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TECHNICAL AND ECONOMICAL ANALYSIS OF RESIDENTIAL SOLAR PHOTOVOLTAIC SYSTEMS

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TECHNICAL AND ECONOMICAL ANALYSIS OF RESIDENTIAL SOLAR PHOTOVOLTAIC SYSTEMS

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Preface

This thesis is composed of three published (or submitted for publishing) papers. The author's contributions are described hereafter.

Chapter 2 is "Levelized cost of Electricity for Solar Photovoltaic, Battery and Cogen Hybrid Systems" published in the journal *Renewable and Sustainable Energy Reviews* (http://dx.doi.org/10.1016/j.rser.2015.12.084). This article was written by A. Mundada, K. Shah and J. Pearce. A. Mundada's contribution to the paper was the literature review, methodology, sensitivity analysis, case study, figures and results, writing and editing paper with multiple revisions. K. Shah's contribution to the paper was working on the technical analysis of the hybrid system. J. Pearce's contribution to the paper was conceiving and designing the study, analyzing the data, writing and editing the paper with multiple revisions.

Chapter 3 is "A Review of Technical Requirements for Plug-and-Play Solar Photovoltaic Microinverter Systems in the United States" which is under review. This article was written by A. Mundada, Y. Nilsiam and J. Pearce. A. Mundada's contribution to the paper was the literature review, review NEC codes and standards for solar technologies, case study, figures, results, writing and editing paper with multiple revisions. Y. Nilsiam developed the streamlined process. J. Pearce's contribution to the paper was conceiving and designing the study, analyzing the data, writing and editing the paper with multiple revisions.

Chapter 4 is "U.S. Market for Solar Photovoltaic Plug-and-Play Systems" which is under review. This article was written by A. Mundada, E. Prehoda and J. Pearce. A. Mundada's contribution to the paper was the literature review, developed methodology for LCOE calculations, case studies, sensitivity analysis, U.S. market and employment analysis, figures, results, writing and editing paper with multiple revisions. E. Prehoda's contribution to the paper was GIS analysis, results, demographic figures, writing and editing paper with multiple revisions. J. Pearce's contribution to the paper was conceiving and designing the study, analyzing the data, and detail U.S. market analysis, writing and editing the paper with multiple revisions.

Acknowledgement

This thesis represents my interest in learning about solar energy development and provided a way for me to push my intellectual studies in the field of renewable energy resources. Coming from an electrical engineering background having only a little experience in the field of renewable energy development, with an immense pleasure, I would like to thank my advisor, Dr. Joshua Pearce for believing in me and providing me with full support and guidance throughout the research work. I would like to acknowledge support from the Conway Fellowship and would like to thank Michigan Tech's Open Sustainability Research group for their assistance and sharing of ideas. I would like to acknowledge my committee members Dr. Lucia Gauchia Babe and Dr. Chelsea Schelly for all their help and advice. I also want to acknowledge Emily Prehoda, Yuenyong Nilsiam, J. DesRochers for their contributions to my research work.

A special thanks to my family for their patience, support and understanding without which this was not possible. My parents and my brother, to whom to whom I dedicate my work, have always encouraged me in my pursuit of education, dreams and happiness. I would also like to thank Karthik Panghat, Kunal Shinde, Kri nga Dou group and Power group and all my other friends for their love and care towards me, encouragement and helping me during my stressful times.

Abstract

Technical improvements and scaling have resulted in a significant reduction in solar photovoltaic (PV) module costs, which have resulted in PV industry growth both globally as well as in the United States. In many regions there have been favorable policies for solar energy due to the positive public response and support for growth of solar energy. As the demand for PV installations continues to increase, the costs continue to decline, feeding a virtuous cycle. This thesis is composed of a three part study directed towards technical as well as economical analysis of new technologies for residential solar photovoltaic systems for increasing in the PV penetration level as well as reducing greenhouse gas (GHG) emissions in the United States.

First, a technical and economical analysis is performed of a complete off-grid hybrid system comprising a solar PV unit, battery storage unit and cogen unit for residential sector in United States. A new method of quantifying the economic viability of off-grid PV+battery+CHP systems by calculating the LCOE of the technology is compared to centralized grid electricity. A case study for residential electricity and thermal demand in an extreme worst case environment (Houghton, Michigan) is provided to demonstrate the methodology. Moreover, a sensitivity analysis was carried out for various input assumptions to provide decision makers with clear guides to the viability of such a hybrid system and to provide support through a preliminary analysis that indicated a potential increase in grid defection in the U.S. in the near future.

Second, a technical evaluation is made as well as safety analysis is made for a fully inclusive, commercial, off-the-shelf PV system (normally consisting of a PV module and microinverter), which a prosumer can install by plugging it into an electric outlet and avoiding the need for significant permitting, inspection and interconnection processes. Such systems are referred to as ‘plug and play solar’ systems. The relevant codes and standards from the National Electric Code, local jurisdictions and utilities was reviewed for PV with a specific focus on plug-and-play solar. A streamlined application process is provided with only technical requirements to ease utility implementation. The results indicated that supporting the installation of plug-and-play solar PV with UL (Underwriters Laboratory) certified microinverters will improve PV system performance, will lead to faster uptake and higher PV penetration levels, will also improve prosumer economics, and more environmentally responsible electric power generation.

Finally, a U.S. market analysis is performed for plug and play solar assuming the U.S. regulations modernize and permit the installation of plug and play solar for the residential sector. This study provides an estimate of this new U.S. market for plug and play PV systems if such regulations are updated by investigating personal financial decision making for Americans. The potential savings for the prosumer are mapped for the U.S. over a range of scenarios. This study shows that this system would generate approximately 108,417 thousand MWh per year and this distributed solar energy, which would provide prosumers approximately $13 billion/year in electricity cost savings.

Chapter 1

Introduction and Overview

1. Introduction and Overview

1.1 Motivation

The main objective of this research was to perform a technical as well as economic analysis of new solar PV technologies for residential sector in United States. It is proposed in this research that installing off-grid or on-grid solar PV technologies for the residential sector will not only increase the PV penetration level in U.S., but it will also help in electricity cost savings and environmentally responsible electric generation.

1.2 Thesis Outline

This study begins with Chapter 2 where a new method to determine the levelized cost of electricity (LCOE) of an off-grid hybrid system comprised of a solar photovoltaic, battery and cogen hybrid systems in order to determine the economic viability of such off-grid hybrid systems installed at residential level.

