MEASUREMENT AND ENHANCEMENT OF THE RESILIENCE OF POWER SYSTEMS WITH A COMBINED DIESEL AND SOLAR POWER BACKUP

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In Partial Fulfillment of the Requirements

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The Division of Biomedical Engineering

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By

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ABSTRACT

Power outages shut down facilities such as hospitals, shelters, and communication services. Each power system needs to be resilient to power outages. In a power system, resilience can be achieved by infrastructure hardening; smart meter (AMI), energy storage, micro grid, renewable energy and accessibility of critical components. Most critical systems, such as hospitals, have a backup power that is deiseal power generator. The resilience of such a power system refers to how a backup power can still supply the critical load or base load for such critical systems when facing to the prime power outage. This thesis studies how the resilience of such a power system can be quantitatively measured and whether a combined diesel and solar backup power can enhance the resilience of the entire power system with an affordable cost. Specifically, the hospitals in Saskatoon were taken as a study vehicle. A literature review was conducted first, which revealed that there was no satisfactory quantitative measurement available in literature for the resilience of power systems on the occasion of prime power outages.

The overall objective of this thesis was thus to develop a quantitative measure for the resilience of power systems with a backup power when facing the prime power outage. The problem is in essence about the reliability of the backup power in the event of the prime grid power is disrupted. A general measure for the resilience of the backup power system (R for short), which can be multiple types of power generators, was developed, which was dimensionless (i.e., independent of the scale of the system). The measure was proved to be reasonable to the extreme cases (i.e., R=0, R=1). The use of the proposed measurement was illustrated for two situations of the backup power: (i) the backup power being a diesel power generator only, and (ii) the backup power being a

combined diesel power generator and solar panel. The situation (i) corresponds to the current situation of the backup power in the hospitals in Saskatoon. The result shows that the resilience of the RUH (royal university hospital) is the highest one (R=70.5%) among the three hospitals in Saskatoon with the other two being SCH (Saskatoon City Hospital) and SPH (Saint Paul Hospital), and the resilience of SPH is the lowest one (R=54%). This result was in agreement with the experience of the managers of the hospitals.

The economics of the combined backup power (diesel plus solar power generators) was studied with the help of a software system called SAM (system advisor model). Specifically, the power generated by and economic attributes of the solar panel of different sizes without battery storage were analyzed for the three hospitals, respectively. Note that the economic attributes are NPV (net present value) and payback time. The resilience of the combined backup power was calculated for different sizes of solar panels with the help of SAM and the proposed measure. The optimal design, namely the size of solar panel, was obtained in terms of the resilience and payback time; specifically, for the RUH, the size of solar panel is 700 KW (R of the solar panel alone is 35%; R of the combined backup power is 98%; the payback is 13.1 years, the capital cost is 1488490$), for the SPH, the size of solar panel is 500 KW (R of the solar panel alone is 25%; R of the combined backup power is 96%; the payback is 11.1 years, the capital cost is 1060390$), and for the SCH, the size of solar panel is 500 KW (R of the solar panel alone is 20%; R of the combined backup power is 94%; the payback is 10.4 years, the capital cost is $1060940). Besides, in the normal situation, the reduction of the grid power by solar power is about 7%. This research can thus conclude that the resilience of the backup power system of the hospitals in Saskatoon can be improved by adding solar panels with an acceptable cost payback time and at the same time the environmental sustainability, related to the fossil fuel power generation, can is also improved.

The primary contribution of this thesis research is the provision of a quantitative measure for the resilience of a power system including a backup power, especially with respect to the recovery stage in the event of the prime power outage. The secondary contribution is the increase of the resilience of the power system of the hospitals in Saskatoon by 25% for SPH, 35% for RUH, and 20% for SCH and the reduction of the use of the grid power by 7% for the benefit to the environmental sustainability.

ACKNOWLEDGEMENTS

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Finally, I am grateful to my family members for their support and constant belief in me.

DEDICATED TO

My father, my mother, my brother, my sisters, and all members of my family for their constant love and unwavering understanding

Wish them healthy and happy

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

Abbreviations

AMI	Advanced Metering Infrastructure
PV	Photovoltaic
SAM	System Advisor Model
NREL	National Renewable Energy Laboratory
RUH	Royal University Hospital
SCH	Saskatoon City Hospital
SPH	Saint Paul Hospital
AGM	Absorbent Glass Mat
LMO	Lithium-ion Manganese Oxide
LFP	Lithium-ion Iron Phosphate
LCO	Lithium-ion Cobalt Oxide
LTO	Lithium-ion Titanate
NMC	Nickel Manganese Cobalt
NCA	Nickel Cobalt Aluminum
KW/h	Kilo Watt/ Hour
CHP	Combine Heat Power
ICU	Intensive Care Unit
CCU	Coronary Care Unit
NICU	Neonatal, Intensive Care Unit
UPS	Uninterruptable Power Supply

MCC	Motor Control Centre
CT scan	Computed Tomography scan
AC	Alternative Current
DC	Direct Current
NPV	Net present value

CHAPTER 1

INTRODUCTION

1.1 General motivation and problem statement

Power outages shut down schools, close businesses and interrupt emergency services including hospitals, shelters, communication services and traffic lights. Severe weather is one of the most significant causes of power outages in the world, but there are other causes, including equipment malfunction, vehicle accidents and lack of experience in operation (economic benefits of increasing electric grid, 2013). As such, a power system needs to be resilient to provide power, especially for the critical load during power outages, and it should be cost efficient as well. The concept of resilience has been studied by researchers from various disciplines such as material science, biology and computer science. Several studies on resilience engineering have been conducted in recent years. There are still some confusions on the definition of resilience. For instance, confusion may arise among resilience and redundancy, reliability, robustness, sustainability, and repairing. Furthermore, how to measure the resilience of a system, especially power systems, is still an open issue.

This thesis was motivated to address the above confusions and problems in the application of power systems of hospitals in Saskatoon. The context of the thesis to resilience is that the main or prime power is the electrical power or grid power with a backup power, and the power outage refers to the prime power outage. The backup power is the existing backup power system (i.e., diesel power) and a renewable power, solar power in this case.

The research questions are:

- *Question 1: How to measure the resilience of a power system, which includes a backup power system, in the event of the prime power outage?*
- *Question 2: How to design a solar panel system, together with the deiseal power, as a combined backup power system, to improve the resilience of the entire power system, while at the same time to reduce the use of the prime power in the normal situation with the solar power?*

On a general note, the above two questions were not well answered by then the literature in the power system. This thesis was designed to study the above two questions.

1.2 Objectives

To answer the questions as mentioned above, the overall objective of this thesis was to develop a quantitative measure for the resilience of power systems on the event of prime power outages. The problem is in essence about the reliability of the backup power in the event of the prime grid power is disrupted. The following specific objectives were defined for this thesis:

- ***Objective 1**: to do a systematic literature analysis in order to reach a unified definition of the resilience of a dynamic system.*

To any property or behavior of a system, the measurement of it must start with the definition of the property or behavior. A brief glance of the literature has made the author of the thesis believe that there is a need of research to clarify the definition of resilience.

- ***Objective 2****: to develop a quantitative measure for the resilience of a power system which has a backup power such as diesel power and solar power.*

The situation considered in this thesis was that there are a prime power generator and a backup power generator. The resilience is not about how the backup power can supply critical loads or base loads when the prime power is down. The essence of the problem is to examine the backup power and its reliability.

- ***Objective 3****: to design a solar power system in the combined backup power system, which contains a diesel power and a solar power generator, to improve the reliability of the backup power system with consideration of the cost (the capital cost, payback time) for the hospitals in Saskatoon (as an example).*

In this thesis, whenever the resilience is concerned, the power needed for the application system is its critical load. For instance, to hospitals, critical loads are loads for lighting and equipment in patient rooms, pharmacies, labs, blood banks, operation rooms, intensive care units, water pumps, CT scanners, and so on (Prudenzi, Fioravanti, & Caracciolo, 2017). Further the improvement of resilience may likely be at the expanse of the cost. Therefore, in designing the solar power system, the trade-off between the resilience enhancement and the cost needs to be taken; yet the rigorously optimization was not taken in this thesis due to the scope of this research. Finally, the process of operating the backup power to supply the power to meet the critical load is out of the scope of this thesis, so is design of the backup power system.

1.3 General research methodology

The general strategy for this thesis research was to take three hospitals in Saskatoon as a study vehicle yet with a proper generalization of the research results whenever applicable. In this way, the research outcome was expected not only to solve a particular application problem, that is, the backup power system of these hospitals in Saskatoon, but also to establish theories and methodologies in the area of resilience engineering. Specifically, for Objective 1, a systematic literature review methodology was taken in order to be comprehensive to the literature on the understanding of the concept of resilience and how the resilience is measured. For Objective 2, the general criterion for developing any such a measure, that is, dimensionless or independent of the scale of an application system, was followed. For Objective 3, a trade-off design between the resilience enhancement and the cost was taken. In the design and analysis of solar power system, the average power per day over a year was considered for the simplicity. This may create some errors in solar power design. However, this error was believed not to compromise the intended purpose, i.e., examining whether the resilience of the entire power system can be enhanced with an affordable cost.

1.4 Structure of the thesis

Chapter 2 will discuss the concept of resilience with the definition of five other relevant concepts and compare them with the concept of resilience. Moreover, various methods for resilience measurement in literature are reviewed in this chapter. Chapter 3 will describe the solar power system, which is a background for the subsequent discussions. Chapter 4 presents a new measure for the resilience of the power system under the situation that the whole power system has one prime power generator and one or more backup power generators. Chapter 5 presents an analysis of the resilience of the existing power system of the hospitals in Saskatoon, which also serves as an illustration of how the new measure presented in Chapter 4 works. Chapter 6 presents a design of solar panels for the three hospitals for the resilience enhancement, the reduction of the use of the prime power, and the cost effectiveness, which also shed some lights on optimal design of solar panels for application systems (e.g., hospitals).

CHAPTER 2

RESILIENCE CONCEPT AND LITRATURE REVIEW

2.1 Introduction

This chapter discusses the concept of resilience along with how resilience can be measured. In literature there are several methods to measure the resilience of a power system, and they will be compared. Section 2.2 describes various definitions of resilience, as the definition of resilience is the basis for measuring resilience. Section 2.3 discusses several closely related concepts to resilience, such as robustness and so on in order to pin-point more accurately the concept of resilience. Section 2.4 presents a systematic review of measurements of resilience. Finally, there is a conclusion regarding the literature and proposed research of this thesis.

2.2 Resilience and its definition

The concept of resilience has been studied and applied in different areas, including material science, biology, and computer science. These different areas provide different understandings of resilience (Gao, 2010). Several definitions of resilience can be found in literature, which are discussed below:

- **Definition 1**: Resilience is the ability of a system to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time at acceptable costs and risks (Haimes, 2009).

- **Definition 2**: Resilience is the ability of a system to prepare for and adapt to the changing conditions, withstand and recover rapidly from disruptions, e.g., deliberate attacks, accidents, or naturally occurring threats or incidents (House, 2013).
- **Definition 3**: Resilience is the ability of a system to prepare for, absorb, recover from, and more successfully adapt to adverse events (Cutter et al., 2013).
- **Definition 4**: Resilience is the property of a system, which shows how the system can recover to function at an acceptable level when the system suffers from a partial damage (Zhang & Lin, 2010; Zhang & van Luttervelt, 2011).
- **Definition 5**: Resilience is the ability of a system to regulate its prior function during disturbance events and to withstand the required operations under both expected and unexpected conditions (Hollnagel, 2016)
- **Definition 6**: Resilience is the intrinsic ability of a system to maintain or regain a dynamically stable state (Dekker, Hollnagel, Woods, & Cook, 2008).

In the above definitions, Definition 1 implies that a system is with a partial damage and clearly states that a meaningful recovery makes sense within an acceptable time duration and cost. However, it is not clear about the notion of the acceptable risk – whether the risk of over duration and/or over the cost limit, or the risk may also mean the risk in terms of recovery. In Definition 2, the phrase ‘changing condition’ is too general in that a condition could mean a pre-condition the system needs to meet in order to perform its function or a condition of the system itself. Further, a change may make sense to the structure of a system or to the parameter of a system, which is not made clear in Definition 2. In Definition 3, the phrase ‘adverse events’ is vague, as an adverse event may not cause any structural change of the condition (in Definition 2) or partial damage (in

Definition 3). Definition 4 does not include the time and cost, which deem important towards a more quantitative measurement of resilience. Definition 5 does not include the notion ‘disruption’ and thus the notion ‘recovery’ but the notion of condition. The notion of condition is however very general, as it does not specify whether the system changes its structure or state or behavior. In later discussions, the former and latter require completely different adaptions with the system to make the system function. Indeed, the former refers to the resilience (according to Definition 4) and the latter to the robustness (see latter discussions in Section 2.3). Indeed, Definition 5 does not distinguish robustness from resilience.

Finally, Definition 6 considers a general system concept, namely stable state. This concept is particularly suitable to a dynamic system. Again, it does not have the concept ‘damage in the structure of a system’. Further, a dynamic system may function in its transient period.

In addition, to a particular type of system, such as service system, resilience is connected to the response behavior of a system in response to disruption (Willis & Loa, 2015); in particular the following aspects embrace the resilience of a service system: monitoring of service performance degradation, feasibility to restore services, the speed of recovery (Willis & Loa, 2015). The disruptions could be natural disaster, industrial accident or terrorist attacks. In the work of (Wang et al., 2014; Wang et al., 2018), the service performance is measured by how the supply meets the demand, and consequently, they bring the demand into the scope of a resilience supply system.

This thesis attempted to give a definition to resilience by combining the aforementioned definitions, because the above discussion shows that none of them is inclusive and precise. Definition of precise information may refer to the paper of Cai et al. (2017).

First, this thesis considered that only a system makes sense to resilience. Further, the general knowledge architecture called FCBPSS (F: function, C: context, B: behavior, P: principle, SS: state-structure) (Lin and Zhang, 2004; Zhang et al., 2005; Zhang and Wang, 2016) is employed to represent a dynamic system. After that, the resilience of a system was defined with the help of FCBPSS, in particular, *resilience stands for the ability of a system to recover its function in an accepted time period and cost through a process of learning and changing itself when the structure of the system and/or the context of the system changes*. The operating principle that governs the recovery process includes: (1) changing the context of a system (e.g., 3D to 2D), (2) changing the operating principle of the system (e.g., walking to crawling), (3) changing the configuration of the system, (4) changing the state of a component of the system (e.g., the length of a bar), (5) changing the behavior of the system, and (6) changing the load or demand of the system.

2.3 Some other concepts relevant to resilience

There are several other relevant concepts, namely robustness, reliability, redundancy, sustainability and repairing, and their relationship with resilience is discussed below.

Robustness

Robustness defines the quality of the system as being able to function under disturbance conditions (Gao, 2010). Robustness deals with small disruptions compared to resilience that deals with severe disruptions such as snow storms or hurricanes (Gao, 2010). Robustness does not cause changes in the structure and in the environment while resilience does.

Reliability

Reliability is also defined as the ability of a system or component to perform its required functions under conditions for a specific period of time (Zhang 2007, Verma et al. 2010). The difference between reliability and resilience is that reliability focuses on the normal conditions and it refers to the life of a system under the normal conditions, but resilience focuses on disruptive events and it refers to recovery after the structural damage of a system under the external and/or internal disturbances (Vugrin, Castillo, & Silva-Monroy, 2017). Usually, the disturbance the resilience of a system concerns is “large”, e.g., the events of hurricanes, earthquakes and snowstorms, which can very likely cause outages (Vugrin, Castillo, & Silva-Monroy, 2017). Furthermore, the difference between reliability and resiliency is that reliability provides protection against foreseeable low-impact, high-probability events, and resiliency provides protection against high-impact, low-probability events (Espinoza, Panteli, Mancarella, & Rudnick, 2016). Table 2.1 shows the comparison of reliability and resilience.

Table 2.1 Characterizing reliability and resilience under the Watsons resilience analysis process

	Reliability	**Resilience**

Event considered	High probability, low consequence hazards	Low probability, high consequence hazards
Risk based	No	Yes
Binary or continuous	Operationally the system is reliable or not- confidence is unspecified	Resilience is considered is continuum- confidence is specified
Measurement focus	Focus is on the measurement to the system	Focus is on the measurement to humans

Redundancy

According to Zhang (2012), redundancy refers to the means of a system to improve resilience as well as reliability. There are two types of redundancy: functional redundancy and physical redundancy. Functional redundancy refers to the fact that a system has several different states and configurations to achieve the same function. A system's state is decided by a system's structure. Physical redundancy refers to the fact that a system has several identical components, among which some remain spare in a normal operation of the system.

Sustainability

According to Zhang (2018), sustainability refers to one of the behavioural properties of a technical system in the context of ecological system and human system. Any technical system needs resources to run and create benefits along with negative side effects to humans. Resources could be created by the ecological system or humans; the latter may also be called synthetic resource and the former natural resource. Non-sustainability then occurs in the following situations:

(1) resources are not enough, either exhausted or supply being short of demand, to run a technical system while the system is critical to human life; (2) negative side effects, e.g., environment pollution, are over a critical level, which threat human life.

Repairing

Repairing is one of the branches of recovery and it recovers the function of a damaged system by replacing parts or by enhancing the damaged system. Repairing is different from resilience in that the resilience of a system does not consider replacement from any external source rather than based on its own. Self-repairing is a kind of resilience, but resilience includes all sorts of change on the system on its own (Liu, Deters, & Zhang, 2010).

2.4 Resilience measurement: a systematic literature review

This section presents a systematic literature review of methods to measure the resilience of a power system. The methodology for this review has four steps: Step 1: determine the database from which information can be found; Step 2: determine keywords that best describe the topic; Step 3: screen out the key entries of reference; and Step 4: analyze key entries of reference.

2.4.1 Selection of databases

The following two online citation databases have been selected for this purpose:

- www.sicencedirect.com
- www. ieeexplore.ieee.org

They cover all the major journals and magazines in the field of resilience measurement in power systems. For instance, IEEE has a power society, and most of archival articles are stored in IEEE database.

2.4.2 Selection of keywords along with the search strategy

The four keywords (i.e., resilience, measurement, power, and system) were selected, along with their combinations, particularly Combination 1: ‘resilience measurement’, Combination 2: ‘resilience measurement’, ‘power system’. There was a restriction regarding years of publications, namely from 2008 to 2018. A filter was applied to all the papers obtained from the search, which has two key phrases: ‘resilience measurement’, ‘power system’. After that, 81 articles were selected from both websites, particularly 19 articles from sicencedirect.com and 62 articles from ieeexplore.ieee.org. Figure 2.1 shows the number of articles versus the years, which contain the keyword ‘resilience measurement power system’, from the database ‘Sciencedirect’. Figure 2.2 shows the number of articles versus the years, which contain the keyword ‘resilience measurement power system’, from the database ‘ieeexplore.ieee.org’.

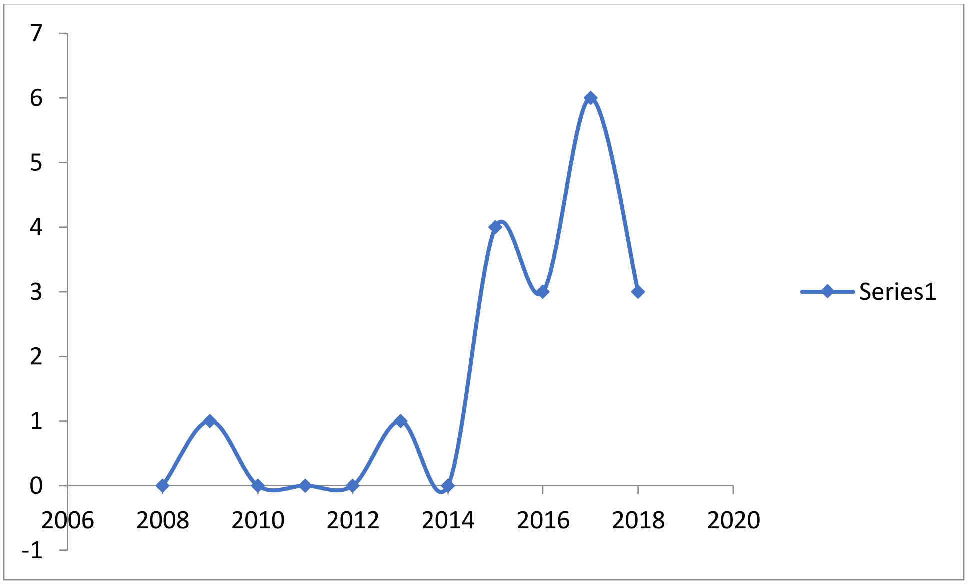

Figure 2.1 Distribution articles (Sciencedirect) containing ‘resilience measurement power system’

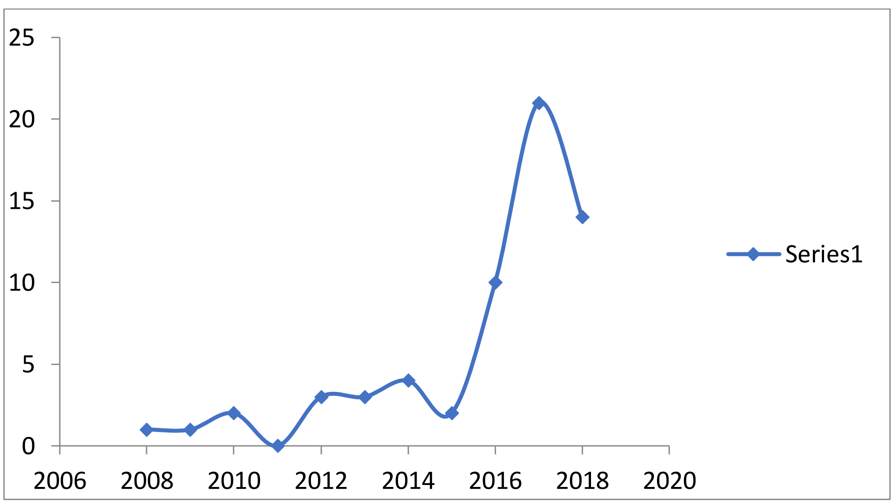

Figure 2.2 Distribution articles (ieeexplore.ieee) containing ‘resilience measurement power system’

2.4.3 Selection of papers

For this analysis, 23 articles (Table 2.2) were chosen for the analysis because they discuss the methodology for measuring resilience of power systems during the years of publication between

2008 and 2018. It is noted that among 81 articles that include the keywords (system resilience, power system), many of them only mentioned the term ‘resilience measurement’ or briefly described the concept of resilience measurement in power systems, and certainly they do not contain any metric system to number system to measure the resilience of a power system. Table 2.2 shows various resilience measurement methods taken from 23 selected literature reviews.

