduced if the lead is recycled. Moreover, results showed that the use of battery storage allowed households to consume a larger share of self-produced electricity, reducing the amount of electricity bought from utilities. Thus, even without policy support households will raise the amount of electricity they produce themselves. The paper concluded with some implications to be considered by policy makers in Germany.

The Denholm paper[24] reviewed energy storage as a solution for the irregularity of technologies relying on renewable energy. The paper provided life cycle assessment results that evaluated the energy requirements and greenhouse gas (GHG) emissions from the construction and operation of different utility scale energy storage systems.

Comparing between the storage systems, BES systems had considerably 4–8 times greater energy requirements associated with plant construction compared to equivalent size PHS and CAES systems, also The operation and maintenance (O&M)energy requirements for BES systems were slightly higher than those for PHS or CAES systems. Concerning GHG it was found that emissions from storage systems resulted from the generation of the electricity stored, as well as from the construction and operation of the storage facility. In addition, the paper stated that the net emissions from stored electricity were dominated by the primary electricity generation emissions, particularly when fossil is used for energy generation; inefficiencies in the storage process were the dominant source of GHG emissions from stored fossil generated electricity especially for PHS and BES. The paper concluded that energy storage systems increased both the input energy required to produce electricity and total greenhouse gas emissions. Nevertheless, energy storage systems when joined with nuclear or renewable sources had substantially lower GHG emissions during their life cycles than from fossil fuel derived electricity sources.

5.2.3.2 Batteries

Liang et al[25] selected Lithium iron phosphate (LiFePO4) battery to be studied and the functional unit was defined as 1MWh to be able to compare the results of the carbon footprints to different batteries; the system boundary included raw materials acquisition, processing, and manufacturing, transport to use phase and excluded recycling to calculate the carbon label of the lithium-ion battery.

The paper further reviewed the components of lithium iron phosphate and the nickel metal hydride batteries (Ni-MH), and a solar cell and calculated their carbon footprint; in addition, it calculated the energy consumption during the entire life cycle of the batteries except for the recycling phase. The paper results showed that using the same functional unit of 1MWh the carbon footprint of lithium iron phosphate battery's raw material was 12.7 kg CO_2eq., which was the lowest compared to the other two batteries- Ni-MH battery's 124 kg CO_2eq and the solar cell's 95.8 kg CO_2eq.- According to the LCA life the GHGs emissions of lithium iron phosphate battery were less during the raw materials assembly stage, production stage and transport stage. While, the repeated charge-discharge in the use stage made it produce more GHG amounting to 720.7 kg CO_2eq. It consumed large amounts of electricity in use phase

[24] Denholm P., and Kulcinski, G. L. (2004). Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems. Energy Conversion and Management. 45. pp. 2153–2172

[25] Liang, Y., Su, J. Xia, B., Yuc, Y., Ji D., Suna, Y., Cuia, C., Zhua, J. (2017). Life cycle assessment of lithium-ion batteries for greenhouse gas emissions. Resources, Conservation and Recycling.117. pp. 285–293

and the carbon footprints produced from it accounted for the most part of the life cycle carbon emissions. The paper concluded that according to the results lithium ion batteries were environmental friendly.

5.2.3.3 Economic Evaluation of Energy Storage

The Camilo paper[26] aimed at investigating the economic profitability of different residential PV systems configurations since there has been a wide spread utilization of renewable micro generation schemes. The paper reviewed studies on the economic assessment of PV systems with the goal of verifying the profitability of PV systems in various viewpoints. The paper relied on Net Present Value (NPV), Internal Rate of Return (IRR), Profitability Index (PI) and Discounted Payback Period (DPP) to conduct the economic assessment, as well as computing levelized cost of electricity (LCOE) for each PV system configuration to assess the influence of the storage device on the economic profitability of the project especially those systems including batteries.

The paper considered four different scenarios analysis: the base-case of Injects all/consumes all where there is no self-consumption in this mode, self-consumption (SC) without storage (ST), self-consumption with storage, and net-metering (NM). Each scenario was applied on four different commercially used PV power kits (PV0.5 kWp, PV 1 kWp, PV 1.5 kWp and PV 4 kWp) and for the storage device a OPzV battery type from FIAMM was used.