In Chapter 3 a review of technical requirements for plug-and-play solar photovoltaic microinverter systems in the United States is completed to permit the installation of plug and play solar systems for residential sector in United States. A prosumer can install such systems by plugging it into an electric outlet and avoiding the need for significant permitting, inspection and interconnection processes.

In Chapter 4 a U.S. market analysis for plug and play solar systems is provided if U.S. regulations mordernize and permits the installation of plug and play solar for residential sector in United States.

Finally, Chapter 5 discusses the conclusions and opportunities for future work drawn from these studies and how they can help in improving the PV penetration in U.S. as well as help in providing environmentally responsible and economical electric generation.

Chapter 2[1]

Levelized cost of Electricity for Solar Photovoltaic, Battery and Cogen Hybrid Systems

[1] Published in the journal *Renewable and Sustainable Energy Reviews,* **57**, (2016), 692–703.

Abstract

The technological development and economic of scale for solar photovoltaic (PV), batteries and combined heat and power (CHP) have led to the technical potential for a mass-scale transition to off-grid home electricity production for a significant number of utility customers. However, economic projections on complex hybrid systems utilizing these three technologies is challenging and no comprehensive method is available for guiding decision makers. This paper provides a new method of quantifying the economic viability of off-grid PV+battery+CHP systems by calculating the levelized cost of electricity (LCOE) of the technology to be compared to centralized grid electricity. The analysis is inherently conservative as it does not include the additional value of the heat form the CHP unit. A case study for residential electricity and thermal demand in an extreme worst case environment (Houghton, Michigan) is provided to demonstrate the methodology. The results of this case study show that with reasonable economic assumptions and current costs, PV+battery+CHP systems already provide a potential source of profit for some consumers to leave the grid. A sensitivity analysis for LCOE of such a hybrid system was then carried out on the capital cost of the three energy sub-systems, capacity factor of PV and CHP, efficiency of the CHP, natural gas rates, and fuel consumption of the CHP. The results of the sensitivity provide decision makers with clear guides to the LCOE of distributed generation with off-grid PV+battery+CHP systems and offer support to preliminary analysis that indicated a potential increase in grid defection in the U.S. in the near future.

Keywords: photovoltaic; cogeneration; off-grid; combined heat and power; CHP; levelized cost of electricity; battery; storage

Nomenclature:

C_{cf}: Capacity factor of CHP(%)

C_s: CHP system size (kW)

d_1: degradation rate of the PV module per year (%)

d_2: degradation rate of the CHP unit per year (%)

dr: discount rate on the hybrid system per year (%)

E_{chp}: Electrical power output of CHP unit (kW)

E_{ff}: Efficiency of CHP unit (%)

E_{tchp}: Rated energy from CHP unit yearly (kWh/year)

E_{tpv}: Rated energy from Solar PV module yearly (kWh/year)

F_{chp}: Fuel cost of the CHP unit yearly ($)

F_{con}: Fuel consumed by the CHP unit yearly (MMBTU/year)

F_c: Cost of fuel per unit thermal energy ($/MMBTU)

H_{chp}: number of hours CHP operates in a year (hours)

I: interest rate on the hybrid system for 100% debt (%)

I_{pv}: Installation cost of Solar PV ($)

I_{chp}: Installation cost of CHP unit ($)

I_{bat}: Installation cost of battery storage unit ($)

M_{pv}: Maintenance cost of Solar PV yearly ($)

M_{chp}: Maintenance cost of CHP unit yearly ($)

O_{pv}: Operation cost of Solar PV yearly ($)

O_{chp}: Operation cost of the CHP unit yearly ($)

P_{cf} : Capacity factor of PV(%)

P_s: PV power system size(kW)

R_{bat}: Cost of battery replacement considered after every 10 years ($)

T : loan return term or lifetime of the hybrid system (years)

T_{chp} : Thermal output of CHP unit (MMBTU/hr)

V_{chp}: Variable Operation and Maintenance cost of the CHP unit yearly ($)

2.1 Introduction

Technical improvements and scaling have resulted in a significant reduction in solar photovoltaic (PV) module costs, which have resulted in PV industry growth both globally as well as in U.S. [1]. In many regions there have been favorable policies for solar energy due to the positive public response and support for growth of solar energy [2-7]. High exergy electricity from PV is not only reliable, safe and sustainable [8-11], but now it has become an economical way of providing global society's energy needs as well [12-13]. As the demand for PV installation continues to increase, the costs continue to decline feeding a virtuous cycle [14-19]. In some regions of U.S. the solar levelized cost of electricity for small-distributed on-grid PV systems is already competitive with conventional utility electrical rates [12, 20-21].

This represents an economic threat to conventional electric utility business models and in response utilities are using a number of mechanisms to discourage the distributed renewable energy generation market including: i) revoking or repealing net metering legislation [22-25]; ii) placing caps on distributed generation [27-28]; iii) specifying solar grid charges [29-32]; iv) continuing manipulation of customer charges to act as disincentives of both energy efficiency and distributed renewable energy [33-35]; and v) placing temporary prohibition of activities on state Renewable Portfolio Standards [36]. Many of the arguments (e.g. iii) are framed as costs of an inherently intermittent electrical source such as solar. However, the potential for economic dispatchable distributed power becomes possible with the simultaneous decline of the cost of battery storage. Current battery costs are between $600-1,000/kWh. The U.S. DOE expects that this cost will decline further to reach $225/kWh in 2020 and will further drop below $150/kWh in the longer term [37]. Economy of scale will also factor into future battery prices, especially with Tesla's battery GigaFactory, which will shortly have battery packs (Power Wall) available for $350/kWh for home use [38]. However, in many applications (e.g. northern U.S. communities) where a battery bank would need to be prohibitively large to cover the load with PV system alone, such systems can be coupled to a cogeneration or combined heat and power (CHP) system.