Table 2.2 Various articles related to resilience measurement in power systems

Resilience measurement in power system
(Advisers, 2013), (Bajpai, Chanda, & Srivastava, 2018), (Bie et al., 2017), (Chanda & Srivastava, 2016), (Chanda et al., 2018), (Espinoza et al., 2016), (Farraj, Hammad, & Kundur, 2018), (Farzin, Fotuhi-Firuzabad, & Moeini-Aghtaie, 2016), (Figueroa-Candia, Felder, & Coit, 2018), (Fthenakis, 2013), (Gao, 2010), (Haimes, 2009b), (Ji, Wei, & Poor, 2017), (Nan & Sansavini, 2017), (Panteli & Mancarella, 2015), (Panteli & Mancarella, 2017), (Panteli, Mancarella, et al., 2017) (Panteli, Trakas, Mancarella, & Hatziargyriou, 2017), (Qazi & Young, 2014), (Stefanovic, Angjelichinoski, Danzi, & Popovski, 2017), (E. Vugrin, Castillo, & Silva-Monroy, 2017), (E. D. Vugrin et al., 2015), (Willis & Loa, 2015b)

2.4.4 Analysis

From Figure 2.1 and Figure 2.2, it can be seen that the subject of resilience measurement has raised great attention in power systems recently, in particular since the year of 2014. The following are discussions of the key idea and methodology in the 23 papers.

2.4.4.1 Phase theory related to resilience along with its assessment or measurement

Four major phases are usually considered for the assessment of a system resilience, and they are (i) threat characterization, (ii) vulnerability of system's components, (iii) system reaction, and (iv) system restoration. The first phase determines the magnitude, probability of occurrence and spatiotemporal profile of a hazard. In this phase a deterministic scenario is built based on the real historic data, followed by probabilistic scenarios for the future conditions. The second phase determines the vulnerability level of each component of a system with three steps: (i) identifying the vulnerable components, (ii) modelling and analysis of the fragility of components, and (iii) assigning a number to the state of vulnerability. The third phase evaluates the performance of critical components when they are under either incident or accident attacks (e.g., extreme weather conditions). In the electrical power system, there are few ways available to this phase such as using the Cascading failure model. This model is a simplified functional model of neural spike responses, which studies the cascading mechanism of blackout (Espinoza et al., 2016). A cascading failure is a process in a system of interconnected parts in which the failure of one or few parts can cause the failure of other parts (Zhang et al., 2008 Zhai et al., 2017). Blackout means a failure of component in a power system. The last phase evaluates restoration of the system that has been partially damaged considering the available human and technical resources as well as the accessibility of the damaged parts (Espinoza et al., 2016).

Vugrin et al. (2015) stated that restoration of a system depends on its three capabilities with either the system own resources or alternative ones. These capabilities are (i) absorptive, which is defined as the ability of a system to mitigate the negative impact of disruption, (ii) adoptive, which is defined as the ability of a system to adapt to disruption, and (iii) restorative, which is defined as the ability of a system to recover from disruption at a reasonable cost (Vugrin et al., 2015).

Nan & Sansavini (2017) stated that the resilience of a system is measured over three phases; see Figure 2.3. The first phase is the original steady of the system between t_0 to t_d. The second phase is the disruptive phase of the system between t_d to t_r, in which the system performance starts dropping until reaching the lowest level at time t_r. The third phase is recovery phase between t_r to t_{ns}, in which system robustness or system redundancy is applied to mitigate disruption. T_{ns} represents a time when the system reaches the new steady phase level.

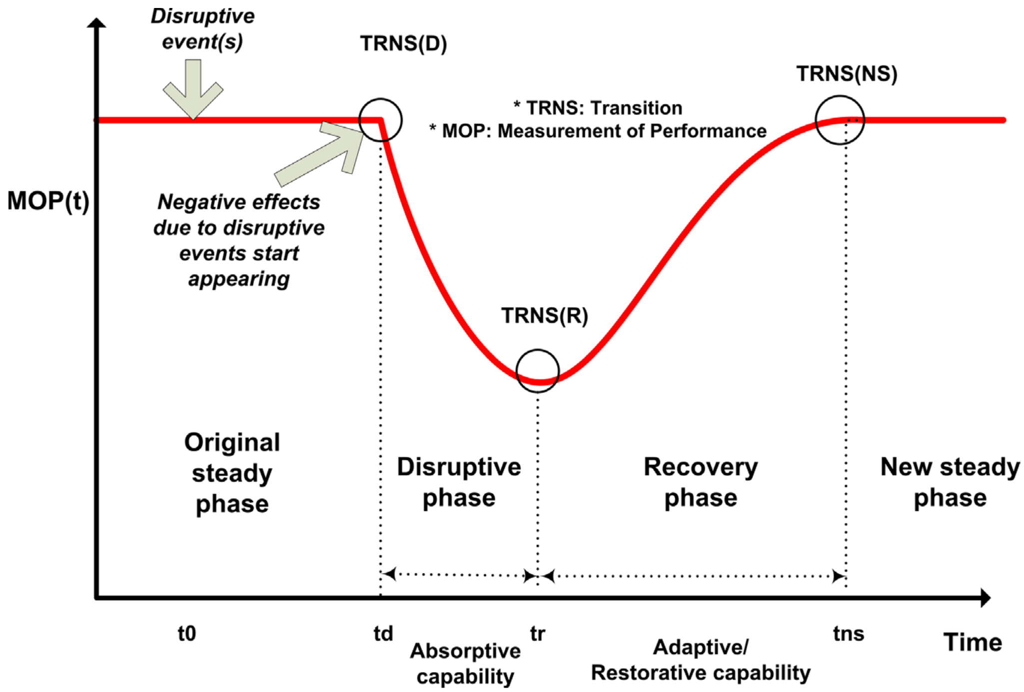

Figure 2.3 System resilience transitions and phases (Nan & Sansavini, 2017).

According to Figure 2.3, the first phase is the original steady phase of the system between t_0 to t_d. The second phase is the disruptive phase of the system between t_d to t_r, in which the system performance starts dropping until reaching the lowest level at time t_r. The magnitude of service reduction in this phase is a function of the system absorptive capability. The third phase is the recovery phase between t_r to t_{ns}, in which system robustness or system redundancy is applied to mitigate disruption. The level of restoration depends on the system adaptation capability to disturbance. T_{ns} represents a time when the system reaches the new steady phase level. This new steady phase may have a different service level compared to that in the original steady phase; thus, a full recovery may not be achieved. For instance, Figure 2.4 shows that only 90% of original service level has been recovered.

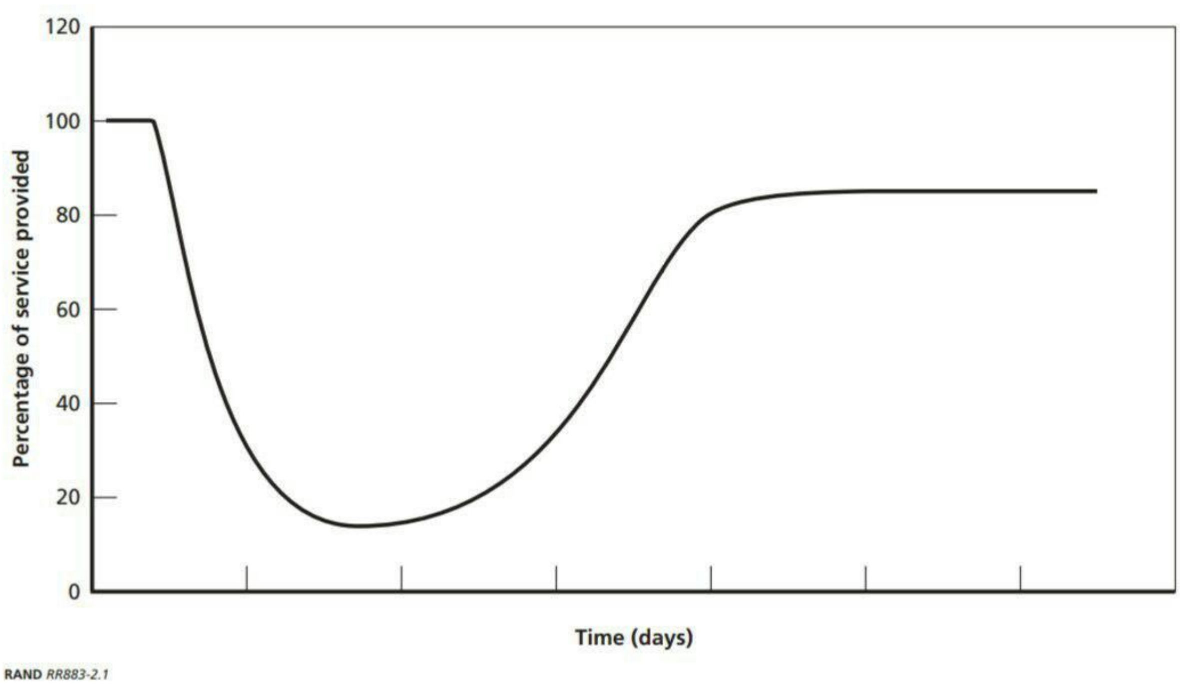

Figure 2.4 The state of service response to disruption (Willis & Loa, 2015).

The level of service recovery is a function of the system design and operation methods. An electricity grid designed with more redundancy and backup resources in place experiences a higher recovery level and hence system resilience. Figure 2.5 shows that System B has a higher resilience compared to that in System A for the same disturbance. In some instances, a power system is rebuilt with additional resources after a disruption. As such, the level and quality of service may become higher than that in original state after the recovery phase as per Figure 2.6 (Willis & Loa, 2015).

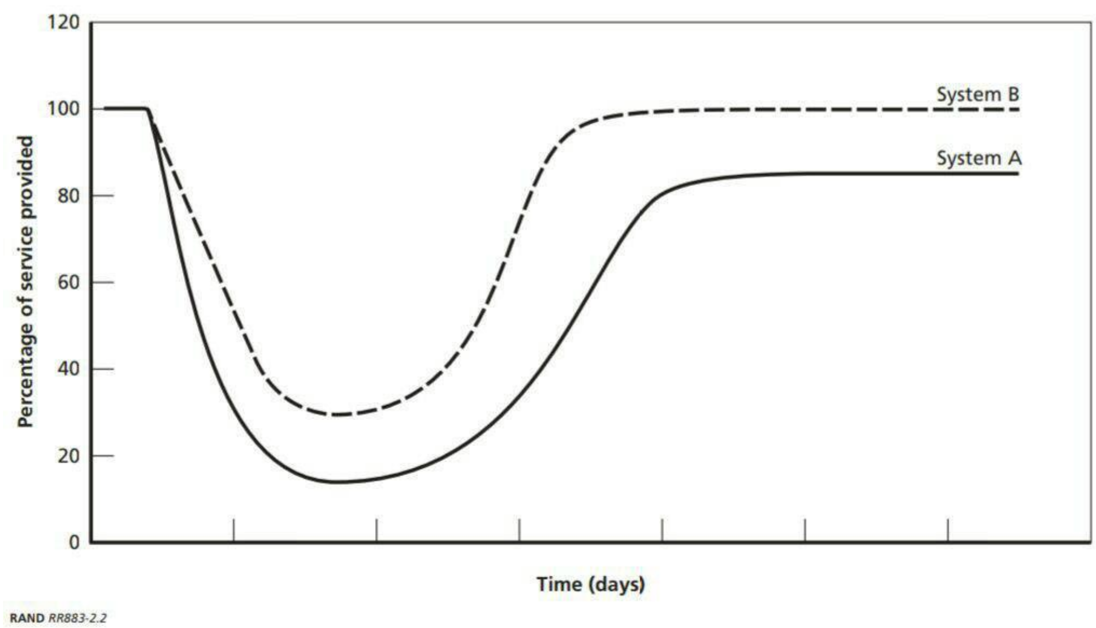

Figure 2.5 Systems with different resilience level to the same disruption (Willis & Loa, 2015).

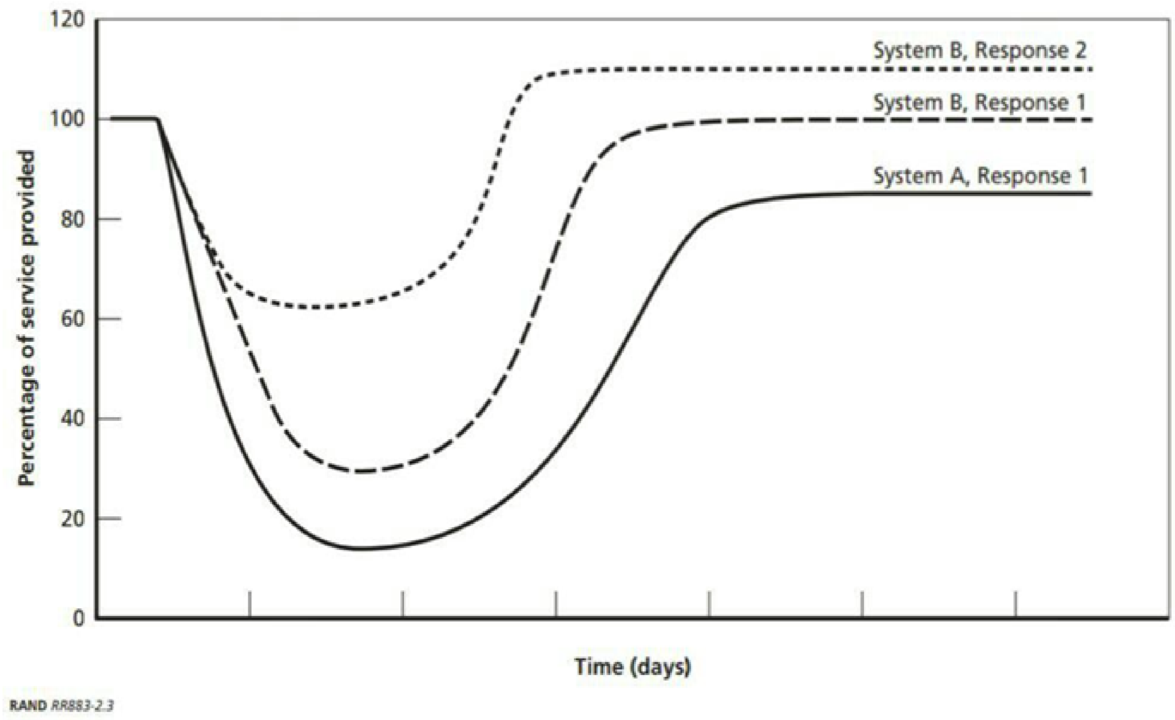

Figure 2.6 Systems with different responses and resilience levels (Willis & Loa, 2015).

2.4.4.2 Quantification methods and metrics for system resilience

Bie et al. (2017) indicated that there are three techniques to quantify the capability of a system pertinent to the notion of resilience in various phases including simulation-based method, the analytical method, and the statistical method. Most of the proposed methods are a combination of analytical and statistical approaches.

Espinoza et al. (2016) proposed two equations to quantify the impact of extreme events in a system including Expected Energy Not Supplied (EENS) and Energy Index of Unreliability (EIU). EENS shows the magnitude of energy deficiency during a period and EIU indicates the percentage of energy deficiency to the total energy demand in a period (Espinoza et al., 2016).

$$EENS = \sum E_k \times P_k \quad (2.1)$$

$$EIU\ [\%] = (EENS/E) \times 100$$

In the above equation, E_k is the energy not supplied with a probability P_k and E represents the energy demand in the whole period. Calculating EENS and EIU enables to analyze the resilience degradation of a system. However, these equations are not able to calculate the recovery performance of a system as one of the main parts of resilience measurement.

Nan & Sansavini (2017) quantify the recovery performance of a system by the following equation (also see Figure 2.3).

$$RP = \frac{MOP(t_{ns}) - MOP(t_r)}{t_{ns} - t_r} \quad (2.2)$$

where

- t_{ns} = the time that system reaches a new service value;
- t_r = the time that system is in the lowest service value;
- MOP ($_{tns}$) = new service value of the system;
- MOP (t_r) = minimum service value of the system;
- RP = resilience performance.

Nan & Sansavini (2017) also defined a new steady state since this level may not be the same as that the original one. The following equation calculates the new steady level.

$$RA = \frac{MOP(t_{ns}) - MOP(t_r)}{MOP(t_0) - MOP(t_r)} \tag{2.3}$$

where

- MOP (t_{ns}) = the new service value of the system;
- MOP (t_r) = minimum service value of the system;
- MOP (t_0) = original service value of the system,
- t_0 = The time that the system is at its original level, which means no disruption happened at this time,
- RA = a new steady level.

Mancarella et al. (2017) proposed a new metric method to quantify a system resilience, namely resilience trapezoid. This method uses different time-dependant phases with consideration of the system infrastructure and operation. They defined the following set of metrics, as illustrated in Figure 2.7.

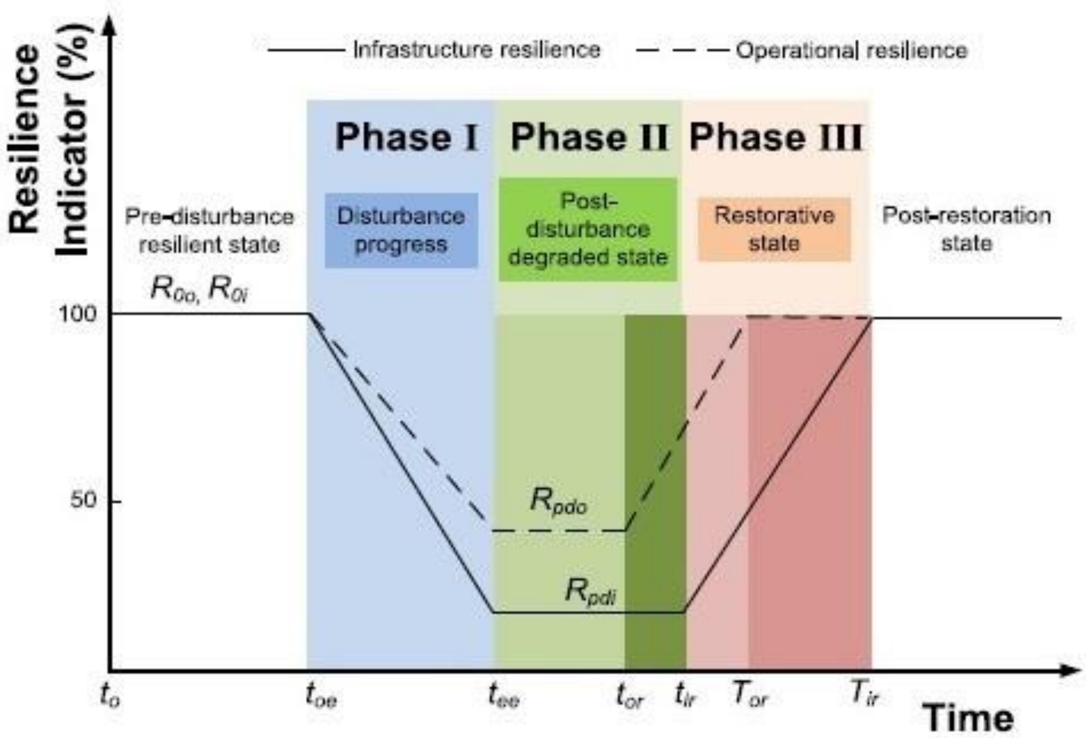

Figure 2.7 Multi-phase resilience trapezoid (Mancarella et al., 2017)

Operational	**Infrastructure**	
$\Phi = (R_{pdo} - R_{0o}) / (t_{ee} - t_{oe})$	$(R_{pdi} - R_{0i}) / (t_{ee} - t_{oe})$	(2.4)
$\Lambda = R_{0o} - R_{pdo}$	$R_{0i} - R_{pdi}$	
$E = t_{or} - t_{ee}$	$t_{ir} - t_{ee}$	
$\Pi = (R_{0o} - R_{pdo}) / (T_{or} - t_{or})$	$(R_{0i} - R_{pdi}) / (T_{ir} - t_{ir})$	

where

- R_{pdo} = minimum service value for the operational;
- R_{0o} = original service value for the operational;
- t_{ee} = the time that system at lowest service value;

- t_{oe} = the time that system starts dropping;
- t_{or} = the time that system starts increasing its value after disruption for the operational;
- T_{or} = the time that system reaches at normal level for the operational;
- R_{pdi} = minimum service value for the infrastructure;
- R_{0i} = original service value for the infrastructure;
- t_{ir} = the time that system starts increasing its value after disruption for the infrastructure;
- T_{ir} = the time that system reaches at normal level for the infrastructure.