The paper studied the economic attractiveness of the prosumer's investment and found that the most cost effective solution was the PV 0.5 kWp of self-consumption without storage. Therefore, a PV system designed for self-consumption, should be sized to the minimum peak consumption throughout the day, avoiding the injection in network, as it presents the most profitable and viable solution for the prosumer. Although storage was not found as a practical option, the PV 1 kWp in the self-consumption with storage scenario was the closest to reach economic viability if there is to be a price reduction in both the PV kit and battery. The paper concluded that self-consumption is to be encouraged in Portugal as those projects proved to be economically feasible.

The Madlener paper[27] assessed the economic viability of second use batteries from electric vehicles for load shifting and peak shaving in residential applications. Results have shown that investments in second-use battery storage systems were profitable for the homeowner under certain circumstances even without financial incentives i.e. for the scenario with the highest increase of the electricity price (S3) investments in storage systems were found to be profitable for all estimated battery costs, while in scenario S2 (4%), the breakeven battery price was found to be 107 €/kWh and in the scenario with the lowest increase of the electricity (S1) the battery price had to be equal or less than 73 €/kWh. The optimal storage size depended on the battery costs as well as on the costs for additional equipment and maintenance. For the battery storage, the economic viability depended on the difference between the electricity price and the feed-in tariff. As residential storage systems were found to be viable in most

[26] Camilo, F. M., Castro R., Almeida, M.E., and Pires V. F. (2017). Economic assessment of residential PV systems with self-consumption and storage in Portugal. Solar Energy. 150. pp. 353–362.
[27] Madlener, R., and Kirmas A. (2017) Economic viability of second use electric vehicle batteries for energy storage in residential applications. The 8th International Conference on Applied Energy – ICAE2016. Energy Procedia. 105. pp. 3806 – 3815.

circumstances, the paper predicted that the number of installed units is supposed to increase in upcoming years as well as the share of renewables.

The Poonpun thesis[28] conducted a cost analysis of grid-connected electric energy storage using different battery energy storage technologies. It aimed at answering the question of how much does storage add to the cost of a kWh of electric energy? through a basic economic analysis of electric energy storage whereas the capital and operating costs of storage units were converted to a cost per kWh of energy stored. The thesis defined energy storage as storing of some form of energy that can be drawn upon at later time to perform some useful operations.

The thesis estimated the cost added to each kWh of electricity by the storage system, in order to compare electricity cost, in US$/kWh, of electricity that is stored after generation with electricity that is used immediately. This was carried out through a life cycle cost analysis. Whereas the annual cost consisted of annualized capital cost, annualized replacement cost, and annual operation and maintenance cost. Cost of electricity was calculated by dividing the total annual cost by the total energy discharged annually from storage system.

The thesis concluded that compared to the wholesale electricity prices in North America, the cost of electricity storage systems had to drop by 50% or more of its present cost, to allow for its widespread use, however cost only is not to be used to take a decision concerning storage systems some other factors should be taken into consideration such as deferral of transmission and generation facilities, the market design, and how markets treat stored energy. In addition, the thesis assumed that when costs of storage are reduced, storage is supposed to help in solving many problems in electrical power and may even generate profits. The thesis also concluded that some parameters had affected the cost of electricity (COE) drastically, such as the parameters of operating condition i.e. the number of discharge cycle per day and operating days per year which lead to variation of the COE. Also, the replacement period had a crucial impact on replacement costs; meanwhile, results showed that operation and maintenance cost when compared with capital cost and replacement cost had the least significant impact. The thesis found that sodium bromide/sodium polysulfide flow batteries were the most cost effective technology of the studied technologies for generation applications. Meanwhile, for transmission and distributions Lead-Acid batteries were the most cost-effective technology.

5.2.4 TSC LCA

5.2.4.1 Goal and scope definition

Based on the literature review conducted above, the LCA for TSC considered the various scenarios modeled in SAM to determine the cradle-to-grave life-cycle impacts.

5.2.4.2 Inventory analysis phase

SAM Simulation 1:

- 5.75kW PV
- 6 kW PV inverter

[28] Poonpun, P. (2006). Economic Analysis of Electric Energy Storage. (Unpublished Master's Thesis). The Department of Electrical and Computer Engineering and the faculty of the Graduate School of Wichita State University.