The passage of the Public Utility Regulatory Policies Act (PURPA) in November 1978 [39], created the impetus for a resurgence of co-generation and significant growth in CHP capacity. Conventional generation is inherently inefficient, only converting on average about a third of the input fuel's potential energy into usable energy. When comparing overall CHP system efficiency to the typical central power station (for electricity) and boiler system (for steam) scenario, CHP offers reductions in total primary fuel consumption on the order of 30% to 35%, which results in a similar CO_2 emissions reduction, consuming the same fuels [40]. However, if coal-fired electric generation is compared to natural-gas fired CHP systems the result is CO_2 emission reductions approaching 60% and even greater reductions in pollutants such as SO_2, NO_X and mercury [41]. More than two-thirds of the CHPs in the U.S. are fueled with natural gas, but renewable biomass and process wastes are also potential fuel sources [41]. According to a 2012 joint report by U.S. D.O.E. and U.S. E.P.A., CHP makes up about 8 percent of U.S. total generating capacity with an installed capacity of about 82 GW (2012) [42]. The CHP technologies have also improved and are now available at a household scale. In a review comparing various CHP technologies depending on size, cost, efficiency and performance parameters for residential use, CHP modules with internal combustion engine technology were found to be more efficient [43-45]. Finally, the development of shale gas has had a significant moderating effect on natural gas prices [40]. For example, average residential natural gas rates for Michigan in 2009 were $11.30/MMBTU and in 2014 they were $8.99/MMBTU [46]. This has assisted in the economic viability of small-scale CHP units. Hence, these three technological developments in PV, batteries and CHP have led to the possibility of grid defection (moving completely off-grid) for a significant number of utility customers and is projected to increase in the future [47]. However, economic projections on such complex systems utilizing multiple technologies and fuel sources is challenging and no comprehensive review is available for guiding decision makers. This paper provides such a means by quantifying the economic viability of off-grid PV+battery+CHP systems by calculating the levelized cost of electricity (LCOE) of the technology and a case study for residential electricity and thermal demand in Houghton, Michigan is provided to demonstrate the methodology. A sensitivity analysis for LCOE of such a hybrid system is then carried out on the following factors: capital cost of the three components, capacity factor of PV and CHP, efficiency of the CHP, natural gas rates, and fuel consumption of the CHP. The results enable the cost of distributed generation with off-grid PV+battery+CHP systems to be compared to the cost of electricity with the conventional grid. The results for potential grid defection are discussed.

2.1.1 Background

The simplified block diagram of the modeled PV + CHP + battery hybrid system considers only AC loads [48] and is depicted in Figure 1. Such a hybrid system is used to satisfy electrical as well as thermal load demand for a residential single-family detached homes. The hybrid system consists of PV and CHP unit, which are both used to generate electricity. Also the waste heat from co-generation units can be used primarily for space heating and cooling and domestic water heating. The use of co-generation units in this way is optimal for energy management [49–51]. Moreover the CHP unit also generates thermal energy, which it uses to partially fulfill thermal load demand and thus offsets the primary furnace and fuel source (e.g. natural gas furnace). The output of PV and the energy stored in the battery is DC, which necessitates a DC-AC inverter to supply the AC load. Moreover, as the output of CHP unit is AC, any excess AC output has to be converted into DC form before storing it in the battery unit. Thus, an AC to DC rectifier is incorporated for this purpose. It should be noted, the dispatch strategy of the system will be reliant on both the load data and the fuel economics for a given region. Parallel topology is employed for the electrical component of the system [52]. Here, the priority given to fulfill the electrical demand will be solar PV followed by the storage battery and finally the CHP unit, in order to minimize fuel use and greenhouse gas emissions. Thus, the PV unit will try to satisfy the AC load demand. If it is incapable of satisfying, then PV and the battery unit will fulfill the load demand, which will help to increase system efficiency. If still the AC load demand is not satisfied the remaining load demand will be served by the CHP unit [53].

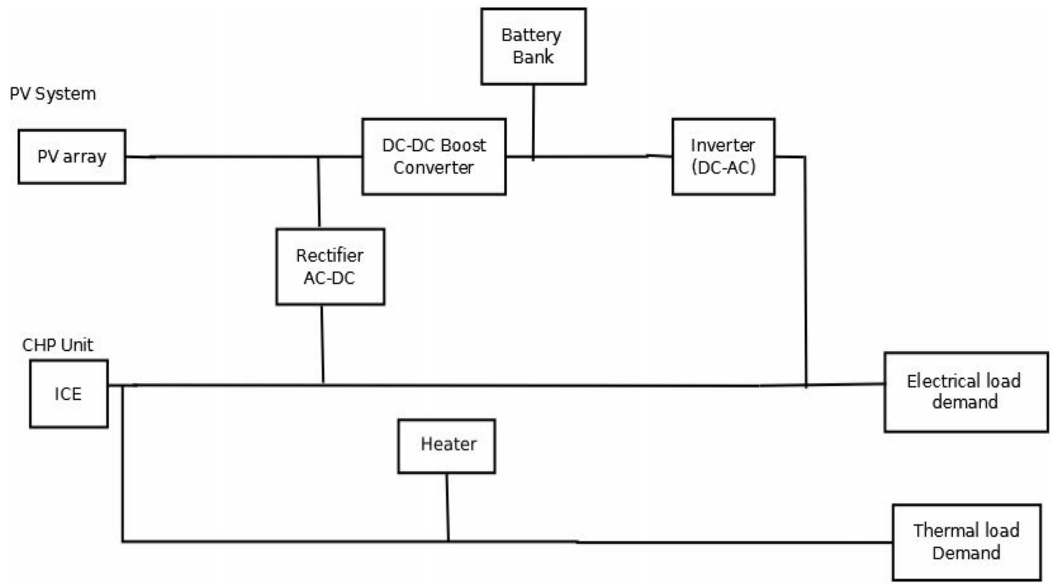

Figure 1. Simplified Block diagram of PV+CHP+Battery Hybrid system

2.2 Methodology

LCOE methods for PV are well established [54-57] and recently standardized in [12]. LCOE of CHP units is slightly more complex because of potentially unknown expenditures for carbon dioxide emissions, but is also well established taking into account the amount of electricity produced, the discount factor, *i*nvestment costs; operations and maintenance costs; fuel costs; carbon costs; and *d*ecommissioning costs [58-61]. Here the LCOE calculation requires determining the cost of generation of energy by the hybrid system and the energy generated by the system in its lifetime and gives cost of energy in ($/kWh). As LCOE is sensitive to the input assumptions a sensitivity analysis is carried out encompassing the following variables:

- Capital cost of the three systems:
  1. PV ($0.50/W to $4.00/W),
  2. Battery storage $250/kWh to $1,000/kWh) and
  3. CHP ($500/kW to $1,400/kW).