ΦΛΕΠ indicates how fast (Φ-metric) and how slow *(Λ-metric)* resilience decreases, how extensive (E-metric) the duration of the post-event degraded state is and how immediately (*Π*-metric) the pre-event state is reached.

Gao (2010) proposed a method to quantify the resiliency that focuses on the recovery phase only with a particular attention to how many ways are available for a system to recover its lost function. His analytical method was proposed for water systems but applicable to power systems. The method came up with a simple formula as: $I_{RC} = I_C + I_R$, where I_{RC} is the total number of ways to recover a lost function, I_R is the number of ways to reconfigure a system, and I_C is the number of ways to replace a component (Gao, 2010) as a system may have spare parts available. It is clear that the larger the number (I_{RC}), the more resilient the system. For example, a system with I_{RC} = 4 is more resilience that a system with I_{RC} = 2. Gao (2010) also considered the cost and/or time in the process of reconfiguration and replacement (see Figure 2.4). Figure 2.4 shows a number of particular ways of resilience versus the cost/time. To a system, the recovery process is always related to time and cost, and indeed the recovery concerns three things: recoverability, time and cost. Therefore, the total number of methods to recover within the required cost and time is a metrics for resilience.

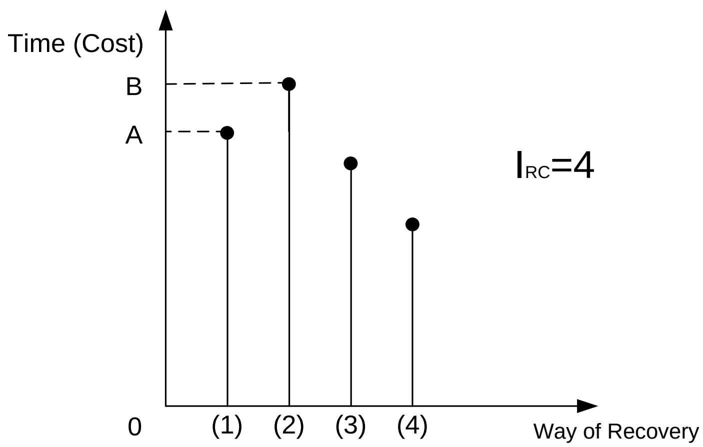

Figure 2.8 A number of particular ways of resilience (Gao, 2010).

3.5 Conclusion

In this chapter, various methods for resilience measurement to power systems as well as other similar systems such as water supply systems were reviewed and analyzed. The review reveals that (1) definition of resilience to engineering systems still lacks a unified one with a particular confusion being the difference between resilience and robustness and (2) accordingly no unified methodology available for objective and quantitative measurement of resilience. Regarding (1), this chapter has provided a more comprehensive definition of resilience to engineering systems. Regarding (2), the current literature appears to have considered the resilience of a system but in a general way such that the capability of adaption of a partially damaged system is measured qualitatively.

As described in Chapter 1, the main objective of this thesis was to understand the resilience of the power system of hospitals, along with its cost implication, in the situation that the main power supply is disrupted, and the backup power supply is put in place. The backup power generator considered in this thesis was a combined power system, which has a diesel power system and a solar power system. The function of the power system in that situation is to supply the critical loads of hospitals rather than the total load. The literature review presented in this chapter can conclude that the objective of research with this thesis is unique and the research outcome is expected to be a meaningful contribution to the field of power system resiliency.

CHAPTER 3

SOLAR SYSTEM

3.1 Introduction

This chapter describes the information of solar panels, inverters, battery storage, the methods of integration of solar panels and battery storage. Specifically, Section 3.2 will describe the solar panel structure. Section 3.3 will illustrate different types of the battery storage in a solar system, and then various methods of integration of the battery storage and the solar system will be discussed in Section 3.4. Section 3.5 is a summary.

3.2. Solar panel structure

Solar panels consist of several solar cells that are connected in series. A group of solar cells that are connected may also be called a module. As such, a solar panel is composed of several modules on a rack. Rack is a framework with rails, bars and hooks for holding the panel. The cell is composed of semiconductor materials that are made of silicon (Mullendore & Milford, 2015). Once a photon or part of light hits a solar cell, an electron in a solar cell gets free. These free electrons generate the current. The current makes sense to the potential or voltage, and the current and the voltage introduce the power, which is called the photovoltaic (PV) power (Mullendore & Milford, 2015). There are different types of solar panels, but the most common one is the monocrystalline and polycrystalline silicon cell. Monocrystalline cells are suitable in the condition of direct light as opposed to polycrystalline cells that are sufficient in the condition of low light (Mullendore & Milford, 2015). There are other materials that can be used in solar cells, including cadmium telluride and copper indium diselenide. Some modules are manufactured with the combination of these materials for different purposes, However; approximately 90 percent of modules are composed of crystalline silicon (Roos, 2009).

3.2.1 Inverter

Solar panels generate direct current (DC) but all other electrical loads in a power system work with alternative current (AC), so the DC power must be converted to the AC power. A sub-system in a solar system, which converts the DC power to the AC power, is called **inverter**. The inverter may also play functions other than the DC-AC conversion function (i.e., DC to AC or AC to DC), such as supplying a power to an on-site load or charging a battery storage, and transmitting a power to a grid (Mandi, 2017). There are many inverter manufacturers available with various technologies, but the two basic types used in solar systems are (i) grid-tied inverters and (ii) battery-based inverters (Mullendore & Milford, 2015).

Grid-tied inverters are used for a PV system without storage. These inverters are also recognized as grid-direct inverters. They convert the DC power to the AC power (Mullendore & Milford, 2015). Grid-tied inverters require an anti-islanding protection to disconnect solar systems to a central grid in the event of outage (Mullendore & Milford, 2015). Figure 3.1 shows the grid-tied inverter in the solar system.

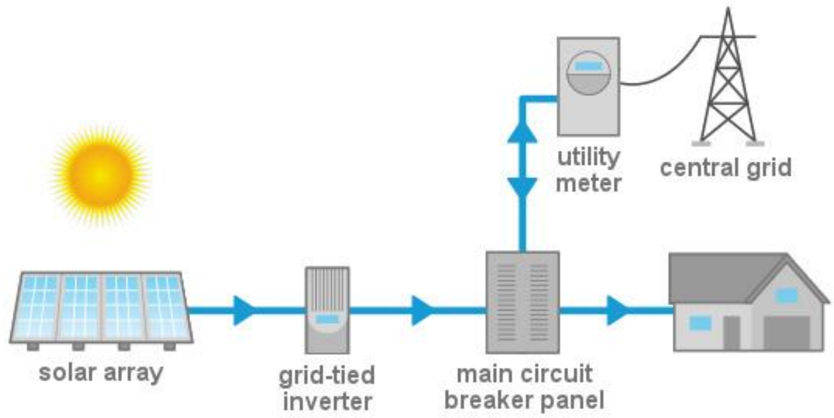

Figure 3.1 The grid-tied solar system (Mullendore & Milford, 2015).

Battery-based inverters are used for the application of solar panels integrated with battery storage. It has also been known as multi-functions, hybrid and bi-directional function (Mullendore & Milford, 2015). This inverter has an automatic switch to disconnect the system from the central grid and continues supplying critical loads during outages. Once the central grid is back to the normal condition, the automated switch reconnects the system to the grid (Mullendore & Milford, 2015). The battery-based inverter also converts the DC to AC power for AC loads, and converts the AC to DC power to charge the battery storage from the AC source (Mullendore & Milford, 2015). Figure 3.2 shows the battery-based inverter in the solar system.

Figure 3.2 Battery-based Inverter does function between battery, load and grid ("Battery-based Inverter ", 2016).

3.2.2 Critical load subpanel

Critical loads are loads in critical systems such as CT scanner and lighting, and these systems must be always available or active. Losing critical loads is a fatal situation to a hospital. The magnitude of critical loads depends on the type of critical systems. In general, the critical loads include emergency lighting, water pumps pressure, elevators, cooling and heating system, and critical equipment systems. To solar systems, it is not cost effective for them to cover all power loads but critical loads in the event of power outages (Mullendore & Milford, 2015).

3.3 Battery Storage

3.3.1 Battery

One of the main components of a solar storage system is battery. The battery consist of one or more electro-chemical cells that convert chemical energy into electrical energy by chemical reactions (Mullendore & Milford, 2015). In solar systems, Batteries can store either excess electricity generated by solar panels or electricity coming from the central grid. The electricity stored in the battery can be used for many purposes including peak shaving, supplying critical loads when the grid is down or when clouds cause a decrease in PV output or during night. There are various types of battery with different chemical compositions, but the two comment types that are used in the solar system are Lead-acid batteries and lithium-ion battery. The Lead-acid battery has been used for a long period time for many purposes including the solar system. The Lead-acid battery includes various types such as Golf cart, flooded type, Gel battery and Absorbent Glass Mat (AGM), among which the Golf cart is the least expensive choice of battery for small budgets but it is only useful for small systems (Lombardi, 2012). Flooded types are the most common batteries manufactured and used in solar panels. They are reliable with reasonable cost. The downsize of the flooded types of battery are that they release gases which are not suitable for indoor use (Lombardi, 2012). Gel batteries are similar to flooded batteries and do not release gas during the charging process. So they can be used indoors (Lombardi, 2012). AGM has all the advantages of previous types but is more expensive than others (Lombardi, 2012).

Lithium-ion batteries are new types of batteries in which technology is still developing (Mullendore & Milford, 2015). There are various types of Lithium-ion batteries available that are used for different purposes such as Lithium-ion Manganese Oxide (LMO), Lithium-ion Iron Phosphate (LFP), Lithium-ion Cobalt Oxide (LCO), lithium-ion Titanate (LTO), Nickel Manganese Cobalt (NMC), and Nickel Cobalt Aluminum (NCA).

- LMO: Lithium-ion Manganese Oxide is an expensive type that has high voltage cathode material as well as high power capabilities; on the other hand, it has lower lifespan (Blair et al., 2014).
- LFP: Lithium-ion Iron Phosphate has lower voltage cathode and good safety properties; on the other hand, it has lower volumetric energy (Blair et al., 2014).
- LCO: Lithium-ion Cobalt Oxide is common cathode material with high specific energy, but it is costly and toxic (Blair et al., 2014).
- LTO: lithium-ion Titanate is promising anode material with good lifetime properties but it has lower capacity as well as being more costly (Blair et al., 2014).
- NMC: Nickel Manganese Cobalt: this type of battery has lower price than LCO with improving safety characteristics (Blair et al., 2014).
- NCA: Nickel Cobalt Aluminum is the same as NMC's cathode material with high specific energy (Blair et al., 2014).

Each battery technology has its advantages and disadvantages. Lead acid batteries are less expensive, and they have a deep-cycle. On the other hand, it has a shorter life span, heavy weight, and large shape (Mullendore & Milford, 2015). Lithium-ion batteries are more compact and lighter, have a longer life span, and their performance in low temperature and frequent cycling is better than that of the lead acid battery. On the other hand, the Lithium-ion battery is more expensive than the Lead-acid battery (Mullendore & Milford, 2015).

There is another type of battery available in a solar system called Hybrid battery ((Mullendore & Milford, 2015). A Hybrid battery is the combination of Lithium-ion and Lead-acid batteries that is being deployed to obtain the benefits of each battery in the solar system.

3.3.2 Main components of in a battery

- Charge Controller: Prevents the battery bank from overcharging by interrupting the flow of electricity from the PV panels when the battery bank is full. The charge controller is connected between the battery bank and the solar array on the DC circuit (Anderson, 2015).
- Battery Bank: A group of batteries wired together. The batteries are similar to car battery, but they are designed specifically to endure the type of charging and discharging that needs to be handled in a solar power system. While many different types of battery and chemical composition are available, lead acid and lithium-ion batteries are the major common types that are used in the system (Roos, 2009).
- System Meter: Measures and displays the solar PV system's performance and status (Roos, 2009).
- Main DC Disconnect: A DC rated breaker between the batteries and the inverter, allows the inverter to be quickly disconnected from the battery bank for service (Roos, 2009).

3.4 Methods of integration of the battery storage and the solar system

In the event of outages, solar panels are linked with the battery storage to supply critical loads, but this system must have islanding equipment to disconnect the solar system from the grid. Islanding equipment typically consists of physical switches to disconnect the solar system from the grid in the event of outages. There are different ways to link solar panels to battery storage. The two main common methods of integrating battery storage with solar panels are DC-couple and AC-couple systems

3.4.1 DC-coupled system

The battery is installed on the same side of the solar panels and is charges by the panels. Solar panels generate electricity into direct current and the battery storage uses direct current (DC) to charge and discharge electricity (Mullendore & Milford, 2015). Battery storage will be charged directly with DC electricity generated by the solar panels. Overcharging also needs to be considered since it could do damage to the storage and eventually pose a safety hazard (Mullendore & Milford, 2015). Charge controller is a device that is placed between the solar panel and battery storage to prevent overcharging batteries as well as step down PV output voltage to a level ("Resilience solar photovoltaic", 2015). Figure 3.3 shows DC-couple system. This system works in a similar manner as grid-tied solar system when the grid is in a normal condition. The battery based inverter converts DC into AC to supply loads or to transfer excess energy to the central grid (Mullendore & Milford, 2015). In the event of outages, the inverter automatically disconnects the solar system from the central grid and the solar system supplies the critical load of an application system such as hospital. Once the grid is back to normal, the inverter detects and automatically reconnects to the central grid (Mullendore & Milford, 2015).

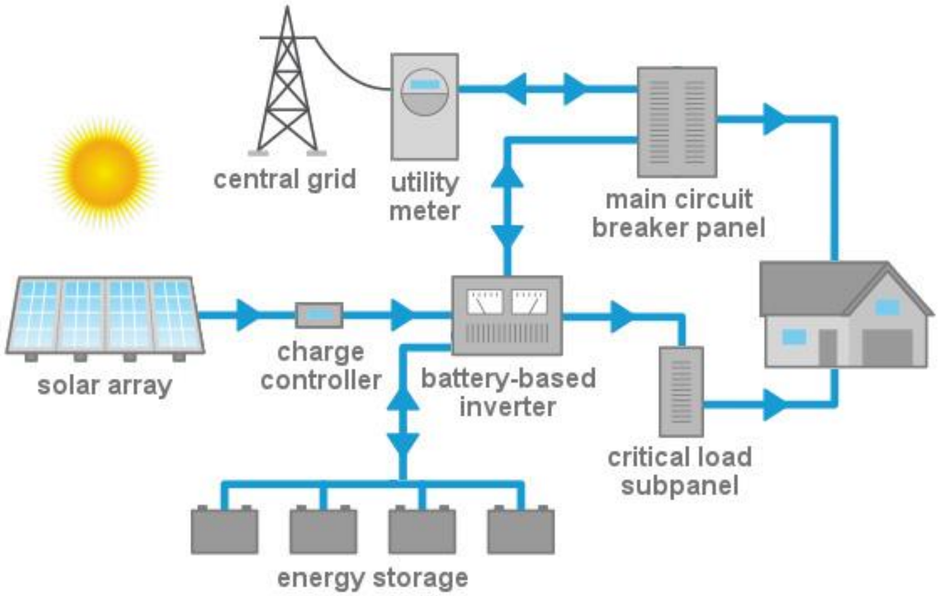

Figure 3.3 DC coupled solar with battery system (Mullendore & Milford, 2015).

3.4.2 AC-coupled system

The battery are installed on the grid side of the system, since electricity is already converted from DC to AC by the inverter (Bloomfied, 2016). Figure 3.4 shows AC-coupled system. This system has two inverters including a grid-tied inverter and a battery-based inverter. The Grid-tied inverter replaces the charge controller in the DC-coupled system. The battery will be charged either from solar panels or the central grid (for the application of peak shaving), but the battery-based inverter must convert electricity from AC to DC since the batteries work with DC. Both the grid-tied inverter and the battery-based inverter are connected to the critical loads subpanel to meet the electricity that is needed by critical loads (Mullendore & Milford, 2015). Under a normal condition, the grid-tied inverter converts electricity from DC to AC and supplies the critical loads subpanel. Excess energy will be transferred by the battery-based inverter either to the main circuit breaker panel and central grid or converted into DC to charge the battery storage. In the event of outages, the battery-based inverter disconnects the solar system to the central grid. So the critical loads subpanel will be supplied with electricity that comes from solar panels that are converted into AC by a grid-tied inverter or electricity that comes from battery storage that are converted into AC by a battery-based inverter (Mullendore & Milford, 2015). Once power is back to normal, the battery-based inverter detects and reconnects the solar system to the central grid.

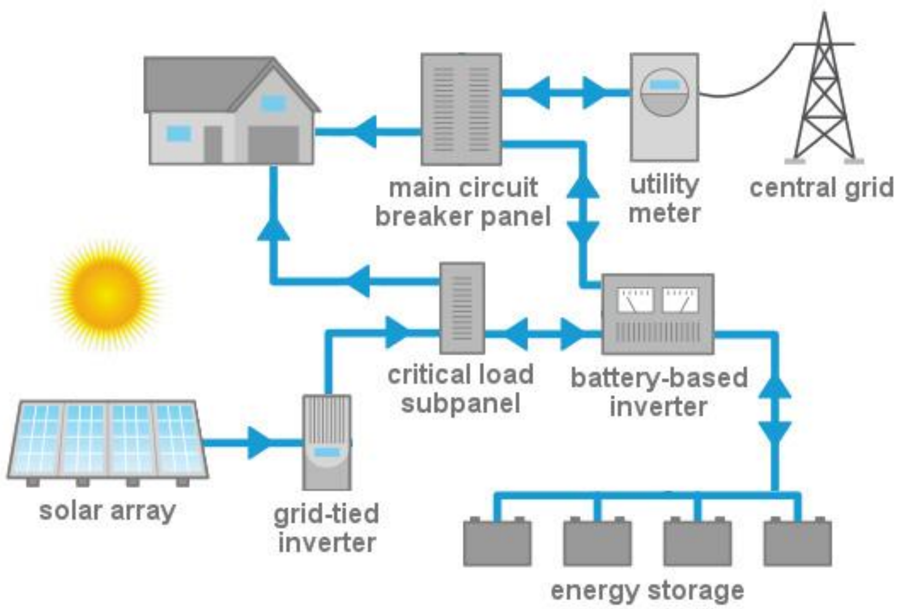

Figure 3.4 AC-coupled solar with battery system (Mullendore & Milford, 2015).

3.4.3 Application and comparison of AC-coupled and DC-coupled systems

In instances where customers need to consume electricity at the time of generation, an AC-coupled system is more efficient than a DC-coupled system. An AC-coupled system has two separate inverters, so it is not necessary to shut down the whole system during the period that the system is in maintenance or trouble-shooting (Mullendore & Milford, 2015). Moreover, it is easy to expand an AC-coupled system, so this system is suitable where a PV system already exists. On the other hand, in applications where customers need to store electricity and use it later, the DC-coupled system is more applicable. A DC-coupled system needs a single power conversion compared to an AC-coupled system that needs two power conversions to store energy. Therefore, a DC-coupled system is more efficient (Ardani et al., 2016). According to California Energy Commission (CEC) database, an AC-coupled system will lose up to 10% power conversion more than a DC-coupled system (Ardani et al., 2016). Furthermore, a DC-coupled is more sufficient for the application where a solar panel and battery storage are installed at the same time. Table 2.1 summarizes key differences and considerations for DC-coupled compared to AC-coupled configurations.

Table 3.1 Considerations and differences between DC-coupled and AC-coupled (Ardani et al., 2016).

Function	**DC-coupled**	**AC-coupled**
Inverter requirements	Typically needs a charge controller to reduce voltage of PV output to the battery. Requires one inverter shared between the battery and the PV array. Even though bi-directional inverters are common, they are not necessary. However, the customers cannot	Needs two inverters including a grid-tied inverter for the PV array and a bi-directional battery-based inverter. Customers are able to charge the battery from the grid or other AC source by bi-directional inverters.

	charge the battery from an AC source with a grid-tied inverter.	
Wiring/conduit requirements	Usually requires less wiring compare to AC-coupled systems.	Usually requires more wiring compare to DC-coupled systems, since the configuration needs two inverters.
Installing PV and battery at same time vs. adding battery to existing PV array	When PV and battery are installed at the same time, this configuration is most common to use since in DC coupling battery with an existing PV array needs replacement of the PV system's grid-tied inverter (with a battery-based inverter) and associated wiring. It often causes violate in terms of ownership agreements for third-party-ownership when to Replace the existing equipment of DC-coupling storage with an existing PV array.	This configuration will be used for an existing PV array. The existing grid-tied inverter can remain in the installation without rewiring the array. When the battery system will operate in parallel with the grid, main PV net energy metering and third-party financing agreements are usually placed at risk, and a new utility interconnection agreement is required Equipment compatibility is to be considered if adding storage to an existing PV array because of various product specifications

		across manufacturers. For instance, product compatibility and communication between the grid-tied inverter and battery-based inverter is critical for matching loads in the system as well as managing PV output (CUNY 2016).
Permitting and interconnection	When PV and storage systems are installed at the same time, usually only one permit and one interconnection agreement are necessary.	Although, PV and storage systems are installed at the same time, authorities having jurisdiction and utilities might need the battery and PV array to be permitted and endorsed for interconnection separately.
System efficiency	Usually is more efficient where PV energy is stored most of the time and used at a later time.	Generally is more efficient in applications where PV energy use at the time of generation.
Self-restarting	This system is capable self-restart even if the inverter shuts down from low battery voltage,	Most AC-coupled systems are not capable to self-restarting when the

	since the charge controller could still charge the batteries.	battery-based inverter shuts down because of low battery voltage.
Incentives	When using a bi-directional inverter, it may need more complicated monitoring to illustrate that the percentage of electricity stored is provided by PV versus the grid—required for ITC and performance-based incentive.	Make the system for simple monitoring if installing a one-way kWh meter to the output of the grid-tied inverter. When batteries are added later on to an existing PV array, they might be eligible for the ITC. The batteries are essential to the operation of the PV system.