- 20 kWh BEES
- 10 kW BEES inverter

SAM Simulation 2:

- 575 kW PV
- 575 kW PV Inverter
- 2 MWh BEES
- 1 MW BEES Inverter

SAM Simulation 3:

- 2.875 MW PV
- 2.875 MW PV Inverter
- 10 MWh BEES
- 5 MW BEES Inverter

SAM Simulation 4:

- 22.76 MW PV
- 22.76 MW PV Inverter
- 38.5 MWh BEES
- 6.2 MW BEES Inverter

SAM Simulation 5:

- 14.2 MW PV
- 14.2 MW PV Inverter
- 10 MWh BEES
- 6 MW BEES Inverter

5.2.4.3 Impact assessment phase

PV:

Based on the literature, it was found that PV systems involve $34 \frac{gCO_2}{kWh_e}$ on average. From this, we calculated the carbon (equivalent) intensity of energy produced from the PV systems proposed in the various simulations.

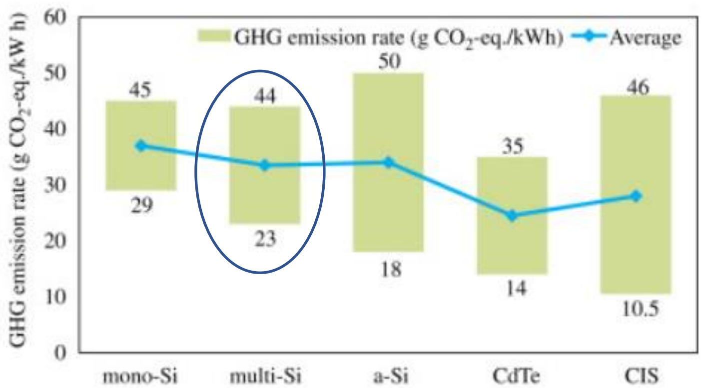

Figure 5-7: PV life-cycle impacts including the balance of system (i.e. inverter).[29]

BEES:

Based on the literature, it was found NMC battery systems such as the one we considered involve 85.6 $\frac{gCO_2}{kWh_e}$ on average. From this, and assuming one full charge/discharge cycle per day and a lifetime of the battery of 15 years, we calculated the carbon (equivalent) intensity of energy discharged from the BESS proposed in the various simulations.

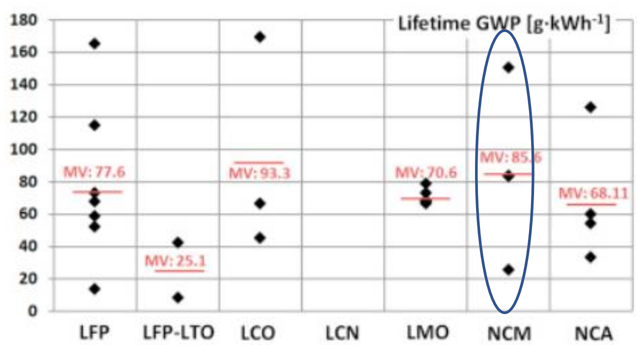

Figure 5-8: Life-cycle impacts of BEES.[30]

BEES Inverter:

[29] Peng, J., Lu, L., & Yang, H. (2013). Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. *Renewable and Sustainable Energy Reviews*, *19*, 255-274.

[30] Peters, J. F., Baumann, M., Zimmermann, B., Braun, J., & Weil, M. (2017). The environmental impact of Li-Ion batteries and the role of key parameters–A review. *Renewable and Sustainable Energy Reviews*, *67*, 491-506.

For the battery inverter, an impact of 25.9 $\frac{kgCO_2}{kW}$ was used.[31]

5.2.4.4 Results

The tables below summarize the total CO_{2e} emissions from the proposed systems. The total impact scales linearly with the size of the system due to the nature of the calculations.

5.2.4.4.1 Simulation 1

Device	kgCO2e/kWh	Size	kWh/day	Lifetime (Years)	Lifetime kWh	Total Impact	Unit
PV	0.034	5.75	25	25	228,281	7,647	kg CO2e
Battery	0.086	20.0	20	25	182,625	15,633	kg CO2e
Battery Inverter	25.9	10	-	-	-	259	kg CO2e

Simulation 2

Device	kgCO2e/kWh	Size kW(h)	kWh/day	Lifetime (Years)	Lifetime kWh	Total Impact	Unit
PV	0.034	575	2,501	25	22,839,539	765,125	kg CO2e
Battery	0.086	2,000	2,000	25	18,262,500	1,563,270	kg CO2e
Inverter	25.9	1,000	-	-	-	25,900	kg CO2e

Simulation 3

Device	kgCO2e/kWh	Size	kWh/day	Lifetime (Years)	Lifetime kWh	Total Impact	Unit
PV	0.034	2,875	12,506	25	114,197,695	3,825,623	kg CO2e
Battery	0.086	10,000	20	25	182,625	15,633	kg CO2e
Inverter	25.9	5,000	-	-	-	129,500	kg CO2e

[31] García-Valverde, R., Miguel, C., Martínez-Béjar, R., & Urbina, A. (2009). Life cycle assessment study of a 4.2 kWp stand-alone photovoltaic system. *Solar Energy*, *83*(9), 1434-1445.