     The high capital costs are the current market prices as of this writing.
- Efficiency of the CHP module: 80% to 98%.
- Capacity factor of the PV: (13% to 18%) and consequently CHP module (55% to 14%).
- Financing terms: interest rate (0% to10%) and discount rate (0% to 10%).
- Fuel cost of natural gas being consumed by the CHP module: ($6/MMBTU to $15/MMBTU)

It should be noted that starting from year one until the loan term, T, the operation and maintenance, fuel cost and the interested amount is considered just as in the case with the generated energy by the system. In this paper the LCOE method represented does not include any incentives as well as any decommissioning cost, carbon cost or refurbishment costs.

The installation cost is taken out of the summation as it is just considered initially. The installation cost will include the cost of solar PV, battery and the CHP module and is given by:

$$I = I_{pv}+I_{chp}+I_{bat} \tag{1}$$

The operation and maintenance will include the operation and maintenance cost for solar PV (including inverter replacement) and CHP module along with variable operation and maintenance cost of CHP module and replacement cost of battery is:

$$O = O_{pv}+ O_{chp}+ M_{pv}+ M_{chp}+ V_{chp}+ R_{bat}$$
(2)

The LCOE of the hybrid system can be determined using:

$$\mathrm{LCOE}=\frac{I+\sum_{n=1}^{T}\frac{(I\times i+O+F_{chp})}{(1+d_r)^n}}{\sum_{n=1}^{T}\frac{E_{tchp}\times(1-d_2)^n+E_{tpv}\times(1-d_1)^n}{(1+d_r)^n}} \tag{3}$$

where:

$$E_{tpv} = 8760 \text{ hrs/year x } P_s \text{ x } P_{cf} \tag{4}$$

and

$$E_{tchp} = 8760 \text{ hrs/year x } C_s \text{ x } C_{cf} \tag{5}$$

The cost of fuel can be determined by multiplying the fuel consumption per hour by the number of hours the CHP is working in a year, which is then multiplied with the cost of fuel in that area:

$$F_{chp} = F_{con} \text{ x } F_c \text{ x } H_{chp}$$
(6)

The fuel consumption can be found out by dividing total electrical and thermal output generated by the CHP by the efficiency of the CHP unit [62-64]:

$$F_{con} = \frac{((E_{chp}\times 3.143)+T_{chp})}{E_{ff}} \tag{7}$$

As can be seen by equation 3, the LCOE greatly depends on the capital costs of the PV, battery and CHP. It also varies depending on the operation and maintenance costs of the sub-systems. Moreover, the fuel cost also affects the LCOE of the hybrid system. The fuel cost depends on the fuel consumption of the CHP unit, which depends on the efficiency and the power to heat ratio of the CHP unit.

2.3 Theory and Calculations for Determining LCOE of the Hybrid System

The choice of discount rate, system costs, average system lifetime and the degradation rate of the entire system every year.

2.3.1 Discount rate

The choice of discount rate can vary depending on the location, the life time of the project and the technologies being used based on investors' perception of financial risk. The DOE discount rate for projects related to energy conservation and renewable energy resources in 2013 was 3% [65], which will be used here.

2.3.2 System cost

System component cost not only depends on the capacity and the variability from vendors, but also on the type of the system and the location where the system is being installed. Installation costs vary widely as a function of location and depends on the engineering costs, permitting and regulations, labor costs and the remainder of balance of system costs (BOS). Capital costs of the major system components are all decreasing.
The PV unit price, is highly dependent on the type of solar PV system, location and type of the dwelling. For an instance, a thin-film solar PV system cost less per Watt as compared to a crystalline silicon PV system [66-67]. The installed prices for residential PV continued their precipitous decline in 2014, falling year-over-year by 12-15% depending on system size range [1]. The installation cost include the module price, labor cost, electrical BOS cost, structural BOS cost, inverter costs, engineering & PII cost [1]. In general, labor cost and BOS of a solar PV system adds up to 50% of the system cost [68], but strategies are being developed to halve these prices [69]. Through industrial symbiosis and manufacturing facilities the solar manufacturing prices have been declining on the economic scale [66, 70, 71]. Finally, installation costs are expected to decrease with technological experience, although not as drastically as hardware costs [72]. The installed PV system median costs for location are summarized in Table 1. Due to technical advancement PV modules are available at historically extremely low prices such as \$0.69/W for Canadian Solar CS6P-280P [75]. The major contribution to the PV capital cost in U.S. is the soft cost which is around 50-70% of the total PV system installation cost which is double the soft cost incurred by the PV installation in Germany (i.e. the U.S. solar PV soft cost is ~ \$0.49/W whereas for Germany it is only ~\$0.18/W) [76].
The engineering, capital cost and efficiency for CHP units as a function of the prime mover technology [44, 77]. The fuel cost varies depending on the efficiency of the CHP unit and the location where the system is installed. Table 2, compares the efficiency of various micro CHP units, which are both sufficient for residential use and available on the market [78]. These are put in context in Table 3, which compares capital cost of different prime mover technologies to large scales [68, 77]. It can be observed from the Table 2 that CHP with ICE technology is suitable and efficient for such type of hybrid system.
Moreover, the cost is also declining and the lifetime is increasing for electrical storage

technology as a whole, although it depends on the type of the battery being used for the system and the battery rating, and number of batteries connected in series or parallel. Historically, deep cycle batteries were preferred for off-grid applications. For example, Trojan T105 RE, with 1000 cycles to 80% discharge rate has a normal lifespan of 10 to 12 years and cost of $0.16/kWh for life time of battery [79]. These battery costs along with the battery technology are evolving quickly as noted above.
Thus, the LCOE of the system is obviously sensitive towards the system cost and sensitivity analysis is carried out. For the case study presented here the capital cost of PV is considered to be $4/W and installation cost of CHP is considered to be $1,400/kW.

2.3.3 Financing

Financing depends on the credit of the individual and the tax laws, which also varies depending on location. Financing can be government incentives, loans, equity financing, mortgage, or debt financing. Debt financing is common as interest payment does not on include taxes. For the case study, 100% debt financing will be used. Moreover, the loan period is different from the life time of the system, it is a guarantee period.