3.5 The calculations of solar panels and battery storage

The rough estimation of a solar panel size for the entire system can be made by the following equation:

$$\frac{\text{Annual electric load consumption}}{365 \times \text{Average solar sunshine} \times \text{a derate factor}} \tag{3.1}$$

where

- The average solar sunshine in Saskatoon = 5.8 (See Appendix A);

- A de-rate factor = 0.86.

A de-rate factor provides allowance for all the potential losses in the solar system, including temperature effects, power conversion from DC to AC, wiring losses, shading, dust, the age of the system (Lombardi, 2012).

The same formula can be used to calculate a solar panel site for critical loads by the following equation:

$$\frac{\text{Essential loads (KW)} \times \text{duration of need}}{\text{Average solar sunshine} \times \text{a derate factor}} \tag{3.2}$$

The rough estimation to calculate the size of battery storage is obtained by the following equation:

$$\frac{\text{Essential loads (KW)} \times \text{duration of need}}{\text{Depth of discharge} \times \text{inverter efficiency}} \tag{3.3}$$

- Depth of discharge = 0.8;
- Batteries can be damaged or have their lifespan significantly shortened if they are discharged too deeply often so there is a rule that to set a maximum depth of discharge of 80 percent (Mullendore & Milford, 2015);
- Inverter efficiency = 0.96.

The inverter efficiency must consider the loss of conversion between DC power to AC power (Mullendore & Milford, 2015). Based on a new technology applied for inverter, the inverter efficiency is around 96 percent ((Mullendore & Milford, 2015).

CHAPTER 4

RESILIENCE MEASUREMENT

This thesis focused on the recovery phase instead of the three or four phases as discussed before, as this phase makes a great sense to resilience while other phases fit well to reliability or robustness. Therefore, this thesis assumed that a disaster has occurred, the main power supply has been disrupted, and the backup power generator is put in place. Under this assumption, the degree of resilience is thus related to the behaviour of the backup power supply system. This thesis further assumed that a full recovery refers to the satisfaction of the critical load of a system, hospital in this case, rather than the total load. Therefore, two attributes were used to quantify the capability of the backup power system in terms of meeting the critical load: (1) the magnitude of the power supplied by the backup power system (denoted as **L**) and (2) the length of time the backup power system can supply the actual power (denoted as **T**). Further, the backup power may fail, and the likelihood of failure can be measured by the probability of failure (denoted as **PF**).

The resilience (denoted as **R**) or degree of resilience in a more precise manner can be quantified by

$$R = FC\ (L/LC) \times FT\ (T/TD) \tag{4.1}$$

where LC: critical load; TD: length of the time of disruption. Note that both LC and TD are known before the resilience of a backup power system can be assessed. LC can be more accurately calculated, but TD can only be estimated (i.e., subjectively determined). FC (.) and FT (.) are two functions and defined as follows:

$$\text{FC} = \begin{cases} 1, & L/LC \geq 1 \\ \text{L/LC}, & \text{L/LC} < 1 \end{cases} \tag{4.2}$$

$$\text{FT} = \begin{cases} 1, & T/TD \geq 1 \\ \text{T/TD}, & \text{T/TD} < 1 \end{cases} \tag{4.3}$$

The likelihood of failure can happen to the actual magnitude of the backup power (L) and can also happen to the actual length of service of the backup power (T). **PFL** denotes the probability that the backup power fails to provide the power larger than CL, and **PFT** denotes the probability that the backup power fails to provide the service longer that TD. The definition of FC and FT is modified into

$$\text{FC} = \begin{cases} 1, & \text{(PFL)(L)/LC} \geq 1 \\ \text{(PFL)(L)/LC}, & \text{(PFL)(L)/LC} < 1 \end{cases} \tag{4.4}$$

$$\text{FT} = \begin{cases} 1, & \text{(PFT)(T)/TD} \geq 1 \\ \text{(PFT)(T)/TD}, & \text{(PFT)(T)/TD} < 1 \end{cases} \tag{4.5}$$

If there is more than one backup power generator, say two, the formula for R, i.e., Equation (4.1) remains the same, but the definition of FC and FT needs to be modified into

$$\text{FC} = \begin{cases} 1, & (\text{PFL1} \times \text{L1} + \text{PFL2} \times \text{L2})/\text{LC} \geq 1 \\ (\text{PFL1} \times \text{L1} + \text{PFL2} \times \text{L2})/\text{LC}, & (\text{PFL1} \times \text{L1} + \text{PFL2} \times \text{L2})/\text{LC} < 1 \end{cases} \tag{4.6}$$

$$FT = \begin{cases} 1, & (PFT1 \times T1 + PFT2 \times T2)/TD \geq 1 \\ (PFT1 \times T1 + PFT2 \times T2)/TD, & (PFT1 \times T1 + PFT2 \times T2)/TD < 1 \end{cases} \quad (4.7)$$

In Equation (4.6) and Equation (4.7), the number '1', '2' represents the backup power generator 1, the backup power generator 2, respectively.

A graphical representation of the resilience measurement formula, i.e., Equation (4.1), is shown in Figure 4.1, which gives a geometrical account for the formula for R. The backup power resilient behavior 1 has the resilience of less than 1, while the backup power resilient behavior 2 has the resilience of 1.

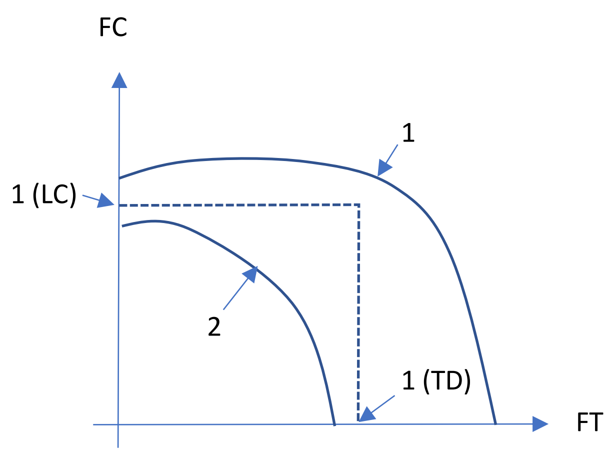

Figure 4.1Resilience measurement for a system. 1, 2: backup power resilient behavior

From the above discussion, one can see that there is a situation where the actual power magnitude by the backup power (L) may be greater than the critical load (CL), and the actual service time (T) greater than the length of the time of disruption (TD). This situation may be called over-resilience. Clearly, the over-resilience will increase the reliability of resilience of a power system (including both the main power and backup power generators). This thesis proposed a concept called **resilience reliability (RR)**, which is defined as the probability that a fully resilient (R=1) system keeps its status. Mathematically, it is defined as follows:

$$\Delta\_L: (PFL \times L - CL)/CL, \text{ assume } PFL \times L > CL \tag{4.8}$$

$$\Delta\_T: (PFT \times T - TD)/TD, \text{ assume } PFT \times T > TD \tag{4.9}$$

$$\Delta\_RR: \Delta\_L \times \Delta\_T \tag{4.10}$$

In the above equations, Δ_RR measures RR.

CHAPTER 5

RESILIENCE ANALYSIS FOR THE HOSPITALS SYSTEMS IN SASKATOON

5.1 Introduction

This chapter discusses the application of the methodology for resilience measurement for power systems to Saskatoon's hospitals. Specifically, the power usage, critical load and resilience of the existing backup power system (diesel power generator) are discussed. There are three hospitals in Saskatoon, namely Royal University Hospital (RUH), Saskatoon City Hospital (SCH) and Saint Paul Hospital (SPH), and all of them are covered in this chapter. Section 5.2 presents (RUH) including the power usage, critical load and resilience of the backup power system. Section 5.3 and 5.4 present SCH and SPH, respectively.

5.2 Power usages, critical loads and system resilience at RUH

5.2.1 Power usages at RUH

The total annual electric load consumption in 2017 at RUH was 25034910 KW/h. Through May to October, RUH consumed more electricity than the rest of the year due to the use of air conditioners. July was the peak consumption month of the year with 2469264.75 KW/h consumed electricity. When the weather was warmer, RUH consumed more electricity, peaking between 9 am and 6 pm.

5.2.2 Critical loads at RUH

Critical loads at RUH are associated with the operations at Intensive Care Unit (ICU), Coronary Care Unit (CCU), Neonatal, Intensive Care Unit (NICU), labs, boiler, freezers in the kitchen, Motor Control Centre (MMC) and Uninterruptable Power Supply (UPS). The critical loads at RUH are between 700 KW/h to 800 KW/h.

5.2.3 Resilience of the current power system at RUH

SaskPower provide electricity to RUH. The reliability of the power from the central grid, supplied by SaskPower is high; RUH experienced power outages on average once in per year. Therefore, the backup power is necessary. All the Saskatoon hospitals currently use the diesel power generator as a backup power, leading to a certain degree of the resilience of their power system (system resiliency for short). The diesel generator stands-by at a normal situation and will be activated only when the main or prime power generator gets outrage. So, the diesel generator only works for a limited period of time. According to the information provided by vendors, a stand-by generator[1] can provide electricity for approximately 200 hours per year. Further, vendors do not recommend running the stand-by diesel generator at their full load capacity, because in practice, a stand-by generator may run as a prime generator as well and in this case, the diesel generator is run with 25% of its capacity for a prolonged time (i.e., the time longer than 200 hours).

RUH has three diesel generators to supply critical loads during power outages (See Figure 5.1 for an example of the diesel generator at RUH). Each diesel generator can provide up to 250 kW/h

[1] There are two types of diesel power generator: stand-by and prime. The former can only run 200 hours.

when it runs at its full capacity. The three stand-by generators are able to provide a maximum of up to 750 KW/h if the enough fuel is available. Given a fuel tank size of 25000 liters, the diesel power can thus generate electricity for 78 hours. To run for 200 hours, the tank needs to be refilled (2 times). As such, there is uncertainty that the stand-by diesel generator can run 200 hours.

Figure 5.1 Diesel generator at RUH.

In the following, the reliability of the backup power system of RUH is discussed, which corresponds to the parameter PFL and PFT in Equations (4.1) for the resilience R. The reliability of the diesel generator is fairly low with a high probability of failures in the areas such as equipment malfunctions, overheating, fuel supply deficiency (Mullendore & Milford, 2015). The Nuclear Plant Aging Research (NPAR) studied the failure of diesel generators based on the historical data of 1984 incidents (Hoopingarner & Zaloudek, 1990), especially on the vulnerability of systems and components in diesel generators. The results are summarized in Table 5.1.

Table 5.1 Failure rates of components in diesel generators (Hoopingarner & Zaloudek, 1990).

Systems and components	Percentage of failures
Instruments and control systems	26
Governor	12
Control air system	2
Wiring and terminations	2
Sensors	2
Fuel system	15
Engine piping	7
Injector pumps	5
Injectors and nozzles	2
Starting system	10
Starting air valve	5
Controls	2
Starting motor	2
Cooling system	10
Piping	3
Pumps	2
Heat exchangers	2
Engine structures	9

Crankcase	3
Cylinder lines	2
Main bearings	2
Other systems	30

It is reasonable to separate the engine failure from the non-engine related failures, as per Table 5.2. From Table 5.2 it is estimated that the engine and non-engine related failures are about 1/3 and 2/3 of the total failures, respectively. Hoopingarner & Zaloudek (1991) estimated that the rate of failure of the engine related components in a diesel generator approximates 5%, so the failure rate of the non-engine components can be estimated as 10%. The overall rate of the system failure is the summation of the engine and non-engine related components failures, i.e., 15%. In another independent study, Prudzeni & Firoravanti (2017) estimated that the failure rate of diesel generators is about 23 % at the time they are called upon in a power outage.

Table 5.2 Vulnerability of the engine and non-engine components in diesel generators (adopted from Hoopingarner & Zaloudek, 1990)

Engine related component	Percentage of failure	None-Engine related components	Percentage of failure
sensors	2	Governor	12
Engine piping	7	Control air system	2

Piping	3	Wiring and terminations	2
crankcase	3	Human error	9
Cylinder lines	2	Starting air valve	5
Main bearings	3	Controls	2
Heat exchangers	2	Pumps	2
Injectors and nozzles	2	Other system	30
Injector pumps	5	------------	-----------
Crank shaft	3	------------	-----------
Total	33	Total	64

Overall, these numbers show the average rate of failure of a diesel generator without considering aging. The average age of diesel generators in Saskatoon's hospitals is around 30 years. Thus, considering aging, the rate of failure of diesel generators in Saskatoon's hospitals could increase to 25%. This number is in line with what Saskatoon's utility managers have indicated during the authors' interviews with them; thus, the reliability of diesel generators in Saskatoon's' hospitals are 75%.

PFL denotes the probability that the backup power does not fail to provide the power larger than CL without consideration of the availability of fuel, so PFL=0.75. PFT denotes the probability that the power system can run for the length of time as designed or as specified. The diesel power system needs fuel. As such, the only uncertainty comes from the availability of the fuel. Let X denotes the amount of fuel in storage (i.e., always available, depending on the size of the tank). To this case, the probability that the backup power is available is 100%. Let Y denote the amount of fuel which is not in storage (i.e., the need of acquisition and transportation from elsewhere). To this case, the probability is less than 100% say h%. It is noted that X+Y are the amount of fuels for the backup power to run a period of time such as 200 hours in the case of RUH.

Let $PFT_X = X/(X+Y)$, which represents the percentage of the fuel in storage (limited by the tank size), and $PFT_Y = Y/(X+Y)$, which represents the percentage of fuel not in storage, which means that the tank needs to be refilled. $PFT_X + PFT_Y = 1$. As such, we have:

$$PFT = PFT_X + h \times PFT_Y. \tag{5.1}$$

Suppose T=200, $PFT_X = 78/200 = 0.4$,

$PFT_Y = 1 - PFT_X = 1 – 0.4 = 0.6$, h=0.90. PFT = 0.4 + 0.9(0.6) = 0.94.

Below shows the calculation of the resilience of the backup power system (diesel generator) at RUH.

- LC = 700 KW/h,
- TD = 200 Hours,
- PFL = 0.75,

- PFT = 0.94,
- L = 700,
- T = 200,
- (PFL)(L)/LC = (0.75)(700)/700 = 0.75<1, FC = 0.75, and
- (PFT)(T)/TD = (0.94)(200)/200 = 0.94<1, FT=0.94.

So R = FC × FT=0.75 × 0.94 = 0.705.

A note is taken care of regarding the estimation TD. First, the TD was estimated based on the interview with the manager of RUH, and their experiences of the past power outage cases led to the time duration of disruption was around 100-150 hours. It was also told by the manager that these diesel generators played their backup power role well in the past years. Note that the diesel power generators at RUH were selected to run for 200 hours (exception was SPH, which was 165 hours). To play safe, we decided the TD is 200 hours, which is larger than the 150 hours, leaving the safety margin of 50 hours. So the value of R found in the above is with some safety margin or conservative. The TD for RHU was also considered for the other two hospitals, because all the hospitals were in Saskatoon and their situations were reasonably considered as similar.

Figure 5.2 shows the resilience of the backup power at RUH with the backup power generator being the diesel power generator.

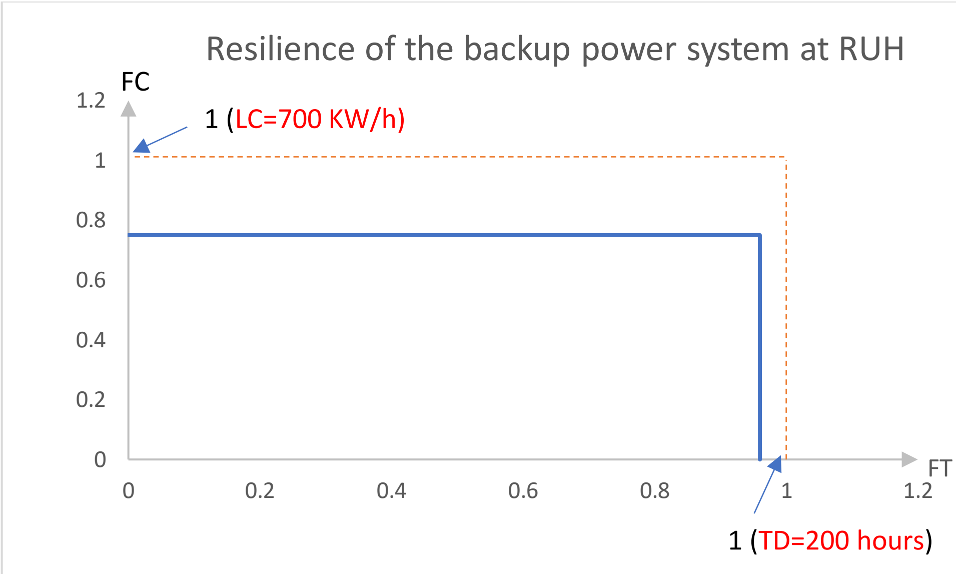

Figure 5.2 Resilience of the power system at RUH with the diesel power as the backup power.

5.3 Power usage, critical loads and resilience of the current power system at SCH

5.3.1 Power usage at SCH

The total annual electric load consumption in 2017 at SCH was 14685269 KW/h. Through May to September, SCH consumed more electricity than the rest of the year due to the air conditioners and July was the highest electric load consumption month of the year with 1550378 KW/h consumed electricity. Furthermore, the time between 9 am to 3 pm was the peak time of the day that SCH consumed the power.

5.3.2 Critical loads at SCH

The critical loads at SCH are associated with boiler fan, fridge, UPS, fans, Magnetic Resonance Imaging (MRI), Computed Tomography scan (CT scanner) and freezer in the kitchen, totaling approximately 1000 KW/h. During the prime power outage, the system is required to still provide power to meet the critical loads.

5.3.3 Resilience of the current power system at SCH

SCH has three diesel generators to supply critical load during power outages (see Figure 5.3 for one of the diesel generators at SCH). Each diesel generator can provide up to 1000 KW/h when it runs at its full capacity. The three stand-by generators can provide a maximum of up to 3000 KW/h if the enough fuel is available. Given a fuel tank size of 45400 liters and each generator consumes 270 liters per hour, and the three diesel generators together generate electricity power for approximately 56 hours. To run for 200 hours, the tank needs to be refilled (3 times). As such, there is uncertainty about whether the stand-by diesel generator can run 200 hours. The reliability of diesel generators is low: as mentioned in Section 5.2.3, the rate of failure of diesel generators at SCH is about 25%. One example of this unreliability occurred in 2010 when SCH shut down entirely due to the failure of all the three diesel generators. Equipment malfunction was the main reason for the incident. In contrast to the situation at RUH, the reliability of power from the central grid, supplied by City of Saskatoon (Light and Power)[2], is low: SCH experienced outages between

[2] It is different from SaskPower.

two to three times each year. Therefore, a resilient backup power system is very important to SCH. In the following, we compute the R for SCH.

Figure 5.3 Diesel generator at SCH.

$$PFT = PFT_X + h\times PFT_Y. \tag{5.1}$$

Suppose T=200. PFT_X= 56/200 = 0.3, PFT_Y= 1 - PFT_X = 1 – 0.3 = 0.7. Suppose h is the same as the one for RUH, so h=0.90. According to Equation (5.1), we get for SCH PFT = 0.3 + 0.9(0.7) = 0.93. Further, we have

- LC = 1000,
- TD = 200 Hours,
- PFL = 0.75,
- PFT = 0.93,

- L = 1000,
- T = 200,
- (PFL)(L)/LC = (0.75) (1000)/1000 = 0.75<1, FC = 0.75.
- (PFT)(T)/TD = (0.93) (200)/200 = 0.93<1, FT=0.93.

So R=FC × FT=0.75 × 0.93 = 0.7.

Figure 5.4 shows the resilience of the backup power at SCH with the backup power generator being the diesel power generator.