5.2.4.4.2 Simulation 4

5.2.4.4.3

Device	kgCO2e/kWh	Size	kWh/day	Lifetime (Years)	Lifetime kWh	Total Impact	Unit
PV	0.0335	22,760	99,006	25	904,048,538	30,285,626	kg CO2e
Battery	0.0856	38,500	20	25	182,625	15,633	kg CO2e
Inverter	25.9	6,200	-	-	-	160,580	kg CO2e

Simulation 5

Device	kgCO2e/kWh	Size	kWh/day	Lifetime (Years)	Lifetime kWh	Total Impact	Unit
PV	0.0335	14,200	61,770	25	564,037,313	18,895,250	kg CO2e
Battery	0.0856	10,000	20	25	182,625	15,633	kg CO2e
Inverter	25.9	6,000	-	-	-	155,400	kg CO2e

6. Appendix

6.1 Advantages of Battery and Demand Response Data

Table 6-1. Simumlation 1 (Monthly 4Bdr Villa Electricity Cost with no Solar or Demand Response: No Battery Scenario)

Month	Site Load (kWh)	PV (kWh)	Load after PV (kWh)	Revenue ($)
January	2177.18	0.00	2177.18	-82.76
February	2024.67	0.00	2024.67	-64.73
March	2598.01	0.00	2598.01	-69.59
April	2733.78	0.00	2733.78	-77.57
May	3433.27	0.00	3433.27	-110.59
June	3698.48	0.00	3698.48	-138.39
July	4165.55	0.00	4165.55	-168.78
August	4266.09	0.00	4266.09	-219.34
September	3738.97	0.00	3738.97	-162.13
October	3301.02	0.00	3301.02	-151.43
November	2783.30	0.00	2783.30	-124.17
December	2350.46	0.00	2350.46	-110.06
Total	37270.79	0.00	37270.79	-1479.53

Table 6-2. Simulation 2 (Monthly 4Bdr Villa Electricity Cost with Solar but no Demand Response: No Battery Scenario)

Month	Site Load (kWh)	PV (kWh)	Load after PV (kWh)	Wasted PV (kWh)	Revenue ($)
January	2177.18	1583.95	593.22	1084.68	-67.50
February	2024.67	2003.62	236.80	1111.44	-53.72
March	2598.01	2139.24	458.77	1001.12	-60.97
April	2733.78	2304.37	501.61	848.49	-64.04
May	3433.27	2496.55	936.72	863.38	-77.00
June	3698.48	2351.46	1422.32	606.45	-87.10
July	4165.55	1982.17	2183.38	313.73	-105.30
August	4266.09	1946.45	2319.65	323.26	-141.32
September	3738.97	1916.65	1883.06	462.26	-112.23
October	3301.02	1725.83	1575.19	463.66	-109.45
November	2783.30	1561.44	1274.67	688.26	-95.88
December	2350.46	785.09	1565.38	502.75	-100.31
Total	37270.79	22796.82	14950.77	8269.50	-1074.83

Table 6-3. Simulation 3 (Monthly 4Bdr Villa Electricity Cost with no Solar but with Demand Response: Battery Scenario)

Month	Energy (kWh)	Charge Cost ($)	Discharge Revenue ($)	Revenue ($)
January	-2643.97	143.04	106.58	-36.46
February	-2635.49	102.89	96.91	-5.98
March	-3434.47	84.33	117.04	32.71
April	-3519.57	99.23	125.31	26.08
May	-4082.59	149.92	122.93	-26.99
June	-4173.48	163.72	108.27	-55.45
July	-4478.88	195.85	76.62	-119.23
August	-4622.85	250.10	138.94	-111.17
September	-4137.95	200.49	127.35	-73.14
October	-3745.26	204.94	171.52	-33.42
November	-3230.06	192.92	149.52	-43.39
December	-2744.53	177.44	143.22	-34.22
Total	-43449.10	1964.88	1484.21	-480.67