2.3.4 Life time of the hybrid system

The life time of hybrid system depends on the life time of the PV as well as CHP module. The average life time of PV module is considered to be 25 years in the analysis here to be conservative, although it is known that PV operate much longer. The life time of a CHP unit is a minimum 10-20 years. Operation and maintenance cost increases with the time and is mainly due to inverter and battery replacement (at 10 years) and to insure the proper performance of the CHP unit. The fuel cost depends on the type of fuel required for the CHP unit, generally natural gas or propane based CHP units are available in market. Here natural gas will be considered primarily for economic reasons and the technical feasibility of scaling. Table 4 and 5 provide the EIA-2015 natural gas rates for the state of Michigan [46].

2.3.5 Degradation rate and the energy generated by the system

The energy output from PV depends on the degradation rate of the modules. The degradation rates for amorphous silicon PV is 0.5-1.0%/year, for crystalline silicon it is 0.1-0.5%, for polycrystalline silicon PV it is 0.1-1.0% and for cadmium telluride 0.1-0.5%/year [80-81]. This degradation is due to chemical and material processes such as weathering, oxidation, corrosion and thermal stress. The degradation rate of the CHP module depends on the type of the technology of prime mover; for all the technologies, however, the degradation annually is below 0.5% [44]. For the case study in this paper the annual degradation of the PV module and the CHP module with internal combustion engine prime mover is considered to be 0.5%.

2.4 Results

2.4.1 Case study: Houghton, Michigan, USA.

A case study was chosen with relatively challenging resources. Houghton, MI is located in the upper peninsula for Michigan, thus it has relatively long winters, poor solar flux distribution and high heat loads relative to most of the rest of the U.S. The case study is for residential sector in Houghton, MI with average electric demand of 9,128 kWh/year [82] and thermal demand of 98.3MMBTU/year [83]. As it is a low-population density isolated community the installation costs of PV are above the national average and will be assumed here to be $4.00/W. Moreover, the minimum capital cost of the PV considered for the sensitivity is $0.5/W. The size of PV required for fulfilling the load demand is 8.133 kW [48]. Whereas the CHP module is assumed to have a capital cost $1,400/kW with an engineering cost of 450$ [44, 77]. The CHP unit with ICE prime mover technology has different minimum cost ranging from $800-$1400/W [77, 84, 85]. Thus, a minimum capital cost of $500/kW was considered for sensitivity analysis. The size of CHP required to fulfill the load demand on an hourly basis throughout the year is 1kWe [48]. A battery storage unit considered is deep-cycle batteries with nominal voltage 48V and 1199A-h costs around $2,000 and has a lifetime of 10 years or more (although as noted earlier this is likely to decline considerably as Tesla batteries become available).

Battery backup banks can be made up of many small batteries which are connected in series and or parallel to give the wattage (V-A) capacity needed. The optimal sized deep cycle lead acid battery storage unit for 1kWe of CHP unit is 4 batteries in series and 8 in parallel for a PV array of 8.1kW and a CHP of 1kWe for a total battery size of 300 Ah [48]. The life span duration of such a battery storage unit is 10 years or more [86,87].

From the results of the HOMER simulation shown in Figure 2 of such an optimized hybrid system run using the above PV, CHP and battery sizing it can be observed that system is able to fulfill the load demand completely for residence in Houghton, MI [48]. It can also be observed that the operating hours for all the three units are different and also varies according to the monthly AC load demand and the solar hours. The thermal load demand of the residence is fulfilled by CHP unit as well as boiler.

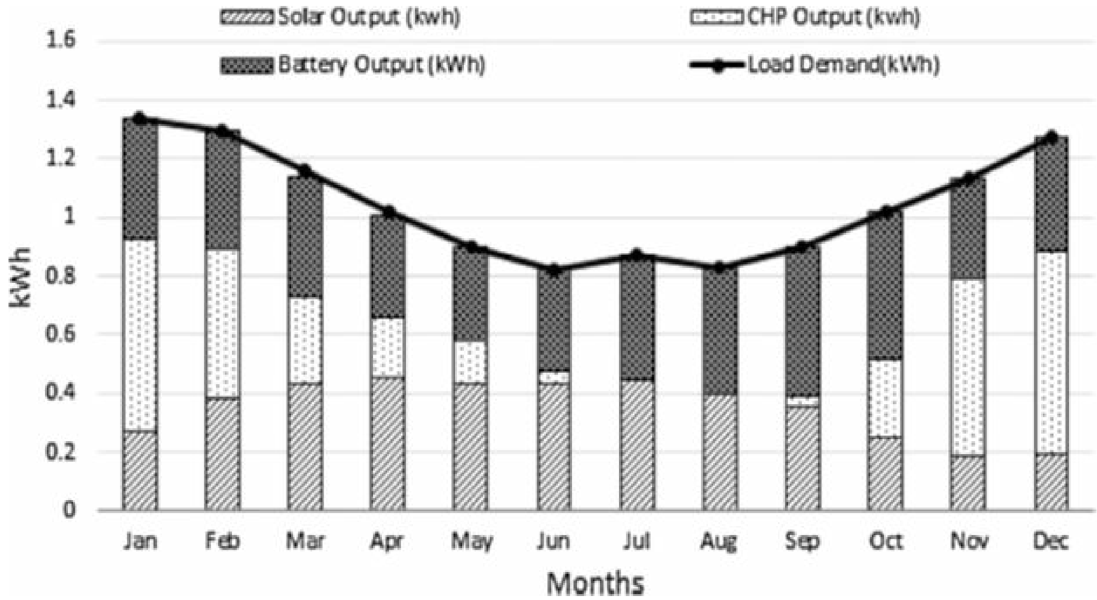

Figure 2. Region Michigan -Houghton. Average hourly energy produced per month by PV, CHP and Battery units to meet the load demand