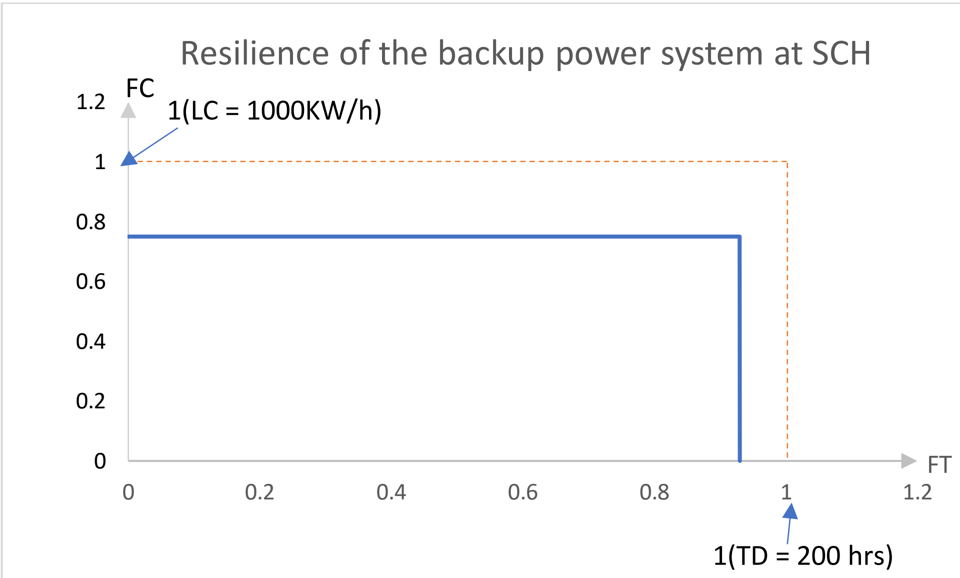

Figure 5.4 Resilience of the power system at SCH with the diesel power as the backup power

5.4 Power usage, critical loads and resilience of the current power system at SPH

5.4.1 Power usage at SPH

The total annual electric load consumption in 2017 at SPH was 15159352 KW/h. Through May to October, SCH consumed more electricity than the rest of the year due to the air conditioners and July was the highest electric load consumption month of the year with 1491372 KW/h consumed electricity. Furthermore, the time between 9 am to 3 pm was the peak time of the day that SPH consumed the power.

5.4.2 Critical loads at SPH

The critical loads at SCH are associated with ICU, CCU, freezer in the kitchen, fans, Pumps, boiler, operating room, radiology, and emergency lighting, totaling approximately 600 KW/h. During the prime power outage, the system is required to still provide power to meet the critical loads.

5.4.3 Resilience of the current power system at SPH

SPH has three diesel generators to supply critical loads during power (see Figure 5.5 for an example of an SPH generator). Each diesel generator can provide up to 600 KW/h when it runs at its full capacity. The three stand-by diesel generators can provide a maximum of up to 1800 KW/h if the enough fuel is available. Given a fuel tank size of 25000 liters and each diesel generator consumes 162 liters of fuel per hour, the diesel power generates electricity power for approximately 51 hours (see Appendix B). To run for 156 hours, the tank needs to be refilled (3 times since. This hospital faces the failure of the diesel generator several times during power outages. For instance, during the power outages, the diesel generator had difficulties in distributing loads equally, and one generator supplied more loads than its capacity and eventually failed. As such, the rate of failure of the diesel generators at SPH is about 25%, similar with the situation at SCH. It is also noted that City of Saskatoon (Light and Power) supplies electric power to SPH, and the reliability of the power from the central grid (Light and Power of Saskatoon) is low: SPH experienced power outages two to three times on average per year.

Figure 5.5 Diesel generator at SPH.

$$PFT = PFT_X + h \times PFT_Y. \tag{5.1}$$

Suppose T=200, PFT_X= 51/200 = 0.25

PFT_Y= 1 – PFT_X = 1 – 0.25 = 0.75, Suppose h is the same as the one for RUH, so h=0.90. According to Equation (5.1), we get for SPH PFT = 0.25 + 0.9(0.75) = 0.925.

Below shows the calculation of the resilience of the backup power system (diesel generator) at SPH.

- LC = 600
- TD = 200 Hours
- PFL = 0.75
- PFT = 0.925
- L = 600
- T = 156
- (PFL)(L)/LC = (0.75) (1000)/1000 = 0.75<1, FC = 0.75.
- (PFT)(T)/TD = (0.925) (156)/200 = 0.72<1, FT=0.72.

So, R=FC × FT=0.72 × 0.75 = 0.54

Figure 5.6 shows the resilience of the backup power at SPH with the backup power generator being diesel power generator.

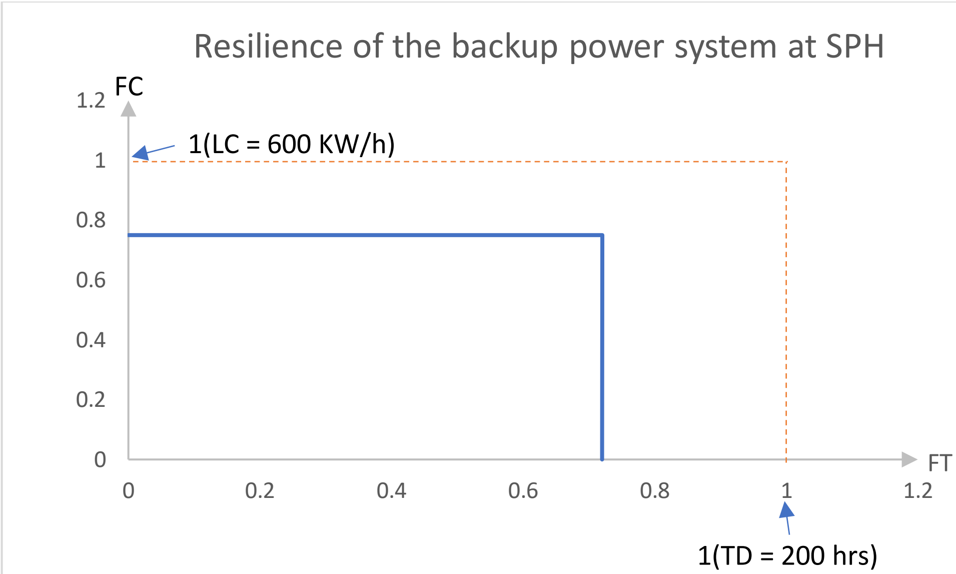

Figure 5.6 Resilience of the power system at SPH with the diesel power as the backup power

5.5 Conclusion

In Chapter 5, the system resilience of the backup power system in the hospitals at Saskatoon was analyzed. In conclusion, the resilience R of the RUH was highest (0.705), followed by that of SCH (0.700) and that of SPH (0.540). Clearly, the enhancement of the resilience of these hospitals, especially SPH is necessary.

CHAPTER 6

COMBINED BACKUP POWER SYSTEM

6.1 Introduction

This chapter presents the design and analysis of a combined backup power system in the case of the hospitals in Saskatoon. This combined system consists of the diesel power generator and solar power generator. The diesel power generator in the hospitals remains because of the high critical load (around 800-1000 KW), while the solar power generator is added on the top of the diesel power generator. The general-purpose software called System Advisor Model (SAM), which is about the analysis of solar power generators (or solar panels), was used for the analysis. The goal of the design is of twofold: resilience enhancement and cost-effectiveness. Section 6.2 introduces the SAM. Section 6.3 presents the methodology in SAM for calculating the net present value (NPV) and the capital cost. Section 6.4 presents the methodology in SAM for calculating the electric power generated by solar panels. Section 6.5 presents the result of the analysis of the three hospitals (SCH, RUH, and SPH) in terms of NPV, capital cost, and payback period for various sizes of solar panels. Section 6.6 presents the analysis of the resilience of the combined backup power system in terms for the same sizes of solar panels considered in Section 6.5. Section 6.7 presents a brief analysis of the backup power which is the solar power with battery. Section 6.8 concludes this chapter by recommending the optimal size of the solar panel for the hospitals in Saskatoon.

6.2 System advisor model

The System Advisor Model (SAM) ("SAM software", 2018) is a software system to analyze the cost and performance of a power system based on renewable energy such as solar energy. The performance considered in SAM is the power, particularly evaluated by the voltage and current, the so-called I-V curve (I: current, V: voltage). SAM can also analyze the economics of the solar power system, including the NPV, net saving system for a year, and payback period. The cost considered in SAM is the net present value and capital cost. SAM needs input data to calculate the NPV, capital cost and payback period of the system. The main input data include: the site of consumption of the electric load (Saskatoon's hospitals), the electricity rates (SaskPower and Light and Power electricity rate), the location and resource of the city (Saskatoon weather) (see Appendix D).

6.3 Net present value and capital cost

The net present value represents the cost minus the revenue associated with a particular power system for a specific period of time (DiOrio et al., 2015). A system with a positive net present value means that the returns will be more than the initial and ongoing cash expenditure while with a negative net present value means that the returns will be less than the initial and ongoing cash expenditure (DiOrio et al., 2015). The capital cost is the initial investment cost of the system. In SAM, the net present value can be found by the following equation:

$$NPV = \sum_{n=0}^{N} \frac{F_n}{(1+d)^n} = Fo + \frac{F_1}{(1+d)^1} + \frac{F_2}{(1+d)^2} + \ldots\ldots + \frac{F_N}{(1+d)^N} \quad (6.1)$$

where

- NPV = net present value;
- F_n = net cash flow in year n;
- N = analysis period;
- d = annual discount rate (Short, Packey, & Holt, 1995).

6.4 Solar power characteristics

The current-voltage (I-V) relation or curve is the basic characteristics of the performance of the photovoltaic device. A fundamental understanding of how solar irradiance, cell temperature, and electrical load affect I-V curve is essential in designing, installing and evaluating PV system applications. The I-V curve represents an infinite number of current, voltage and power, generated by solar panels at specific cell temperatures (PV Module Current-Voltage Measurements, 2016). Figure 6.1 shows the I-V curve for Sun power SPR-E19-310-COM. It should be noted that each module has a specific I-V curve, and the curve corresponds to specific solar irradiances and cell temperatures. The reference value for solar irradiance is 1000 W/m², and the reference value for cell temperature is 25 C. It should be noted that increasing solar irradiance would increase short-circuit current (I_{sc}) and maximum power (P_{mp}) linearly. However, the voltage rises slightly. Even though increasing cell temperature increases the current slightly, the power and voltage decrease significantly (PV Module Current-Voltage Measurements, 2016).

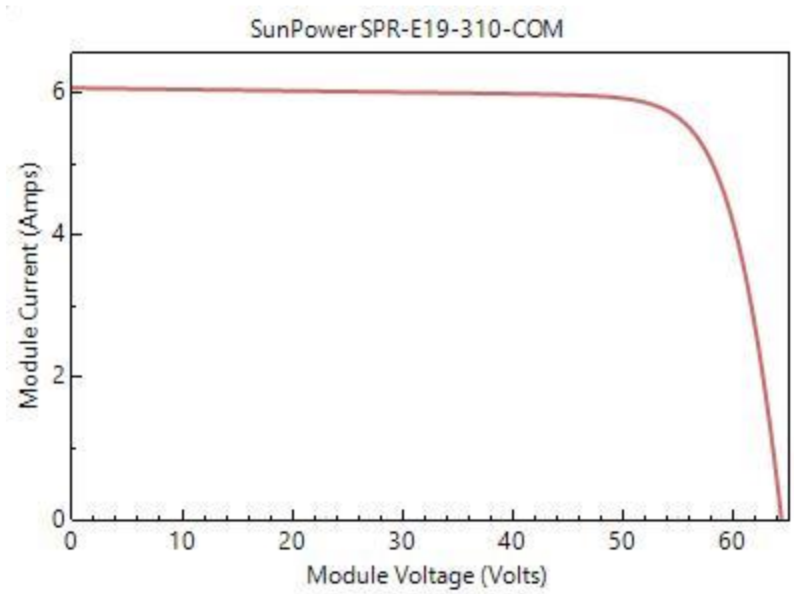

Figure 6.1 I-V curve for SPR-E19-310-COM

SAM is a software to calculate the DC power from the solar module, and a brief of introductions of SAM is given in Appendix C. SAM has the following assumptions:

Assumption 1: All modules in the system operate at their maximum power, and the voltage corresponds to the maximum power, extracted by the losses due to the subarray mismatch and inverter operating voltage limit.

Assumption 2: The maximum power of a subarray is determined by the maximum power of a single module multiplied by the number of modules in the subarray.

Assumption 3: All subarrays in the system have the same number of modules, and therefore operate at the same voltage.

Assumption 4: All modules in each subarray operate uniformly. That means the module mismatch phenomenon is ignored (Gilman et al., 2018).

Assumption 5: The temperatures in all cells in a module are the same.

Further, the following procedure is followed by SAM: Step 1: Calculate the photovoltaic cell temperature. Step 2: Calculate the module's DC power output from its physical characteristics, effective irradiance, and cell temperature (Gilman et al., 2018).

The current and voltage at the maximum power point is calculated by the following equations (Gilman et al., 2018):

$$I_{mp} = I_{mp,ref} \times (C_0 E_e + C_1 E_e^2) \times [1+\alpha_{sc,ref} (T_c - 25)] \tag{6.2}$$

$$V_{mp} = V_{mp,ref} + C_2 s \Delta T_c \ln (E_e) + C_3 s \times [\Delta T_c \ln (E_e)]^2 + \beta_{mp} (T_c - 25) \tag{6.3}$$

The module's DC power output is at its maximum power point (Gilman et al., 2018).:

$$P_{mp} = V_{mp} \times I_{mp} \tag{6.4}$$

where

- $V_{mp,ref}$ = reference Max Power Voltage (V);
- $I_{mp,ref}$ = reference Max Power Current (A);

- $\alpha_{sc,ref}$ = normalized short circuit current temperature coefficient (1/C);
- C_0, C_1 = coefficients relating Imp to G;
- C_2, C_3 = coefficients relating V_{mp} to G (C_3 is in 1/V);
- ΔT_c = Sandia temperature parameter ΔT (C);
- T_c = Cell temperature;
- β_{mp} = maximum power voltage temperature coefficient (V/C);
- V_{mp} = Module voltage (V);
- I_{mp} = Module current (A);
- P_{mp} = Module power (W)
- T_C = Cells temperature.

6.5 Economics of solar panels for Saskatoon's hospitals

In this section, various options of solar panels in terms of sizes were analyzed for RUH, SCH, and SPH for the information of NPV, capital cost, and payback period. The resilience of these options is also discussed with the goal being to look for a cost effective and highly resilient backup power system for the hospitals. Note that battery storage was not considered in this thesis, because battery storage is not suitable to a long period of operation (e.g., 200 hours) in the case here.

6.5.1 Solar panels for SCH

The total space at SCH is approximately 11520 m^2, as per the Google map. It was assumed that the net usable area is around 80% of the entire gross area, so the available space to install solar panels at SCH is approximately 9600 m². The critical load at SCH is 1000 KW/h (see the previous discussion). Table 6.1 shows SAM calculations for various sizes of solar panel, including the total land area, capital cost, net present value, and payback period. Based on the maximum available land at SCH, the highest possible power that can be generated by the solar panel system is about 500 KW/h.

Table 6.1 The cost and space associated with various sizes of solar panel for SCH

PV size (KW)	Total land area (m^2)	Capital cost ($)	Net present value ($)	Payback (year)
100	1618	205855	61544.8	9.43
200	3642	419627	135785	8.93
300	5260	633399	182240	9.54
400	6880	847172	222880	9.98
500	8903	1060940	256836	10.4

Figure 6.2 shows the power generated from various sizes of solar panel added to the power from the central grid in the normal situation at SCH. The blue part in the figure is the power generated from the grid, and the green part in the figure is the power generated by the solar panel (PV 500 kW in particular). The parts which represent the power generated by the solar panel with the power size less than 500 kW are covered by the green part. It is noted that the solar panel size PV 500 was the maximum size of solar panel to SCH. From this figure, it can be found that (1) the maximum power generated from the solar panel (PV 500 kW) is 415 KW at the time of 1 pm in June, (2) the maximum power generated form the grid is 2700 KW at the time of 1 pm in May and

(3) the total power generated from both the grid and from the solar panel is 15442992. This information suggests that the addition of solar power definitely save the cost of the power from the grid, and this cost saving will eventually off-set the initial investment cost for solar panel, which has been shown in Table 6.1 (last column).

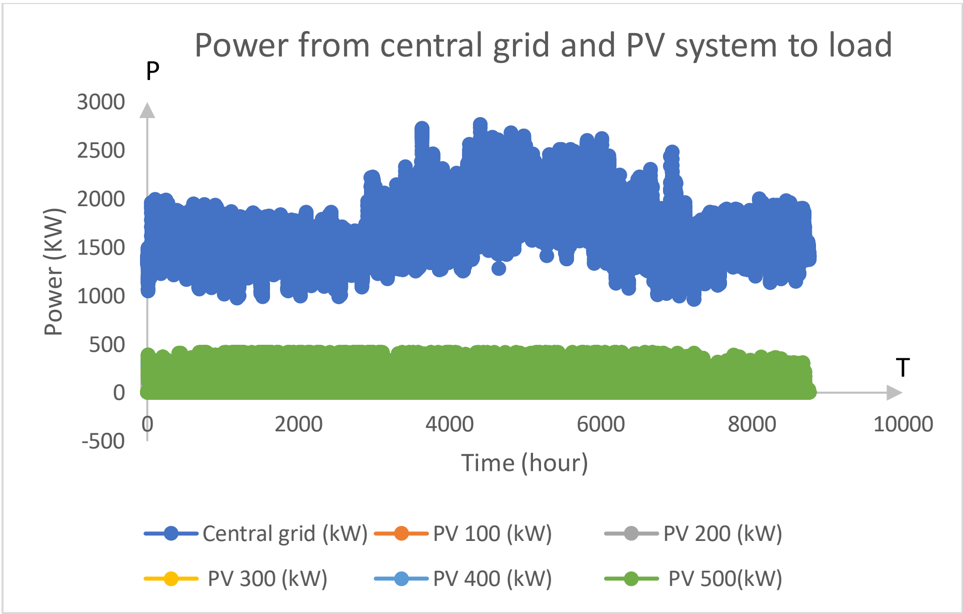

Figure 6.2 Power from various solar panels and the central grid at SCH. The PV 200 – PV 400 are covered by PV 500

6.5.2 Solar panels for RUH

The total space at RUH is approximately 15840 m², as per the Google map. It was assumed that the net usable area is around 80% of the entire gross area, so the available space to install solar panels at RUH is approximately 15840 m². The critical load at RUH is 700 KW/h (see the previous discussion). Table 6.2 shows SAM calculations for various sizes of solar panels, including the total land area, capital cost, net present value, and payback period. Based on the maximum available land at RUH, the highest possible power that can be generated by the solar panel system is about 700 KW.

Table 6.2 Various sizes of solar panels associated with cost and space for RUH.

PV size (KW)	Total land area (m^2)	Capital cost ($)	Net present value ($)	Payback (year)
100	1618	205855	47908.9	10.7
200	3642	419627	113877	9.8
300	5260	633399	147498	10.6
400	6880	847172	170910	11.3
500	8903	1060940	187560	11.9
600	10521	1274720	194565	12.6
700	12140	1488490	204578	13.1

Figure 6.3 shows the power generated from various sizes of solar panel added to the power from the central grid in the normal situation at RUH. The interpretation of Figure 6.3 is the same as that of Figure 6.2. It is noted that PV 700 kW is the maximum size of solar panels to RUH. From this figure, it can be found that (1) the maximum power generated from the solar panel (PV 700 kW) is 610 KW at the time of 1 pm in June, (2) the maximum power generated form the grid is 4500 KW at the time of 3 pm in July, and (3) the total power generated from both the grid and from the solar panel is 26100952. This information suggests that the addition of solar power definitely save

the cost of the power from the grid, and this cost saving will eventually off-set the initial investment cost for solar panel, which has been shown in Table 6.2 (last column).

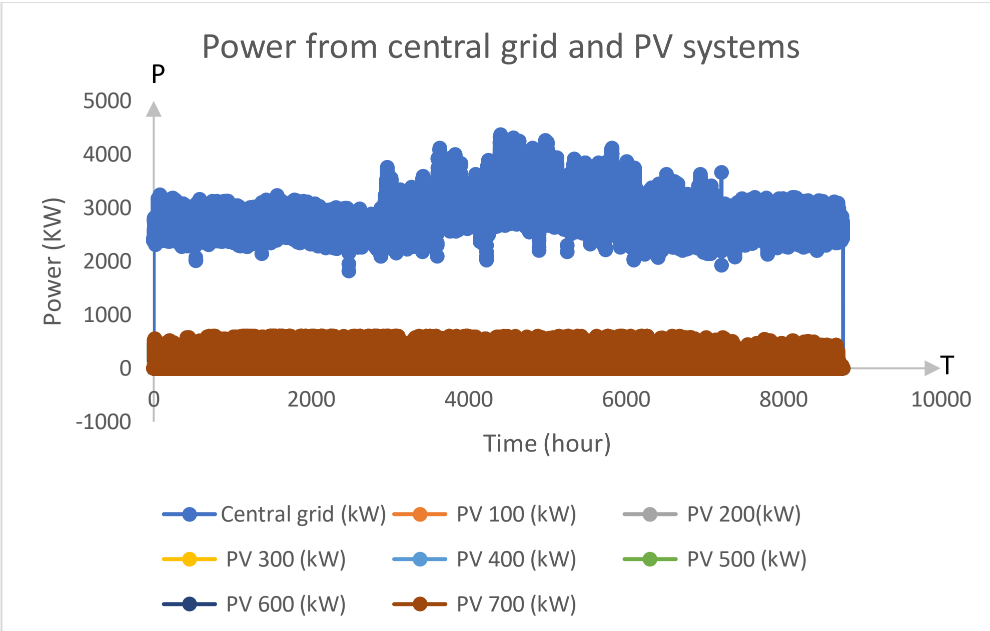

Figure 6.3 Power from central grid and PV systems at RUH. PV 100 – PV 600 are covered by PV 700

6.5.3 Solar panels for SPH

The total space at SPH is approximately 12000 m², as per the Google map. It was assumed that the net usable area is around 80% of the entire gross area, so the available space to install solar panels at SPH is approximately 10000 m². The critical load at SPH is 600 KW/h (see the previous discussion). Table 6.3 shows SAM calculations for various sizes of solar panels, including the total land area, capital cost, net present value, and payback period. Based on the maximum available land at SPH, the highest possible power that can be generated by the solar panels system is about 500 KW.