Table 6-4. Simulation 4 (Monthly 4Bdr Villa Electricity Cost with Solar and Demand Response: Battery Scenario)

Month	Energy (kWh)	Charge Cost ($)	Discharge Revenue ($)	Revenue ($)
January	-1060.02	120.41	126.22	5.81
February	-1020.25	86.42	110.45	24.03
March	-1728.47	72.08	125.05	52.97
April	-1777.59	82.37	132.06	49.69

May	-1749.15	113.77	136.91	23.14
June	-1974.63	111.82	126.51	14.69
July	-2439.66	131.64	89.99	-41.65
August	-2658.99	174.80	157.02	-17.78
September	-2346.91	151.00	139.69	-11.31
October	-1948.82	158.48	184.66	26.18
November	-1692.73	158.20	166.82	8.62
December	22675.80	148.76	999.65	850.89
Total	2278.58	1509.75	2495.04	985.29

6.2 System Advisor Model (SAM) Parameters and Assumptions

6.2.1.1 Location and Resource

SAM uses a comma-separated text format (CSV) for its solar resource data sets and comes with a pre-loaded database for various global locations. Data for Abu Dhabi was used as it was the closest city to Dubai with complete solar resource data in SAM. Abu Dhabi solar resource data includes historical data for wet bulb and dry bulb temperature (°C), pressure (mbar), wind direction (degrees) and wind speed (m/s), ground reflectance (albedo, 0..1), aerosol optical depth (0..1), beam normal irradiance (W/m^2), and diffuse horizontal irradiance (W/m^2). Given beam normal irradiance and diffuse horizontal irradiance, SAM can calculate global horizontal irradiance (W/m^2). With average temperatures of 27 °C and nonexistent snowfall, the Abu Dhabi/Dubai area is an ideal location for solar panel installation. It is necessary to consider soiling losses associated with the photovoltaic system due to dust accumulation and will be factored into the Losses section of the model.

Table 6-5. Annual averages calculated in SAM

Parameter	**Value**
Global horizontal irradiance (kWh/m^2/day)	144.0
Direct normal (beam) irradiance (kWh/m^2/day)	6.29
Diffuse horizontal irradiance (kWh/m^2/day)	1.66
Average temperature (°C)	27.1

6.2.1.2 Module

Five different module performance models are available in SAM; this simulation makes use of the California Energy Commission Performance Model. The California Energy Commission (CEC) Performance Model with Module Database contains a library of module parameters for commercially available photovoltaic system and can calculate solar energy-to-electricity conversion efficiency. The CEC Module Database allows users to simply input the type of modules used and auto-populates important parameters for calculations. The developers have installed both 60-cell and 72-cell TrinaSolar Duomax photovoltaic panels, however it is unclear which type of module is installed on each residence. For the purposes of this model, 60-cell modules are used for all simulations. This module type is listed in SAM as *Trina Solar TSM-260PEG5* (data sheet).

Table 6-6. PV cell model used in simulations

Type	Brand	Model	Size (mm x mm)	Output power (W)	Efficiency
60 Cell Multicrystalline module	TrinaSolar	DUOMAX Dual Glass Module	992x1658	260	15.8 %

SAM applies a temperature correction to predict the effects of cell temperature on module performance. The Nominal operating cell temperature (NOCT) method has been utilized in this simulation, which determines cell temperature based on module parameters included in the CEC Module Database. Ambient temperature data and wind speed from the selected Abu Dhabi weather file are used in SAM's temperature correction algorithms.

6.2.1.3 Inverter

SAM utilizes the Inverter CEC Database to calculate the system's AC output from logged inverter parameters within the database. The developers have installed ABB brand PVI and TRIO inverters on the different villa types (town house, semi-attached, and stand-alone) in clusters C1 and C2. The developers note that inverters in clusters C3, C4, and C5 have not yet been installed. For the purposes of this model, the ABB PVI-5000-TL-OUTD-S inverter with 97% efficiency is used for larger cluster simulations and the ABB PVI-3.0 OUTD-S-US-Z-M-A inverter is used for single residential simulations.