The engineering cost for the hybrid system should also be considered to get precise results. Here it is assumed that the dispatch strategy considered ensure that the CHP operational time is minimized to reduce the fuel consumptions and the concomitant fuel costs and GHG emissions. The capacity factor of the PV is considered to be 15.3% for Houghton based on solar data and that of the CHP is considered to be 36.28% with an efficiency of the CHP module of 83% [48]. Moreover, historically the efficiency of ICE technology based CHP module varies from 75-80% [77, 84]. Today, the CHP modules with ICE technology available on the market have efficiencies of around 80%-95% [88-91]. Thus for the sensitivity analysis the efficiency of CHP unit has been considered to be 80%-98%. Along with it 100% debt financing was used. The operation cost for the PV is 1.5% of the PV installation cost; whereas the maintenance cost, which is mainly due to inverter replacement, is 9% of the PV installation cost [12]. The battery is to be replaced after 10 years and cost of the replacement is considered in the operation and maintenance cost. The operation and maintenance cost for ICE based CHP unit is $50/year whereas the variable operation and maintenance cost is $0.08/kWh [44]. The fuel used by the CHP module is natural gas and in Houghton the rates are $8.90/MMBTU [46]. Thus, following the equations above the total fuel cost for the CHP module is $341.53/year.
The electricity price for residential sector in Houghton varies from $0.21/kWh to $0.24/kWh [92], electric utility company annual reports the electricity rates for Houghton in 2013 was $0.22/kWh. It has been observed that this electricity rates are escalating. For example: the electricity rate in Houghton in 2003 was $0.1459/kWh and in 2013 it was $0.22/kWh (i.e. an increase by almost 50% in a duration of 10 years). Thus, to compare the LCOE of the hybrid system with the rates of electricity it is important to consider the escalation rate of electricity each year. This escalation rate is due to a number of factors that are difficult to estimate so the estimated cost of electricity after 25 years with varying escalation rates 0% to 6% is shown in Figure 3.

Figure 4A-F shows the effects on the LCOE of the hybrid system of financing assumptions. The LCOE of the system with with different discount rates of 0%, 3%, 5% and 10% and interest rates of 0%, 1%, 2%, 3%, 5% and 10% with all other factors maintained for a loan term vary from 25 years are shown. For Figure 2 it is clear that LCOE decreases as the interest rate falls for the same discount rate. The LCOE for 0% interest rate and 0% discount rate has minimum value $0.212/kWh. Moreover, for each discount rate the minimum LCOE will be observed with 0% interest rate, for example, the LCOE for the hybrid system when the discount rate is 5% is $0.229/kWh (25 year loan term); when discount rate is 3% is $0.223/kWh (25 years loan term).

Figure 5A-C shows how the LCOE of the system varying as a function of the capital cost of the PV and CHP with capital cost of battery held constant. The discount rate for this case is 3%, 2% interest rate, 25 years loan term, whereas this will affect the operation and maintenance cost of the PV module. In Figure 5A-C, the capital cost of the CHP module is $1,400/kW, $1,000/kW and $500/kW respectively, whereas the installation cost of PV module is varied from $0.50/W to $4.00/W for each case. It can be seen that the LCOE is obtained with installation cost of PV at $0.50/W and capital cost of CHP is $500/W is $0.063/kWh. The capital cost of the modules plays an important role in LCOE of the hybrid system, whereas a small change in capital cost of the CHP module does not change the LCOE of the system by large values. For example when installation cost of the PV subsystem is $1.00/W with the capital cost of CHP of $1,400/kW, the LCOE of the hybrid system is $0.086/kWh (25years), however, when the capital cost of CHP module is $1,000/kW the LCOE of the hybrid system is $0.085/kWh. Furthermore, if the capital cost of the battery is reduced with minimum capital cost of CHP module and installation cost of PV module the LCOE value can be reduced more. Figure 3D gives the LCOE of the system with installation cost of PV at $0.50/W and the capital cost of CHP $500/kW and varying capital cost of battery sub-system between $1,000 and $250, respectively. Note, that this capital costs change also effects the battery replacement cost. It can be seen that the LCOE of the hybrid system is $0.053/kWh and is obtained when installation cost of CHP module is $500/kW, whereas the capital cost of PV module and battery is $0.50/W and $500 respectively. With the battery cost declining by another 50%, the LCOE declines by another approximately 2 cents per kWh.

Figure 6 shows how the LCOE of the system is affected by change in the capacity factor of the PV and the CHP sub-systems. As already mentioned, by minimizing the capacity factor of the CHP sub-system the LCOE of the complete system can be reduced. The capacity factor of the PV and CHP will affect the rated energy generated by each other. The total energy out of the system is the energy contribution of PV and the CHP sub-systems. If the capacity factor of the PV module is increased this will increase the rated energy output of the PV and will reduce the contribution by the CHP. The capacity factor of the PV module is varied 13%, 15.3% and 18% and the resultant CHP capacity factor is summarized in Table 6. For this case the discount rate is 3% and interest rate is 2% with 25 years loan term and the results are shown in Figure 6. It can be observed that we get minimum LCOE $0.225/kWh when capacity factor of PV module is 18% and CHP module is 14.32%.

Figure 7 shows how the LCOE of the system is affected by the change in the efficiency of the CHP module. The change in the efficiency also impacts the fuel consumption of the

CHP module and hence the total cost of fuel. The efficiency of the CHP is varied from 85% to 98% and all other factors are kept unchanged. As the efficiency increases the total fuel cost is reduced and thus the LCOE of the system. For example the LCOE of the system is \$0.239/kWh for 90% efficient CHP and is \$0.241/kWh for 85% efficient CHP module. The minimum LCOE \$0.237/kWh is obtained when the efficiency is maximum 98% (25 years).

Figure 8 shows how the LCOE of the hybrid system varies with change in rates of natural gas (\$/MMBTU). As can be seen from Table 3 the natural gas rates have varied historically and is difficult to predict into the future so a sensitivity analysis on natural gas rates was performed to investigate the effects on the LCOE of the hybrid system. The natural gas rates are varied from \$6/MMBTU to \$15/MMBTU and LCOE of the system has been determined. From the results summarized in Figure 8 it is clear that the natural gas rates have a muted effect the LCOE rates of the system. For example the LCOE is \$0.258/kWh when natural gas rates are \$15/MMBTU, whereas it is only 2 cents less (\$0.232/kWh) when natural gas rates are reduced by nearly a factor of three to \$6/MMBTU.