Table 6.3 Various sizes of solar panels associated with cost and space for SPH.

PV size (KW)	Total land area (m^2)	Capital cost ($)	Net present value ($)	Payback period (year)
100	1618	206570	69562.4	8.8
200	3642	420026	132361	9
300	5260	633482	164954	10
400	6880	846938	194754	10.6
500	8903	1060390	220155	11.1

Figure 6.4 shows the power generated from various sizes of solar panel added to the power from the central grid in the normal situation at SPH. The interpretation of Figure 6.4 is the same as that of Figure 6.2. It is noted that PV 500 kW is the maximum size of solar panels to SPH. From this figure, it can be found that (1) the maximum power generated from the solar panel (PV 500 kW) is 415 KW at the time of 2 pm in June, (2) the maximum power generated form the grid is 2800 KW at the time of 3 pm in July and (3) the total power generated from both the grid and from the solar panel is 15923769. This information suggests that the addition of solar power definitely save the cost of the power from the grid, and this cost saving will eventually off-set the initial investment cost for solar panel, which has been shown in Table 6.3 (last column).

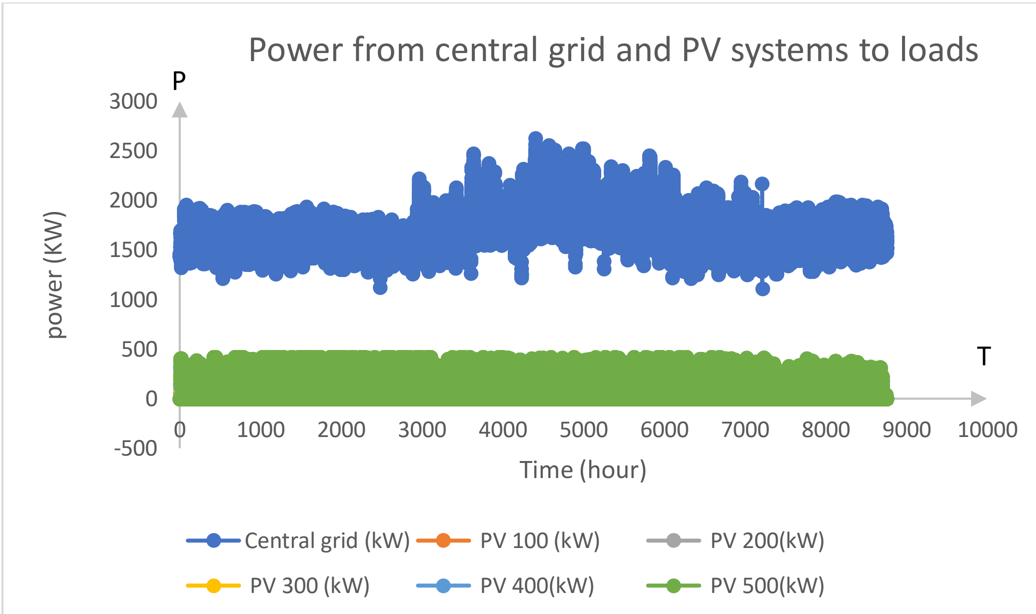

Figure 6.4 Central grid and solar system provide power at SPH. PV 100 – PV 400 are covered by PV 500

6.6 Resilience analysis for the combined backup power (solar plus diesel)

Inclusion of solar power into the whole power system in the hospitals can definitely increase the resilience of the backup power system. It is noted that the solar power system was not considered to totally replace the diesel power, and this is because the solar power system can only run at daytime. In the following, the resilience of the combined backup power system, namely diesel plus solar power, for the three hospitals in Saskatoon will be calculated.

6.6.1 Resilience of the combined backup power (solar plus diesel) in SCH

Consider the combined backup power of diesel (denoted as the backup power 1) and solar power (denoted as the backup power 2) generators and calculate the resilience of this backup power system and consider the size of the solar power varies from 100 KW to 500 KW. The LC and TD remain to be the same as the situation that the solar power is not added, i.e., LC=1000 kW, TD=200 hours. The parameters for the diesel power generator remain the same, which means: PFL1 = 0.75, PFT1 = 0.93, L1 = 1000 KW/h, and T1 = 200 h.

To PFT2 and PFL2, both depends on the availability of the solar source, which has a high uncertainty. Both PFT2 and PFL2 are assumed to be 60% according to Demuth et al. (2009). T2 can be infinitely long, as long as the solar source does not stop. To L2, first of all, it changes hourly, and it is a periodic function with its period being 24 hours. According to SAM, for Saskatoon, the power generated by solar panels with different sizes within one day is shown in Figure 6.5. L2 is calculated by the following steps. Step 1: get the total power per day from Figure 6.5; Step 2: L2 is obtained from the total power per day divided by 24. After that, R can be found by Equation (4.6) for FC, Equation (4.7) for FT and Equation (4.3) for R. Figure 6.6 shows the resilience of the combined backup power system with different sizes of solar panels. From this figure, it can be found that (1) the resilience of the combined backup power system increases, (2) when the backup power operates at two distinct phases with a different resilience (Phase I: the diesel power runs until its limit arrives at Point W on the FT axis in Figure 6.6; Phase II: from Point W to '1' on the FT axis in Figure 6.6), and (3) the solar power alone as the backup power is not a viable system from the point of view of resilience, as the power generated by solar panel is far less than CL (see Figure 6.6 from W to '1' on the FT axis).

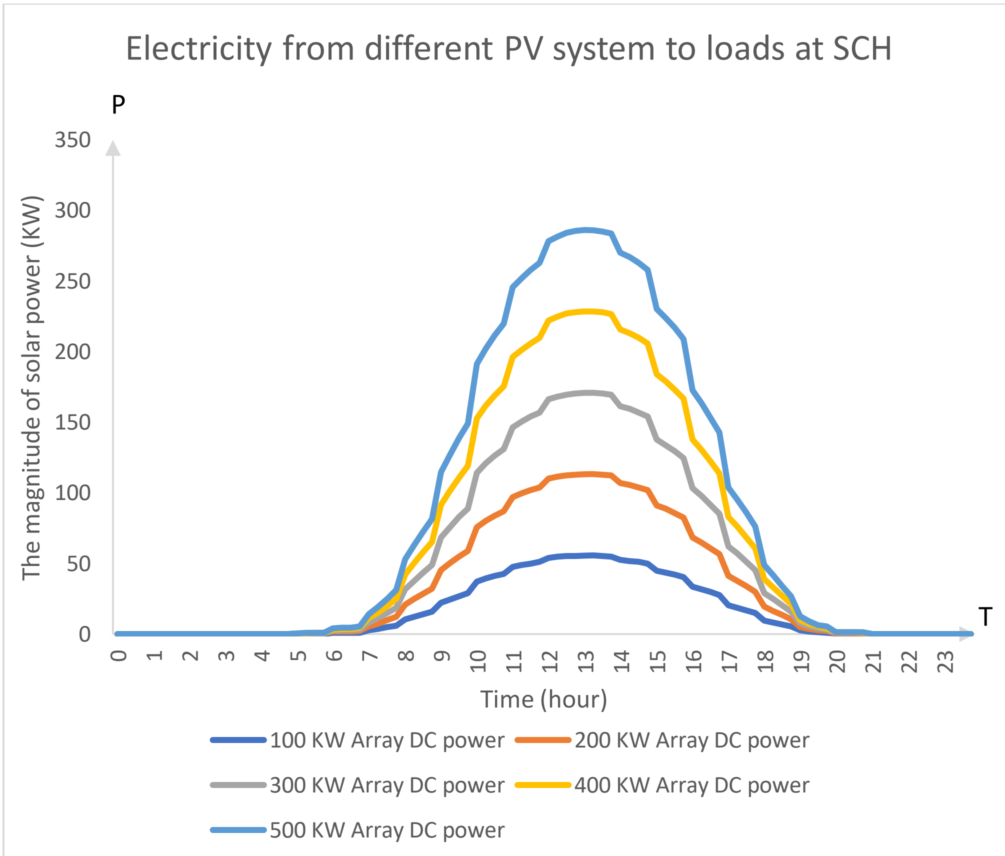

Figure 6.5 The average electricity per day over a year generated by solar panels at SCH

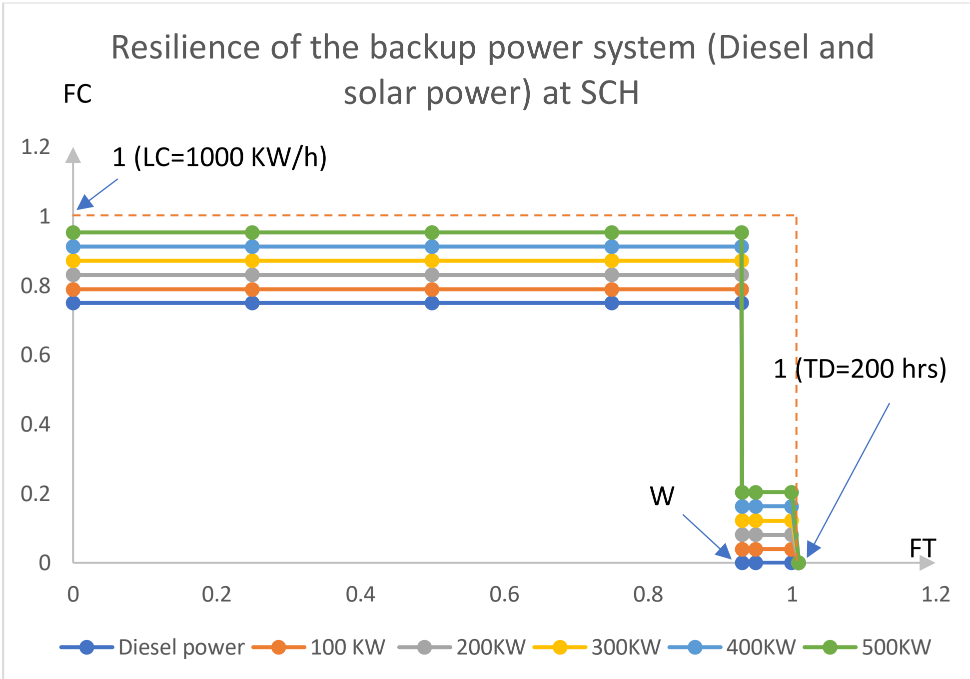

Figure 6.6 Resilience by the diesel power and various sizes of solar panels at SCH

6.6.2 Resilience Calculated for RUH

Consider a combined backup power of diesel (denoted as the backup power 1) and solar power (denoted as the backup power 2) generators and calculate the resilience of this backup power system and consider the size of the solar power varies from 100 KW to 700 KW. The LC and TD remain to be the same as the situation that the solar power is not added, i.e., LC=700 kW, TD=200 hours. The parameters for the diesel power generator remain the same, which means: PFL1 = 0.75, PFT1 = 0.94, L1 = 700 KW/h, and T1 = 200.

To PFT2 and PFL2, both depends on the availability of the solar source, which has a high uncertainty. Both PFT2 and PFL2 are assumed to be 60% according to Demuth et al. (2009). T2 can be infinitely long, as long as the solar source does not stop. To L2, first of all, it changes hourly, and it is a periodic function with its period being 24 hours. According to SAM, for Saskatoon, the power generated by solar panels with different sizes within one day is shown in Figure 6.7. L2 is calculated by the following steps. Step 1: get the total power per day from Figure 6.7; Step 2: L2 is obtained from the total power per day divided by 24. After that, R can be found by Equation (4.6) for FC, Equation (4.7) for FT and Equation (4.3) for R. Figure 6.8 shows the resilience of the combined backup power system with different sizes of solar panels. From this figure, it can be found that (1) the resilience of the combined backup power system increases, (2) when the backup power operates at two distinct phases with a different resilience (Phase I: the diesel power runs until its limit arrives at Point W on the FT axis in Figure 6.8; Phase II: from Point W to '1' on the FT axis in Figure 6.8), and (3) the solar power alone as the backup power is not a viable system from the point of view of resilience, as the power generated by solar panel is far less than CL (see Figure 6.6 from W to '1' on the FT axis).

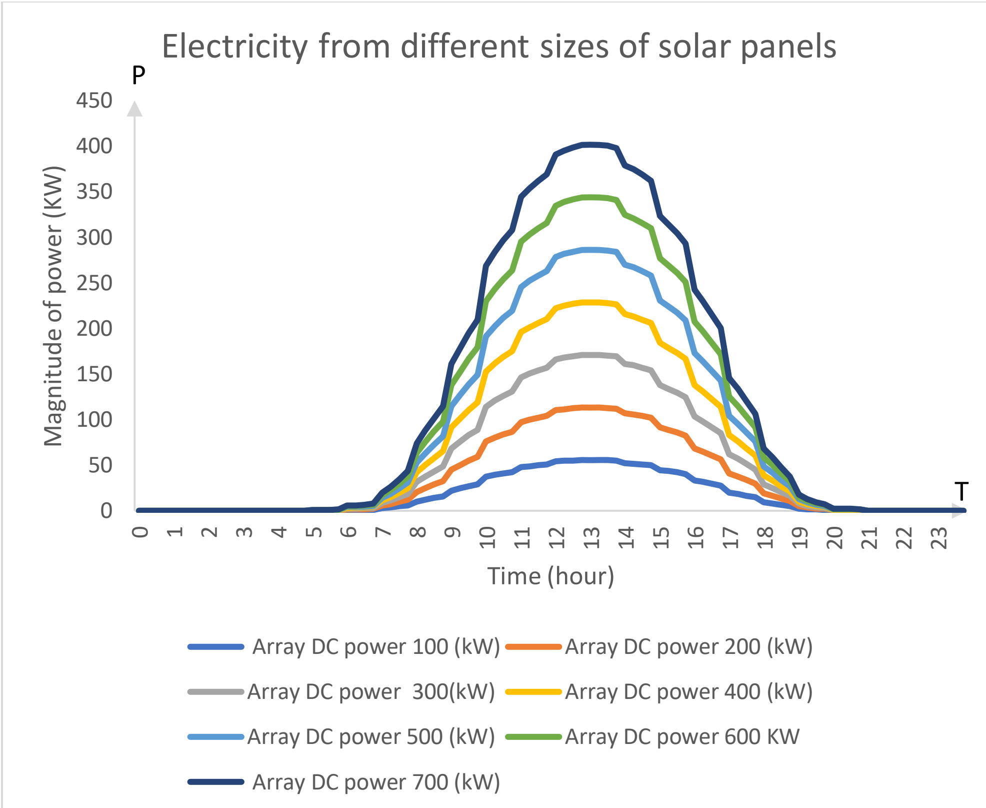

Figure 6.7 The average electricity per day over a year generated by solar panels at RUH

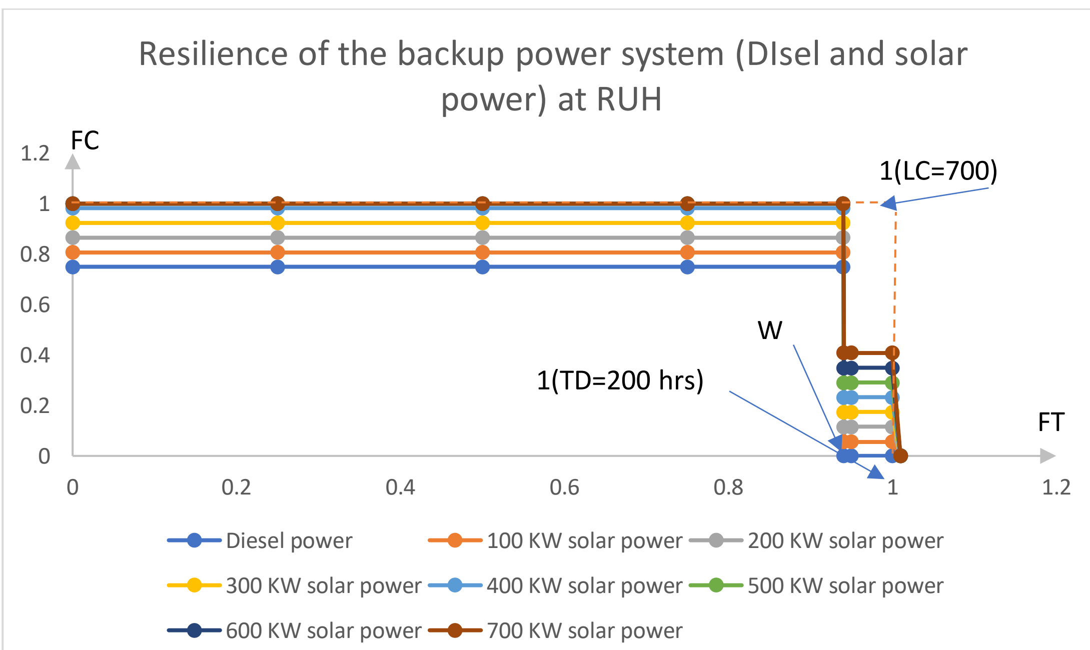

Figure 6.8 Resilience by various sizes of solar panels at RUH

6.6.3 Resilience calculated for SPH

Consider a combined backup power of diesel (denoted as the backup power 1) and solar power (denoted as the backup power 2) generators and calculate the resilience of this backup power system and consider the size of the solar power varies from 100 KW to 500 KW. The LC and TD remain to be the same as the situation that the solar power is not added, i.e., LC=600 kW, TD=200 hours. The parameters for the diesel power generator remain the same, which means: PFL1 = 0.75, PFT1 = 0.925, L1 = 600 KW/h, and T1 = 200.

To PFT2 and PFL2, both depends on the availability of the solar source, which has a high uncertainty. Both PFT2 and PFL2 are assumed to be 60% according to Demuth et al. (2009). T2 can be infinitely long, as long as the solar source does not stop. To L2, first of all, it changes hourly, and it is a periodic function with its period being 24 hours. According to SAM, for Saskatoon, the power generated by solar panels with different sizes within one day is shown in Figure 6.9. L2 is calculated by the following steps. Step 1: get the total power per day from Figure 6.9; Step 2: L2 is obtained from the total power per day divided by 24. After that, R can be found by Equation (4.6) for FC, Equation (4.7) for FT and Equation (4.3) for R. Figure 6.10 shows the resilience of the combined backup power system with different sizes of solar panels. From this figure, it can be found that (1) the resilience of the combined backup power system increases, (2) when the backup power operates at two distinct phases with a different resilience (Phase I: the diesel power runs until its limit arrives at Point W on the FT axis in Figure 6.10; Phase II: from Point W to ‘1’ on the FT axis in Figure 6.10), and (3) the solar power alone as the backup power is not a viable system from the point of view of resilience, as the power generated by solar panel is far less than CL (see Figure 6.10 from W to '1' on the FT axis).