Table 6-7. Inverter models used in simulations

Type	Brand	Model	Maximum output power (Wac)	Efficiency
Single Phase string inverter	ABB	PVI-5000-TL-OUTD[32]	5000	96.1 %
Single Phase string inverter	ABB	PVI-3.6 OUTD-S-US-Z-M-A	3600	95.7%

Based on both information from the Sandia inverter library and CEC database, SAM will calculate key parameters related to inverter efficiency and operation, as well as displaying an efficiency curve.

6.2.1.4 System Design

Residential PV is installed at a 5° tilt angle with a 50° azimuth angle towards the southeast.

6.2.1.5 Shading and Snow

SAM can model the effects of shading from snow, trees, buildings, or self-shading. Because the Dubai/Abu Dhabi climate is so hot and dry with little likelihood of snow, this model assumes no effect

32 http://search.abb.com/library/Download.aspx?DocumentID=9AKK106103A4855&LanguageCode=en&DocumentPartId=&Action=Launch

from snow shading. Without detailed blueprints of the villas that include height of surrounding trees and buildings, it was difficult to make detailed assumptions about self-shading or shading from trees and buildings. For the purposes of this simulation, there is assumed to be no effect from self-shading and surrounding buildings and trees.

6.2.1.6 Losses

The program factors in soiling and electrical losses that are not captured within the losses of the module and inverter. Soiling refers to the accumulation of particles or other contaminants on the surface of solar panels, blocking the full irradiance and intensity of sunlight and leading to decreased energy output. A study of a small scale, grid connected photovoltaic system located in Abu Dhabi by Hanai et al. found a drop in efficiency of 5.79% caused by approximately a month's worth of dust accumulation.[33] A study based in Abu Dhabi identified the effects of dust deposition on evacuated tube collectors associated with a solar desalination plant, and found that dust deposition has strong seasonal effects that may be seen most during the summer months of June through August.[34] Monthly soiling loss values were extrapolated from the paper's data and are tabulated below. The average value of extrapolated soiling loss values is 5.13%, reasonably close to the Hanai's reported value of 5.79%.

Table 6-8. Monthly percentage energy loss due to dust deposition, Abu Dhabi

Month	Monthly Soiling Loss Value (%)
January	3
February	3.1
March	3.8
April	4.2
May	5.5
June	8
July	11.5
August	6
September	4.5
October	4.5
November	4
December	3.5

DC losses that may be accounted for in SAM as percentages include module mismatch, diodes and connections losses, DC wiring losses, tracking error, nameplate losses, DC power optimizer loss, and total DC power loss. Loss information on module and inverter datasheets is limited or nonexistent so default SAM values are used for DC losses. AC losses include losses not accounted for by the inverter CEC performance model but due to limited inverter data, the default SAM value of 1% is used.

[33] https://ac.els-cdn.com/S0960148110002661/1-s2.0-S0960148110002661-main.pdf?_tid=31d3f2e0-ae4b-4f04-a649-b4051748b174&acdnat=1525403307_8f959c5d3fe1faef10e7bacaa5b15720

[34] https://ac.els-cdn.com/S0011916409000228/1-s2.0-S0011916409000228-main.pdf?_tid=89368423-3096-4547-80fb-9b3871b89c48&acdnat=1526303953_2521f75c0666a62b2864c22d31476d9f

Table 6-9. DC Losses, SAM Default Values

Loss Type (%)	Central Inverters	Microinverters
Module mismatch	2	0
Diodes and connections	0.5	0.5
DC wiring	2	2
Tracking error	0	0
Nameplate	0	0
DC power optimizer loss	0	0

Examination of results show that energy losses are caused primarily from DC/AC conversions and internal module/inverter configurations.

6.2.1.7 Lifetime

SAM allows for single year or multi-year analysis of system lifetime and degradation based on a constant degradation rate. For the purposes of this analysis, a 0.5% degradation rate is applied over a 25-year period. The degradation rate describes the system's annual output reduction as a percentage of total AC output.

6.2.1.8 Battery Storage

The primary battery type chosen for the simulation is Lithium Ion Cobalt Oxide (LCO) and Vanadium Flow. The model allows users to set a desired battery bank size defined by bank capacity and bank power, or to specify the number of cells in series and number of strings in parallel. The desired bank size option is used with values tabulated below. Voltage properties are set from standardized values and are also tabulated below. Some default LCO and vanadium flow voltage properties were used, and those values are denoted with an asterisk.