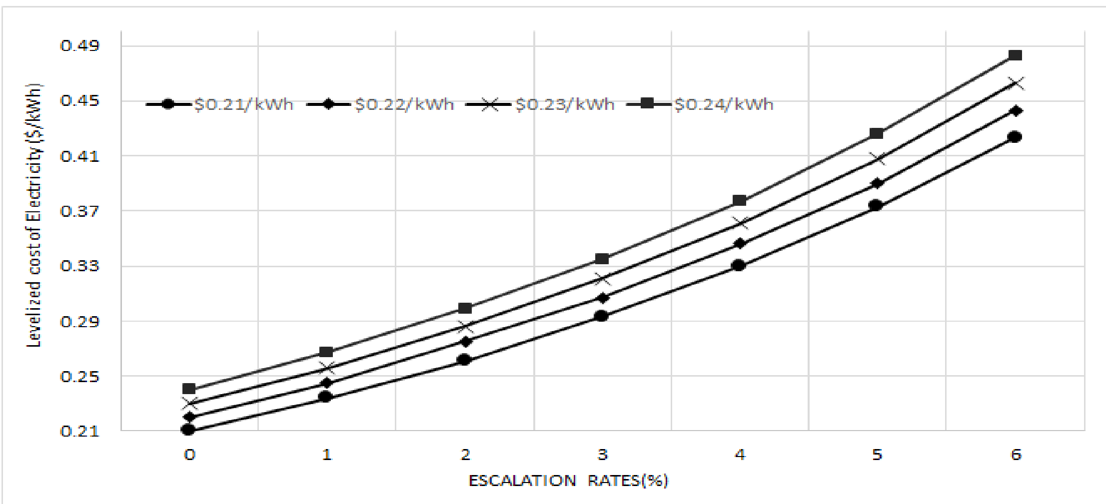

Figure 3. The levelized cost of electricity for central generation, which depends on the current electricity rates in the residential sector of Houghton, MI withvarying escalation rates determined with NRELs LCOE calculator [93].