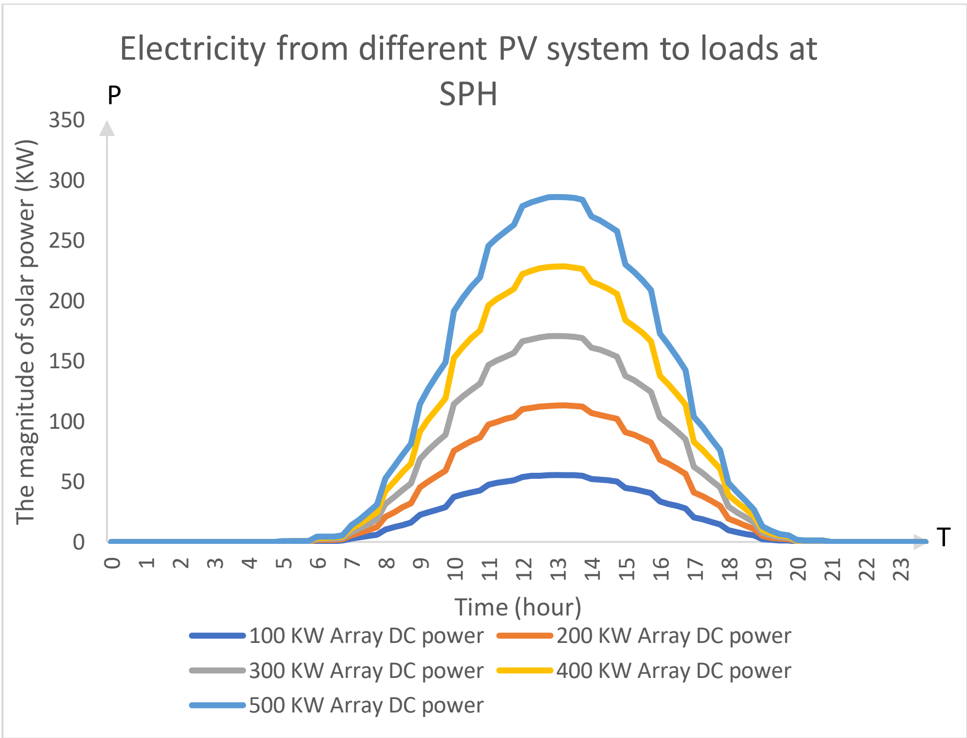

Figure 6.9 The average electricity per day over a year generated by solar panels at SPH

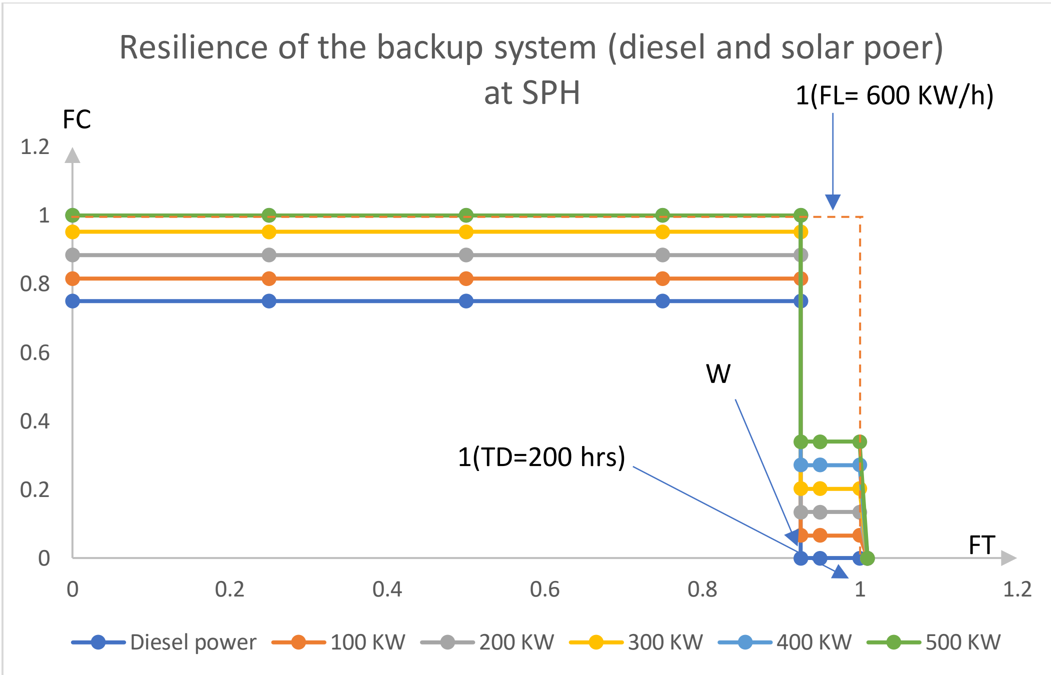

Figure 6.10 Resilience by various sizes of solar panels at SPH with refilling fuel tank

6.7 Resilience of the solar panel with battery storage as the backup power

Battery Capacity is the maximum amount of power that a solar battery can store, measured in kilowatt-hours (kWh). In the context of solar battery, a power rating is the amount of electricity that a battery can deliver at a time, and it is measured in kilowatts (kW). Figure 6.11 shows 500 KW solar panels with 500 (kW) battery capacity. It can be seen from Figure 6.10 that solar power with battery storage is not a viable backup system, as the power provided by solar panels and battery storage is far less than the size of critical loads (1000KWh) at SCH. Besides, the capital cost of the system with battery storage will increase from $1060940 to $1215938, and the payback time will increase from 10.8 years to 17.8 years.

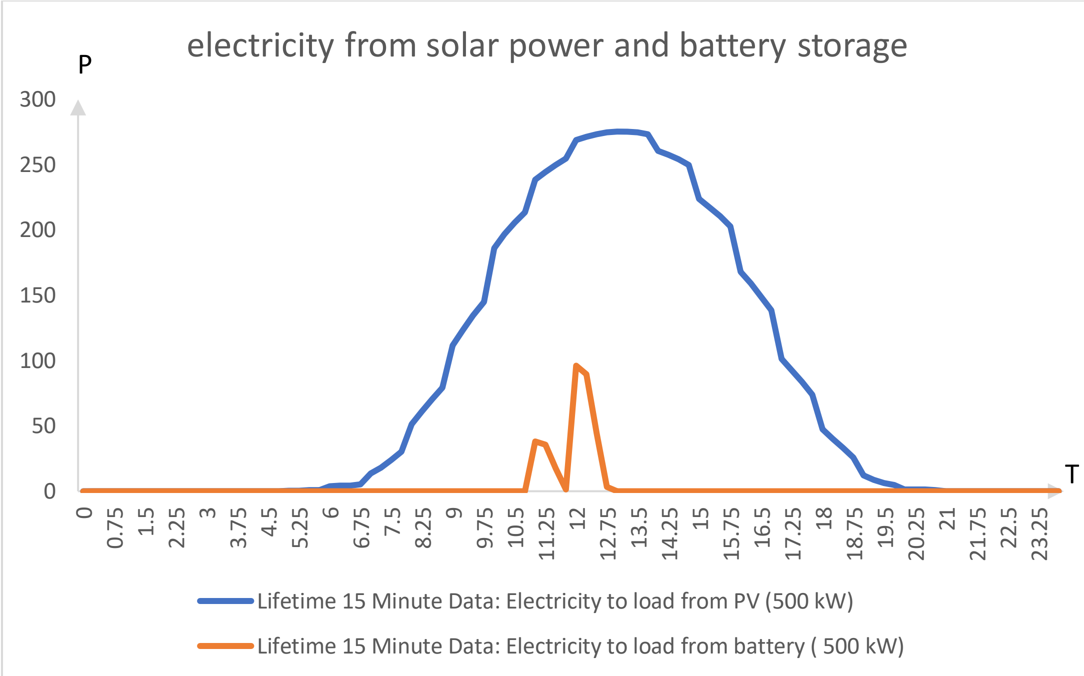

Figure 6.11 Power generated by 500 KW solar panel and 500 KW battery storage

6.8 Conclusion

This chapter studied the combined diesel power and solar power generators in terms of the resilience and economics. Both the normal situation and the situation of the prime power outage were studied. The software SAM was used to analyze the power generated and the economic attributes such as NPV and the payback time. It can be concluded from the results obtained that (1) addition of the solar power can reduce the use of the prime power by 6% for RUH, 7% for SCH, and 7% for SPH. in the normal situation, (2) addition of the solar power can increase the resilience by 20% for SCH, 35% for RUH, and 25% for SPH in comparison with the diesel power as the backup power alone, and (3) the solar power alone as the backup power is not a viable solution, because the power generated is far less than the CL of the hospitals in Saskatoon and besides, it varies hourly in a day and varies monthly by monthly.

CHAPTER 7

CONCLUSION AND FUTURE WORK

7.1 Overview

This thesis studied how to enhance the resilience of the power system in hospitals and reduce electricity bills by installing a solar system with consideration of its cost. The particular application taken throughout the thesis was Saskatoon's hospitals (RUH, SCH, and SPH). The thesis had three specific objectives, which are revisited herein:

- ***Objective 1****: to do a systematic literature analysis in order to reach a unified definition of the resilience of a dynamic system.*
- ***Objective 2****: to develop a quantitative measure for the resilience of a power system which has a backup power such as diesel power and solar power.*
- ***Objective 3****: to design a solar power system in the combined backup power system, which contains a diesel power and a solar power generator, to improve the reliability of the backup power system with consideration of the cost (the capital cost, payback time) for the hospitals in Saskatoon (as an example).*

These objectives were achieved by the research in this thesis. A literature review was conducted first to seek the unified definition of resilience of a dynamic system such as power system and the methodology for measuring its resilience (in Chapter 2). In order that no any important literature is missed, a systematic methodology for literature review was taken. This review helped to propose a new methodology for measuring the resilience of a power system. In Chapter 3, solar panels were discussed and analyzed, which provided a background for the idea to add a solar power system to the existing electric power system with diesel power as a backup. In Chapter 4, a new measure for the resilience of power systems was proposed, which meets the criterion of independence of the scale of the power system. Then, the analysis of the resilience of the current power system of the hospitals in Saskatoon by employing the proposed measure was presented in Chapter 5, which showed that the resilience of the power system of the hospitals in Saskatoon is about 0.7 and it needs to be improved. In Chapter 6, the proposed measure was applied to designing a solar power system in the combined backup power system that includes solar panels and diesel generators. Various sizes of solar panels for RUH, SCH, and SPH were analyzed as well in terms of NPV, capital cost, payback period, and total land area with the help of the software called SAM.

7.2 Conclusions

The problem of resilience of the power system in thesis is in essence the problem of the reliability of the backup power system. Power outage refers to the disruption of the prime power. When this event occurs, the backup power system is put in use to maintain the continuity of the power supply. The major conclusions can be drawn as follows:

(1) Understanding of the resilience to a dynamic system such as power system still needs to be improved. Resilience differs from robustness, reliability, sustainability, fault tolerance, and repairing. The new definition put in this thesis can unify all the definitions in literature.

(2) The proposed resilience measure is dimensionless and in the value range of [0, 1], and it has a clear physical meaning for the two extreme situations, R=0, R=1.

(3) The added-on solar system (to the diesel backup power system) without battery storage can improve the resilience of the backup power system significantly (by 25% in the case of the power system of the hospitals in Saskatoon).

(4) The added-on solar system (to the diesel backup power system) without battery storage can also reduce the consumption of the prime power (assuming the fossil fuel power generator) significantly (by 7% in the case of the power system of the hospitals in Saskatoon).

(5) The payback time for the added-on solar system (to the diesel backup power system) is reasonable (11 to 13 years in the case of the power system of the hospitals in Saskatoon).

7.3 Major contributions

The main contribution of this research lies in the area of resilience engineering, specifically how to measure the resilience of the power supply system to a particular application, e.g., power supply system to hospitals. In the current literature, the closed one to the proposed measure in this thesis is the work of (Panteli et al., 2016). In their work, the resilience of a power system was considered for three regimes: disaster event period, post-disaster event period, and restoration period. In the different regimes, different resilience metrics were defined. These metrics were further based on the so-called fragility probability function, which estimates the failure probability of a system under a particular disaster event (e.g., bad weather). The measure for resilience was further expressed by the area of the metrics × time period. They also proposed the concept called operational resilience and infrastructure resilience with former defined as the local operation (e.g., reconnection of the transmission line) and the latter defined as the repair of the infrastructure. There are a couple of differences of the proposed measure in this thesis from their measure. First, the repair of infrastructure is not considered in this thesis according to the definition of resilience proposed in this thesis, which puts emphasis on the restoration with the system's own resource, energy and/or knowledge. Second, due to this first difference, in this thesis, the context where the resilience is considered is that the system has a backup power along with a prime power. The disaster event (regardless of the cause) is the disruption of the prime power. Then the resilience refers to the performance of the backup power in terms of the amount of power that can be generated by the backup power and the length of time that the backup power can run. In essence, the resilience of the total power system in the case of this thesis is the reliability of the operation of the backup power. The reliability includes both the equipment for power generation and the resource used in power generation. A care is taken of that here the concept of considering the equipment and resource is different from the concept of distinguishing the operational resilience and infrastructure resilience in (Panteli et al., 2016). The two aspects of the resilience, equipment and resource, is rooted to the I-S framework of service systems, that is, a service system is viewed to have two layers: infrastructure (equipment), I, and substance (resource), S, so the I-S framework (Zhang and Luttervelt, 2011; Zhang and Wang, 2016). Third, the area concept is also used in the measure proposed in this thesis, namely one being supply time and the other being supply amount, but the FC and FT functions proposed in this thesis are more general than the supply time and supply amount, and in fact, FC is a function of the supply amount and FT is a function of the supply time, and further they are with respect to the demand which has two aspects: amount and time. Nevertheless, in this thesis, the FC and FT are considered as independent of each other for simplicity. The future work should consider that they are dependent on each other.

7.4 Limitation and future work

7.4.1 Limitations

The first limitation of the thesis is the assumption that FC and FT are independent of each other. In reality, this may not be true, that is, the length of operational time may be dependent on the magnitude of the power generated, especially in the case of the diesel power. Therefore, the resilience of the backup power system should be the area covered by the FC-FT curve.

The second limitation of the thesis is that in the analysis of the resilience of a solar power system, the average solar power over a year is considered, which is far accurate with respect to the real situation where the solar power performance depends on months in a year.

7.4.2 Future work

To address the first limitation, a future work is directed to study the dependency of FC and FT in the resilience analysis and to develop a resilience measure which is based on the area of the FC-FT curve and changes with respect to time during the recovery period (i.e., TD period).

To address the second limitation, a future work is directed to take into account of the fact that the solar power generation performance changes with respect to time (monthly and weekly). This work can be performed with the first future work, i.e., to consider the resilience to change with respect to time.

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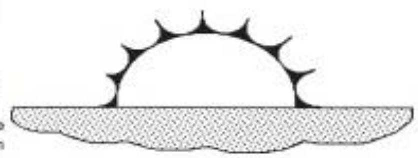
APPENDIX A: THE AVERAGE SOLAR SUNSHINE PER DAY IN CANADA

The Figure A.1 shows the average solar sunshine per day in Canada’s cities ("Sun Insulation hours per day in Canadian Cities," 2017).

SUN INSOLATION HOURS PER DAY IN CANADIAN CITIES



Find your city or one nearby and use the appropriate figure in the average sun hours per day line of the array size worksheet on page 9.

Province, City	High	Low	Average
British Columbia			
Cranbrook	7.4	3.3	5.4
Dease Lake	6.2	2.4	4.3
Fort St John	7.4	3.2	5.3
Kamloops	7.5	2.9	5.2
Pentiction	7.3	2.7	5.0
Port Hardy	6.0	1.7	3.9
Prince George	7.3	2.6	5.0
Prince Rupert	5.8	1.5	3.7
Sandspit	6.5	2.0	4.3
Smithers	6.4	2.1	4.3
Vancouver	7.4	2.3	4.9
Victoria	7.9	3.0	5.5
Alberta			
Calgary	7.8	3.1	5.5
Edmonton	7.6	3.1	5.5
Fort McMurray	7.1	3.3	5.2
Grande Prairie	7.5	3.2	5.4
High Level	6.9	3.1	5.0
Medicine Hat	8.0	3.5	5.8
Saskatchewan			
Cree Lake	7.2	3.2	5.2
Estevan	8.3	3.6	6.0
Regina	8.1	3.1	5.6
Saskatoon	8.1	3.5	5.8
Swift Current	7.8	3.2	5.5
Manitoba			
Churchill	7.2	2.4	4.8
Dauphin	8.3	3.2	5.8
The Pas	7.8	3.0	5.4
Thompson	7.3	3.2	5.3
Winnipeg	7.9	3.3	5.6
Ontario			
Armstrong	7.3	2.2	4.8
London	7.1	2.5	4.8
Moosonee	7.2	2.4	4.8
Ottawa	7.2	2.7	5.0
Red Lake	7.0	3.1	5.0
Sault St. Marie	7.1	2.5	4.8
Thunder Bay	7.2	2.0	4.6
Toronto	7.6	2.5	5.1
Vineland	7.2	2.8	5.0
Wiarton	7.1	3.0	5.0
Windsor	7.3	2.6	5.0

Province, City	High	Low	Average
Quebec			
Chibougamau	6.8	2.8	4.8
Gaspe	6.6	2.9	4.8
Inukjuak	6.3	1.5	3.9
Kuujjuaq	5.7	2.1	3.9
Kuujjuarapik	5.9	2.3	4.1
Montreal	7.3	2.8	5.1
Natashquan	6.7	2.5	4.6
Nitchequon	6.5	2.3	4.4
Quebec City	7.0	2.3	4.7
Roberval	6.8	2.9	4.9
Sept-Iles	6.8	2.6	4.7
Val-d´Or	7.2	2.9	5.1
Schefferville	6.4	2.1	4.3
New Brunswick			
Charlottetown	7.1	2.6	4.9
Fredricton	7.2	2.1	4.7
Moncton	7.2	2.4	4.8
St. John	7.1	2.4	4.8
Nova Scotia			
Halifax	7.2	2.7	5.0
Sable Island	6.0	1.6	3.8
Sydney	6.8	2.3	4.6
Yarmouth	6.9	2.2	4.6
P.E.I.			
Charlottetown	6.9	2.1	4.5
Newfoundland			
Daniel´s Harbour	5.9	2.1	4.0
Gander	6.3	1.8	4.1
Stephenville	5.9	2.0	4.0
St. John´s	6.2	1.7	4.0
Yukon			
Haines Junction	6.9	1.0	3.9
Watson Lake	6.4	3.0	4.7
Whitehorse	6.5	3.0	4.8
NWT			
Fort Simpson	6.9	2.6	4.8
Fort Smith	7.0	2.9	5.0
Yellowknife	7.2	1.7	4.5

7

Figure A.1 the average solar sunshine per day in Canada’s cities ("Sun Insulation hours per day in Canadian Cities," 2017).

APPENDIX B: FUEL SUPPLY FOR DIESEL GENERATORS

Table B.1 shows the fuel supply for diesel generators with different generators' power ("Approximate Diesel Generator Fuel Consumption Chart,").

Generator Size (kW)	1/4 Load (gal/hr)	1/2 Load (gal/hr)	3/4 Load (gal/hr)	Full Load (gal/hr)
20	0.6	0.9	1.3	1.6
30	1.3	1.8	2.4	2.9
40	1.6	2.3	3.2	4.0
60	1.8	2.9	3.8	4.8
75	2.4	3.4	4.6	6.1
100	2.6	4.1	5.8	7.4
125	3.1	5.0	7.1	9.1
135	3.3	5.4	7.6	9.8
150	3.6	5.9	8.4	10.9
175	4.1	6.8	9.7	12.7
200	4.7	7.7	11.0	14.4
230	5.3	8.8	12.5	16.6
250	5.7	9.5	13.6	18.0
300	6.8	11.3	16.1	21.5
350	7.9	13.1	18.7	25.1
400	8.9	14.9	21.3	28.6
500	11.0	18.5	26.4	35.7
600	13.2	22.0	31.5	42.8
750	16.3	27.4	39.3	53.4
1000	21.6	36.4	52.1	71.1
1250	26.9	45.3	65.0	88.8
1500	32.2	54.3	77.8	106.5
1750	37.5	63.2	90.7	124.2
2000	42.8	72.2	103.5	141.9
2250	48.1	81.1	116.4	159.6

APPENDIX C: SAM METHODS TO CALCULATE SOLAR POWER

Simple Efficiency Module Model is a simple description of module performance that measures the module's DC output at the maximum power point from the module area, a table of conversion efficiency values over a range of irradiance values, and temperature correction parameters (Gilman et al., 2018). The simple efficiency model is the least accurate of the three models for predicting the performance of specific modules (Gilman et al., 2018).

California Energy Commission (CEC) Performance Model with Module Database is an performance of the six-parameter, single-diode equivalent circuit model used in the CEC New Solar Homes Partnership Calculator ("Incentive Eligible Photovoltaic Modules in Compliance with SB1 Guidelines," 2014) and is an extension of the five-parameter model. The model measures the photovoltaic module DC output using equations with parameters stored in SAM's CEC module library (Gilman et al., 2018)

CEC Performance Model with User Entered Specifications is the same implementation as the CEC performance Model with Module Database, but with a coefficient calculator (Dobos, 2012). To calculate the model parameters from the standard module specifications provided on manufacturer data sheets. It would be possible to implement the six-parameter model for modules not included in the CEC module library (Gilman et al., 2018).

Sandia PV Array Performance Model with Module Database is an implementation of the Sandia National Laboratories photovoltaic module and array performance model (Kratochvil, Boyson, & King, 2004). This empirical model measures module voltage and power at five points on the module's I-V curve using data measured from modules and arrays in realistic outdoor operating conditions (Gilman et al., 2018). Table C.1 shows module model variable definition for all modules.

Table C.1 Module Model Variable Definitions (Gilman et al., 2018).

Symbol Description	Name in SAM
G_b	effective beam irradiance (W/m^2)
G_d	effective sky diffuse irradiance (W/m^2)
G_r	effective ground-reflected diffuse irradiance (W/m^2)
AOI	incidence angle (deg)
Z	sun zenith angle (deg)
T_{dry}	ambient dry bulb temperature (_C)
T_{dew}	dew-point temperature (_C)
P_{atm}	atmospheric pressure (mbar)
v_w	wind speed (m/s)

h	elevation above sea level (m)
hr	hour of day local time (h)
β_s	subarray tilt angle (deg)
γ_s	subarray azimuth angle (deg)
P_{mp}	module power (W)
V_{mp}	module voltage (V)
I_{mp}	module current (A)
V_{oc}	operating open circuit voltage (V)
I_{sc}	operating closed circuit current (A)
λ_m	module efficiency (%)
T_c	cell temperature (_C)

APPENDIX D: RUNNING SAM SOFTWARE FOR A SOLAR SYSTEM

Create a project

When you open SAM, it displays the welcome page to create or to open a file. To create a new file, start a new project. Now you have to choose your model. In our case, we select photovoltaic (detailed), commercial (distributed). Figure D.1 shows step by step of this trend.