Table 6-10. Battery properties set as default inputs by SAM

Parameter	LCO Battery	Flow Battery
Desired bank capacity (kWh DC)	*Simulation-dependent*	*Simulation-dependent*
Desired bank power (kW DC)	*Simulation-dependent*	*Simulation-dependent*
Desired bank voltage (V DC)	503.2*	48*
Cell nominal voltage (V DC)	3.7*	1.4*
Cell internal resistance (Ohm)	0.001*	0.001*
C-rate of discharge curve	0.2*	0.2*
Fully charged cell voltage (V)	4.2*	1.7*
Exponential zone cell voltage (V)	4.15*	1.55*
Nominal zone cell voltage (V)	3.7*	1.4*
Charge removed at exponential point (%)	0.4*	10
Charge removed at nominal point (%)	78.4*	85

The batteries are set to be connected at post-inversion on the AC side of the PV array (AC Connected). AC to DC and DC to AC conversion efficiencies are both set at 96%.

6.2.1.9 System Costs

Inputs in this section define installation and operating costs of the project. Direct capital costs, the expense of specific project components applied during the first year, are calculated individually for the modules and inverters. Costs of energy values in $/W dc for the module and inverter were obtained from GTM Research's *U.S. Solar Market Insight* report and NREL's *U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017* report[35] respectively. The cost in $/kWh dc for the battery bank was obtained from the U.S. Department of Energy's *Overview of the DOE VTO Advanced Battery R&D Program* presentation.[36] These values are tabulated below and factor into the calculation of total capital cost. Default program values for miscellaneous installation costs were assigned values of zero since there was not enough data to accurately estimate values. These values may be adjusted once a quote for installation is provided from selected contractors. Values for operation & maintenance (O&M) are calculated as 1% of the capital expenditure cost (CAPEX).

Table 6-11. Capital cost values of system equipment

Equipment	Direct Capital Cost
PV Module ($/W dc)	0.80
Inverter ($/W ac)	0.63
LCO battery bank ($/kWh)	450
Flow Battery bank ($/kWh)	900

6.2.1.10 Financial Parameters

Because the net capital cost has been calculated in the previous System Costs section, the Project Term Debt section is essentially irrelevant. Debt percent is set at 0% since no information was provided regarding project debt and load terms. An analysis period of 25 years is set to observe long-term behavior and degradation of the system. The Dubai Statistics Center reports on annual inflation rates of 4% for the region and Diamond provided a value of 1% for the real discount rate. Nominal discount rate is calculated by SAM to be 5%.

6.2.1.11 Incentives

Currently, the Dubai Energy and Water Association (DEWA) offers no incentives for energy storage. Additionally, the Incentives section of the model is designed for the American Federal and State tax credit and incentive system and does not translate well to the tax credit and incentive structure that exists in Dubai and the United Arab Emirates. All values in the incentive section have been set to zero for simplicity.

6.2.1.12 Electricity Rates

Electricity is billed using a simple tiered slab tariff. Since SAM is designed primarily for United States-based applications, inputs for OpenEI U.S. Utility Rates and Rate Data were ignored. Regarding excess generation, DEWA does not offer energy storage incentives and is in the primary stages of planning large-scale solar power integration, however does have an agreement with TSC to operate a net-

[35] https://www.nrel.gov/docs/fy17osti/68925.pdf
[36] https://www.energy.gov/sites/prod/files/2016/06/f32/es000_howell_2016_o_web.pdf

metering structure where excess electricity is purchased back by DEWA at sell rates. For this model, it is assumed that all generation is sold at sell rates and all load is purchased at buy rates.

Table 6-12. Energy Charge Rates, DEWA Tariff, formatted for SAM input

Tier	Maximum Usage (kWh)	Price ($/kWh)
1	0-2000	0.063
2	2001-4000	0.076
3	4001-6000	0.087
4	6001 and above	0.10

6.2.2 Electric Load, Simulations 1-5

Energy usage may be added to the model as an input of time series load data in kWh. SAM can accept values for hourly load data for one year and calculates total energy consumed (kWh) per month and annually, as well as peak power (kW) per month and annually. Monthly loads for each Sustainable City villa type are tabulated below and have been scaled accordingly for large cluster storage analysis.