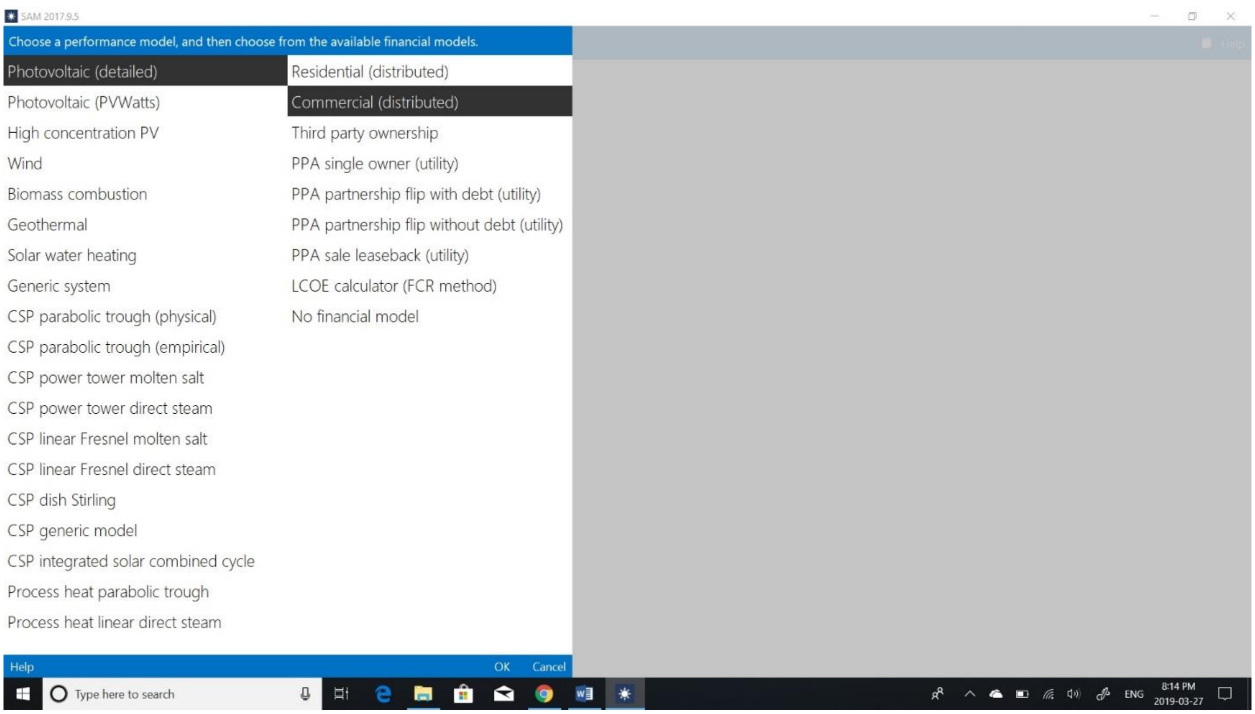


Figure D.1 Creating a new project in SAM

Location and resource

The location and resource page provide access to the solar resource library, which is the collection of weather data from different locations. In this page, you could select the location of your site by typing its name. Figure D.2 shows the location and resource page.

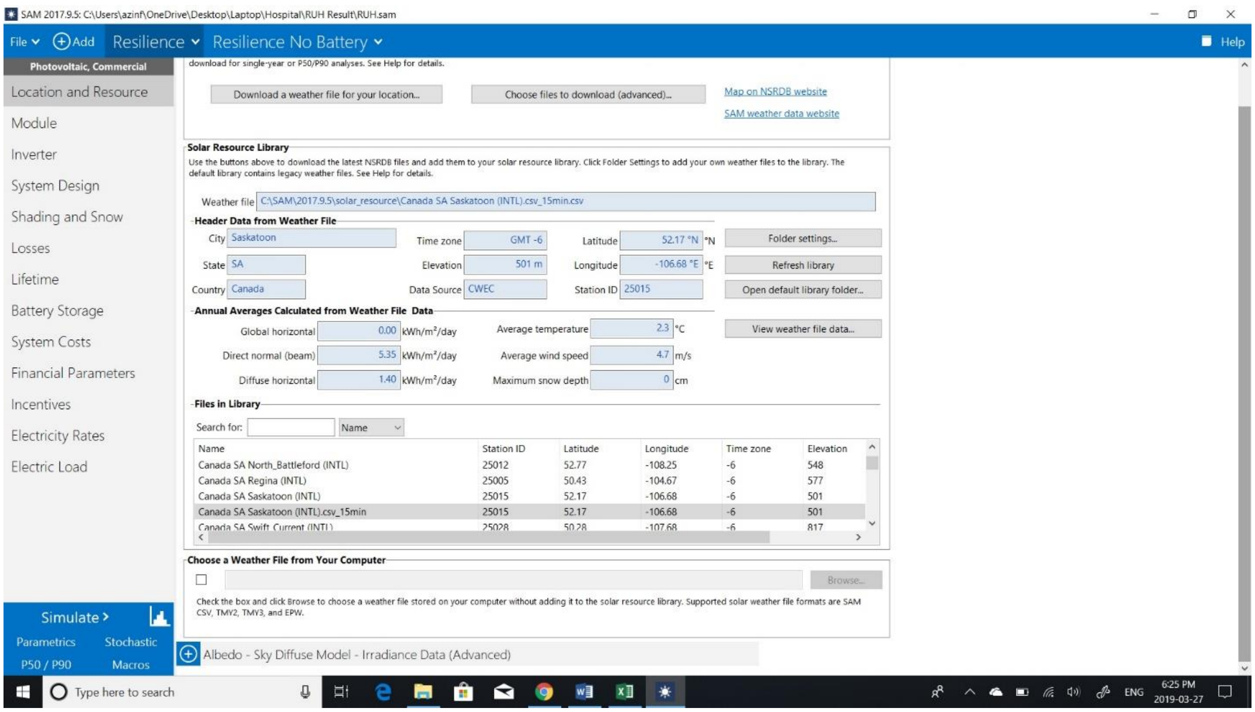


Figure D.2 the location and resource page in SAM

Module

In the module page, you could select a specific module for solar panels. Each module has its own specific information. You can see all the information on this page. Figure D.3 shows the module page.

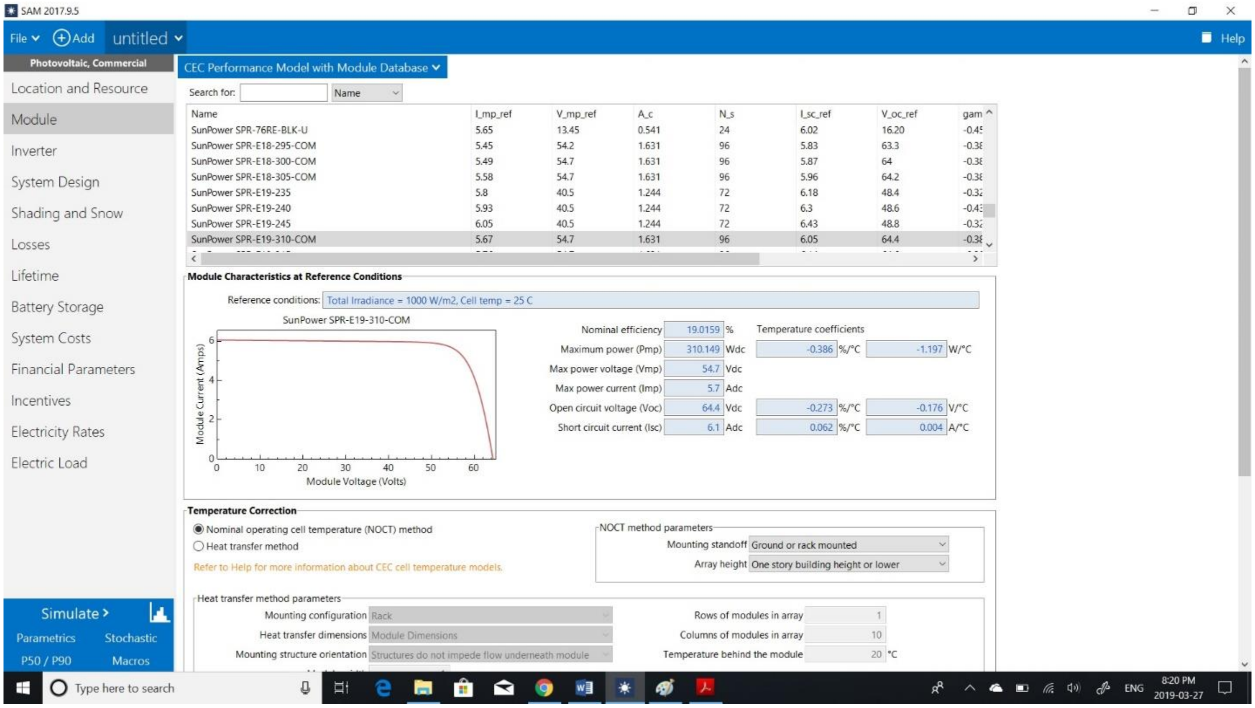


Figure D.3 The module page in SAM

System design

In system design page, you could select your desire array size. When you select your desire panels size, SAM automatically calculates the total requirement land area on this page. Figure D.4 shows the system design page in SAM.

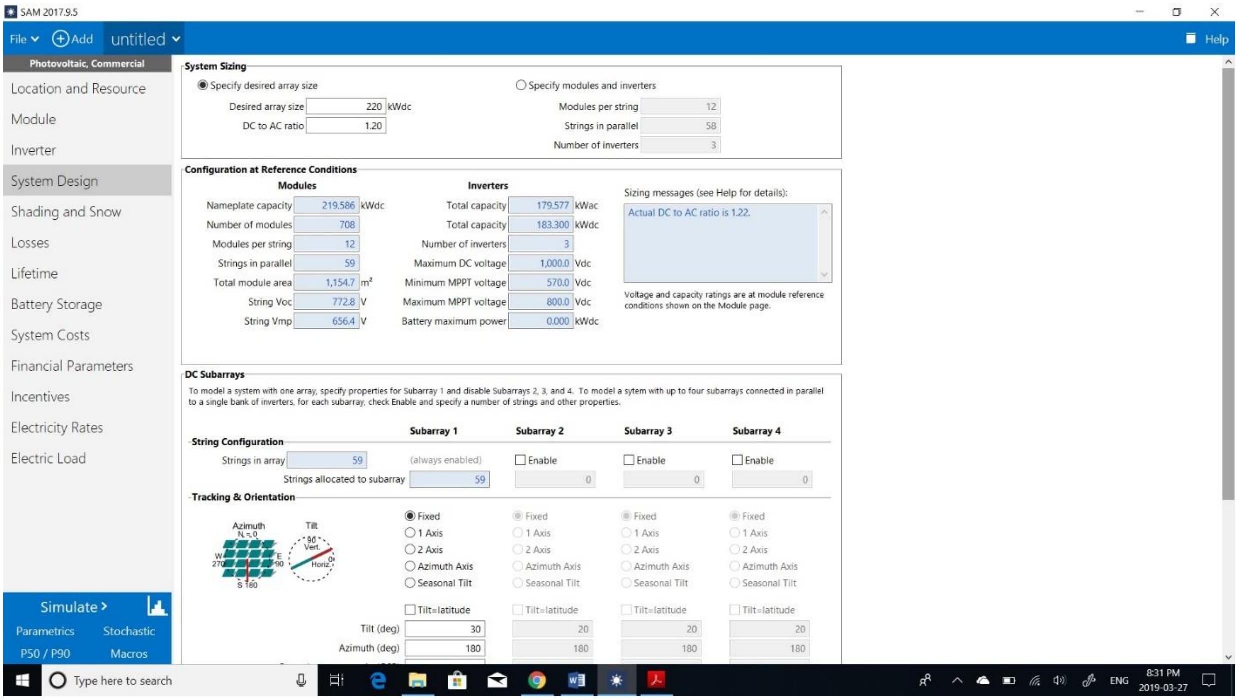


Figure D.4 The system design page in SAM

Battery storage

The battery storage model allows you to analyze the performance of the following type of battery

- Lead-acid battery
- Lithium-ion battery

You can model the system with a battery connected to either the DC or the AC side of photovoltaic system. To model a photovoltaic system with a battery storage on the battery storage page, choose enable battery, then select the desire size of battery storage and select the battery type. Figure D.5 shows the battery page in SAM.

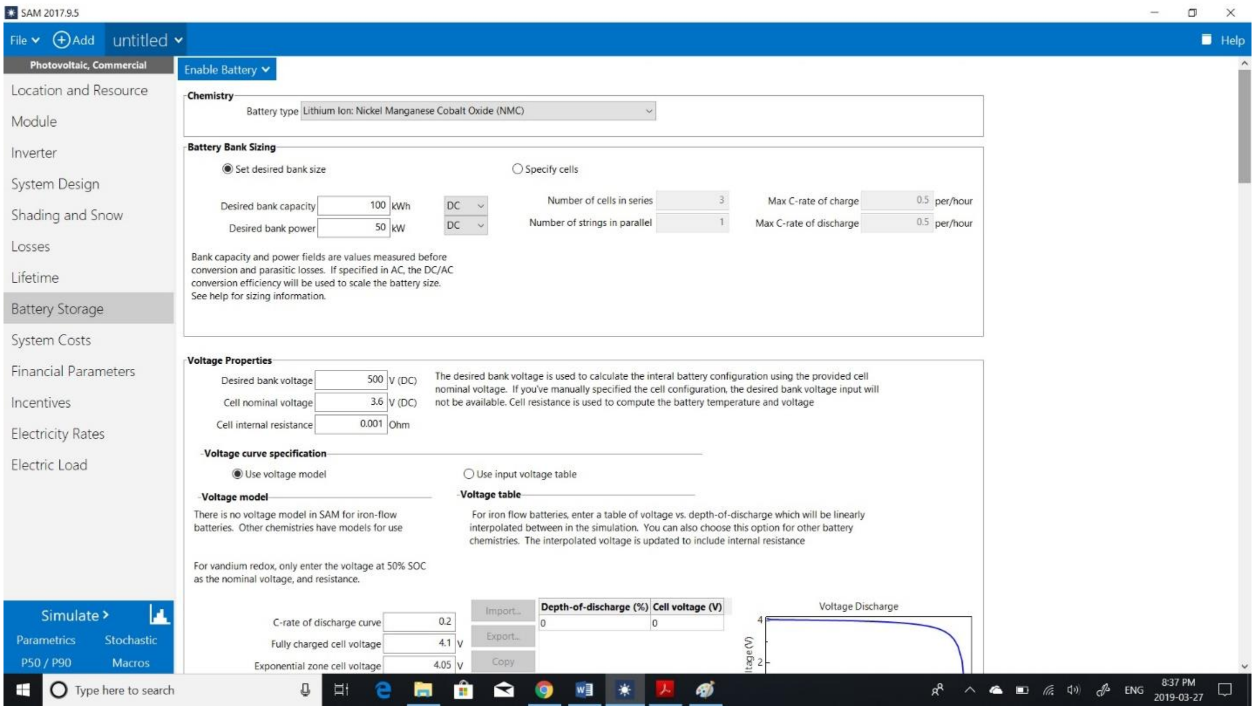


Figure D.5 the battery storage page in SAM

Electricity Rates

In electricity rates page, you could download the electricity rate of an electric utility company. This utility rate can apply for the system. For example, you can download the electricity rate of SaskPower for RUH and apply this rate for RUH analysis. Figure D.6 shows the electricity rate page in SAM.

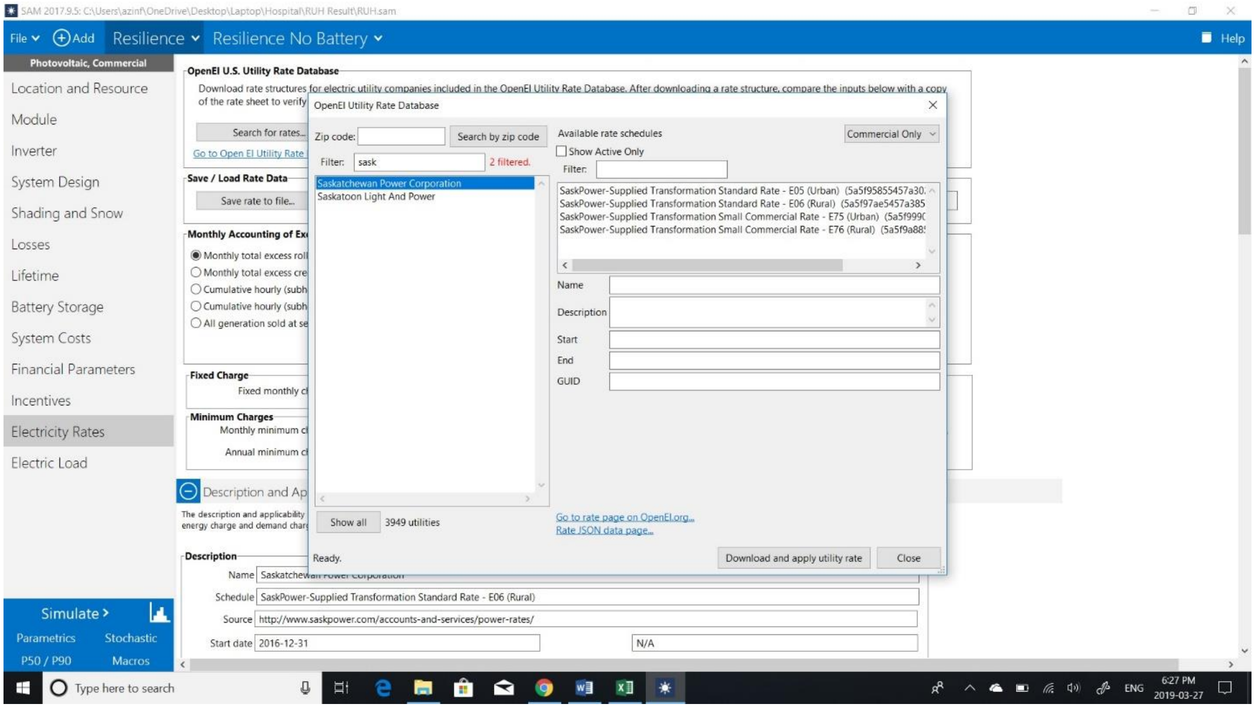


Figure D.6 electricity rate page in SAM

Electric load

You could upload your electric load data in electric load page. Firstly, select edit data and then select import data and upload your loads file. It is noted that the electric load data should be either for an hour interval or 15 minutes interval electric loads data. Figure D.7 shows the electric load page in SAM. SAM can analyze only these two interval conditions. Secondly, you could modify your electric load data by click on Normalize supplies load profile monthly utility bill data.

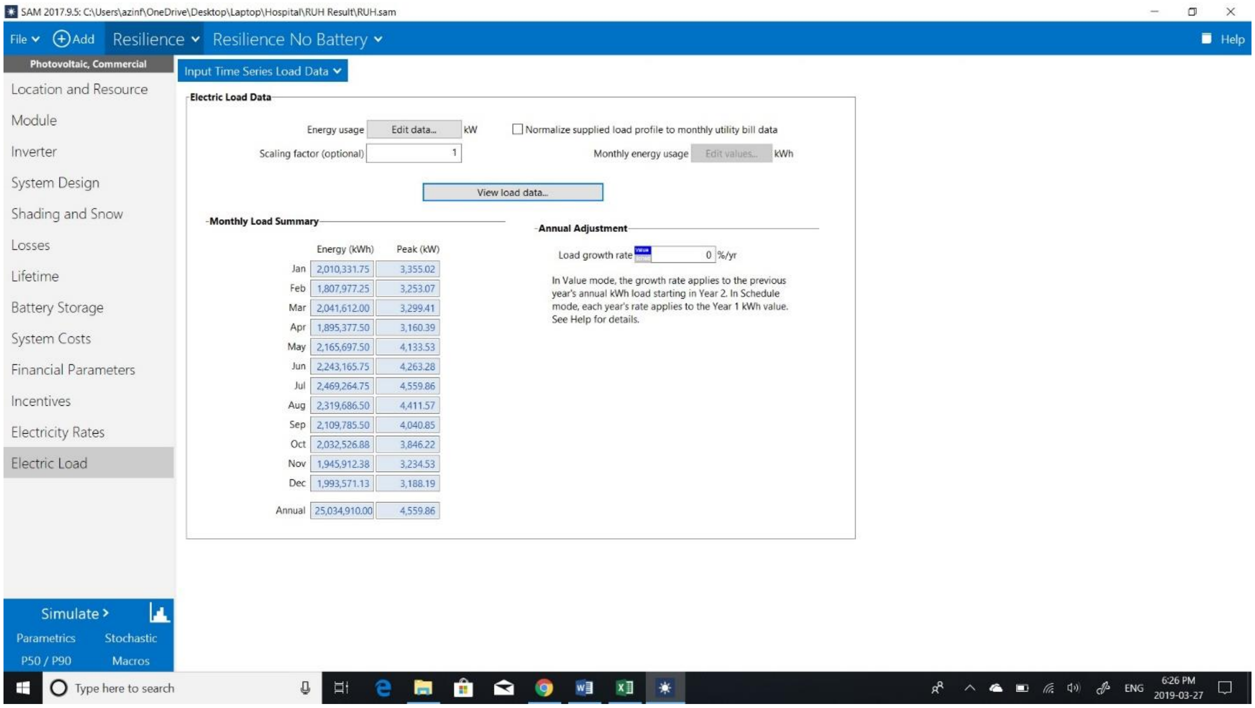


Figure D.7 electric load data page in SAM

Simulation

The last step is to simulate your data by clicking om simulate data. In the output, you could get different parameters such as NPV, capital cost, payback period, monthly energy production, energy saving in a year, and so on.