Table 6-13. Monthly load data across simulation types in The Sustainable City

Month	Simulation 1: Four-Bedroom Villa (kWh)	Simulation 2: One Villa Cluster (kWh)	Simulation 3-5: Entire Residential Area (kWh)
January	2,134	178,996	1,390,070
February	1,980	165,814	1,280,400
March	2,556	215,190	1,606,820
April	2,693	229,294	1,679,160
May	3,390	290,222	2,051,720
June	3,659	314,752	2,189,870
July	4,127	355,673	2,440,450
August	4,222	363,714	2,487,060
September	3,700	318,529	2,212,900
October	3,261	279,260	1,987,090
November	2,744	232,242	1,698,130
December	2,308	193,568	1,479,710

6.3 List of Acronyms and Abbreviations

BESS	Battery Energy Storage System
CAPEX	Capital Expenditure
CF	Capacity Factor
DEWA	Dubai Electricity & Water Authority
DR	Demand Response
EPRI	Electric Power Research Institute
EV	Electric Vehicle
kW	Kilowatt

kWh	Kilowatt-hour
LCA	Lifecycle Analysis
LCO	Lithium-Ion Cobalt
LCOE	Levelized Cost of Energy
MW	Megawatt
MWh	Megawatt-hour
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
PV	Photovoltaic
RFB	Redox flow battery
SAM	System Advisor Model
SMUD	Sacramento Municipal Utility District
T&D	Transmission and Distribution
TMY	Typical Meterological Year
TOU	Time of Use
TSC	The Sustainable City
UAE	United Arab Emirates
ZNE	Zero Net Energy

6.4 BESS Cost Assumptions

For this analysis, lithium-ion batteries were estimated at $450/kWh and flow batteries were estimated at $900/kWh. It is worth noting that cost estimates for lithium-ion vary widely between sources and between system size; although the technology is mature, it has not yet reached the level of maturity of photovoltaic solar panels (as observed by widely accepted values for PV panel costs per kWh from residential to grid-scale applications). It is also worth noting that flow battery technology is extremely nascent and has just begun to be adapted for commercial offerings, therefore costs are loosely estimated across a small number of sources.

Lithium-ion costs were primarily based on NREL's 2016 report titled "Installed Cost Benchmarks and Deployment Barriers for Residential Solar Photovoltaics with Energy Storage: Q1 2016"[37]. Both estimates for a residential PV-plus-storage system and a commercial PV-plus-storage system (large battery case) put the cost of a lithium-ion battery at $500/kWh. Other sources based on experts from the Energy Storage North America conference[38] place the approximate cost of a lithium-ion battery at $300/kWh. The research team opted to meet slightly above the middle of these two figures at $450/kWh to provide a more conservative overall financial estimate. Indeed, increased market competition and product offerings in the region will drive costs down in the future.

37 https://www.nrel.gov/docs/fy17osti/67474.pdf?utm_source=New%20Report%20Shines%20Light%20on%20Installed%20Costs%20and%20Deployment%20Barriers%20for%20Residential%20Solar%20PV%20with%20Energy%20Storage&utm_medium=email&utm_content=nrel&utm_campaign=NewsRelease

38 https://www.power-eng.com/articles/2018/04/energy-storage-not-at-tipping-point-thoughts-on-why-and-when.html

It was more difficult to find vanadium flow battery costs that were corroborated between sources. From a firsthand source at Primus Power, a Bay Area-based company that is working to bring zinc bromine flow battery storage systems to market, we surmised that flow batteries are best suited for deep, repetitive block charge/discharge cycles (i.e. grid-scale large storage applications). In addition, typical flow battery chemical mixtures are not as energy dense as Lithium-ion, meaning the system will need to be physically larger to accommodate more chemical mixture in order to achieve the same amount of storage capacity as Lithium-ion. Flow BESS also have various components like pumps and valves that need to be replaced over time. For these reasons, our research team opted to estimate the cost of a vanadium flow battery system at $900/kWh. Some university research groups are estimating flow battery costs to be much lower, around $100/kWh[39] but there is no indication that these estimates take into account the cost of infrastructure, components, lifetime fixed and variable O&M, and marketing. Because flow is a very nascent technology that will need more research and market testing to become viable, the estimated cost of $900/kWh is a rough estimation of what it would cost to commission and build a megawatt-scale flow battery system for use at TSC. This price will undoubtedly drop over time as flow becomes a more viable and widely-studied/manufactured technology in the energy market.

[39] https://www.altenergymag.com/article/2018/09/are-sulfur-flow-batteries-the-answer/29441