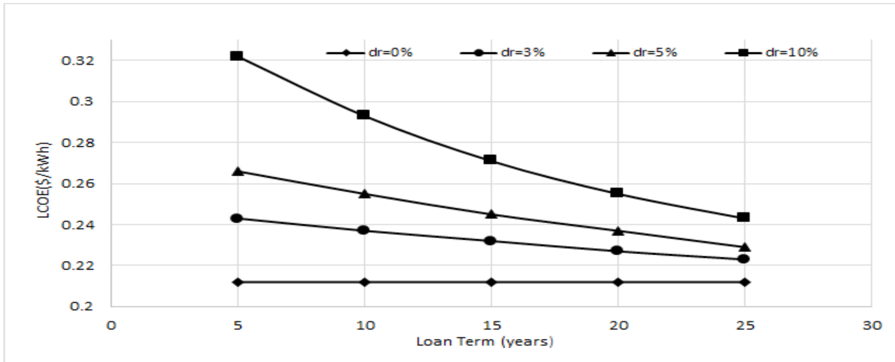

Figure 4a

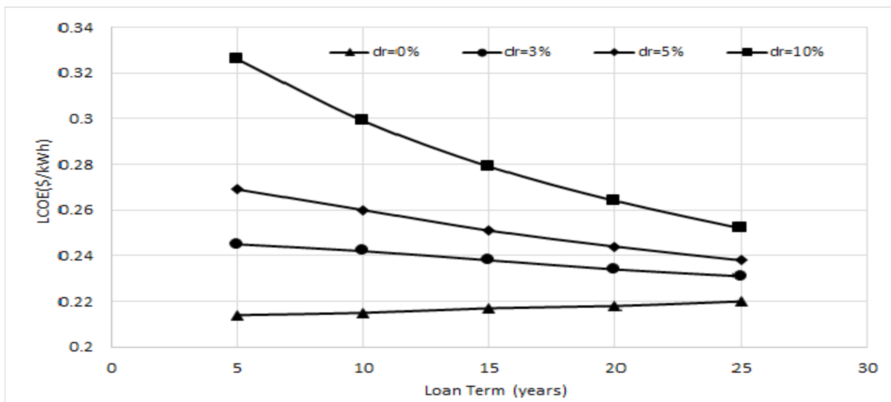

Figure 4b

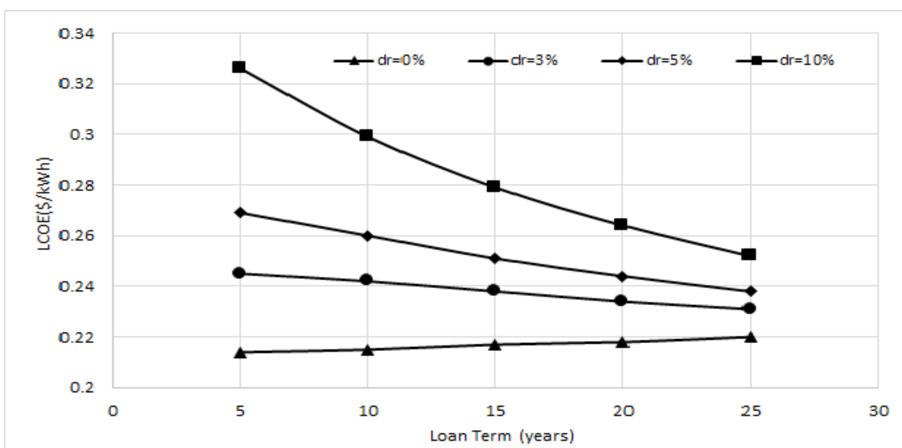

Figure 4c

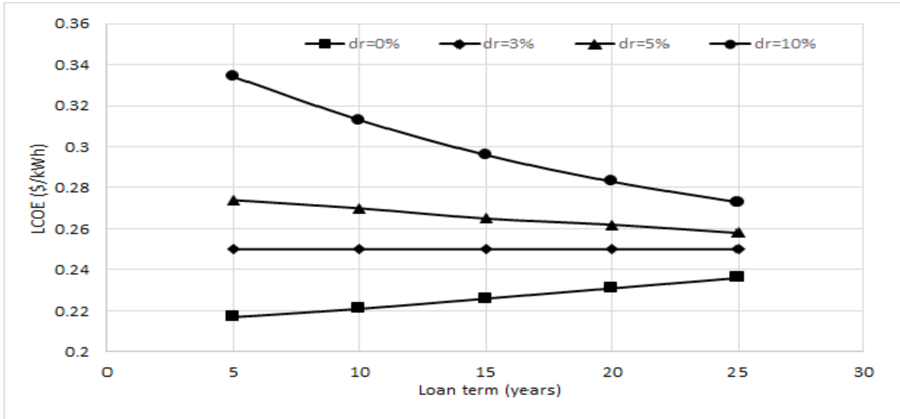

Figure 4d

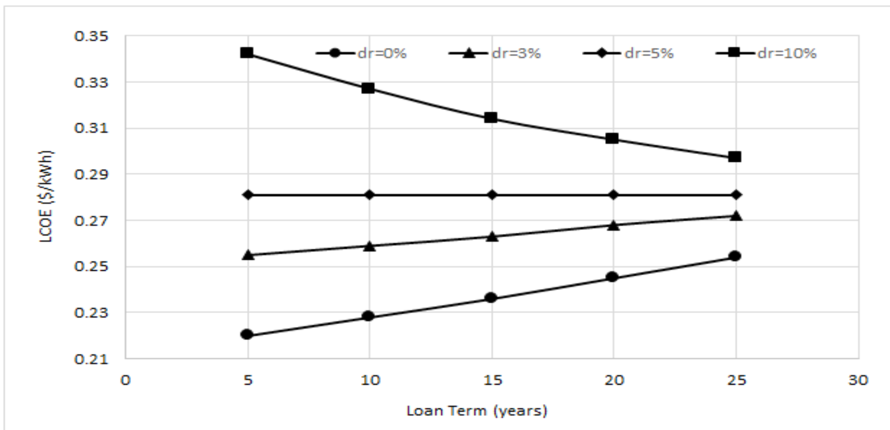

Figure 4e

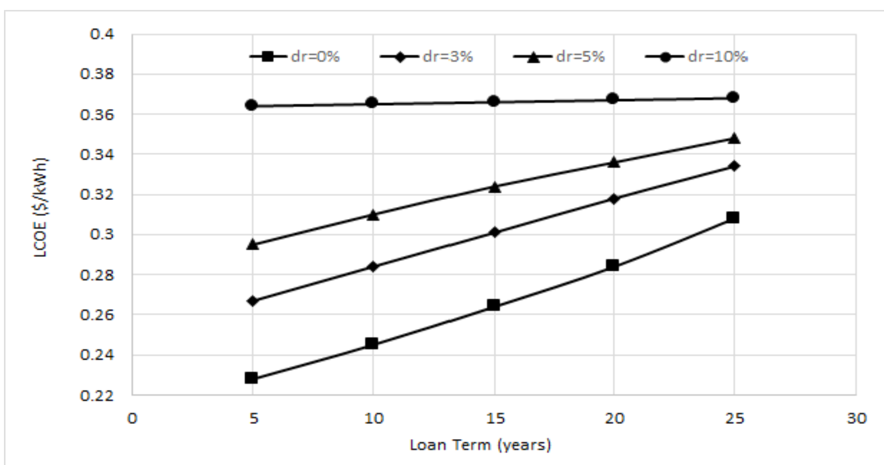

Figure 4f

Figure 4: LCOE of the system for varying discount rate (0%,3%,5%,10%) and interest rates (A=0%,B=1%,C=2%,D=3%,E=5%,F=10%). Assumptions: Installation cost of PV=$4/W, CHP=$1950/kW and battery=$2,000/kWh, the total energy output=14,000 kWh/year, degradation rate=0.5%/year and loan term of 25 years.

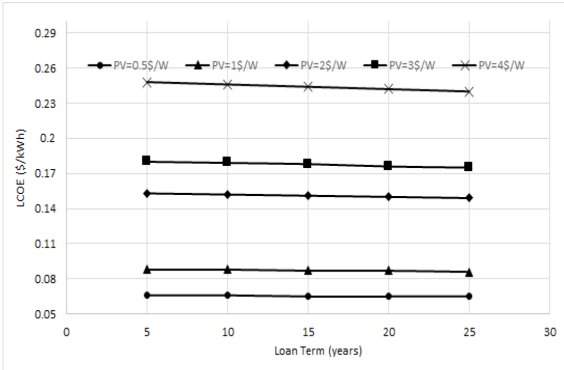

Figure 5a

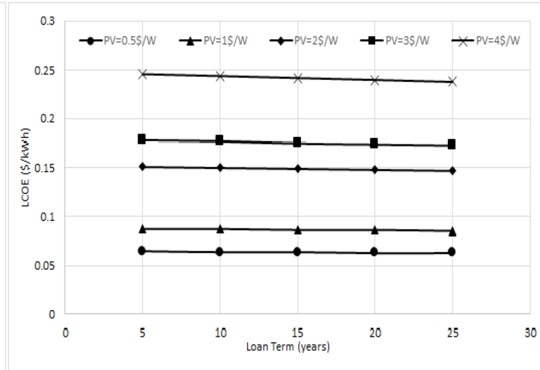

Figure 5b

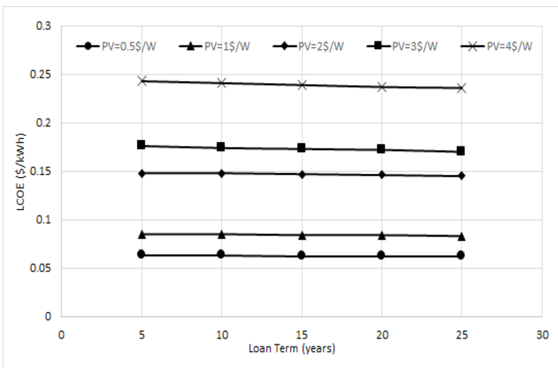

Figure 5c

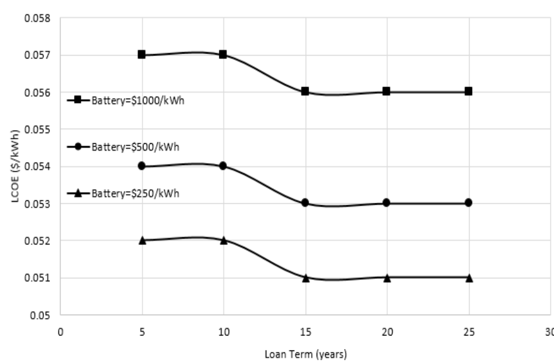

Figure 5d

Figure 5: LCOE of the system for varying installation cost of PV (0.5$/W, 1$/W, 2$/W, 3$/W, 4$/W) and CHP capital cost (A=$1400/kW, B=$1000/kW, C=$500/kW). Assumptions included installation cost of battery of $2000/kWh, loan term is 25 years, degradation rate=0.5%/year, total energy output=14,000Wh/year, discount rate=3% and interest rate=2%.
Figure 5d: LCOE of the system for varying installation cost of battery ($1000/kWh,$500/kWh, $250/kWh) with minimum installation cost of PV and capital cost of the CHP module for loan term of 25 years. Assumptions included, degradation rate=0.5%/year, installation cost of PV=$0.50/W, capital cost of CHP=500$/kW, total energy output=14,000Wh/year, discount rate=3% and interest rate=2%.

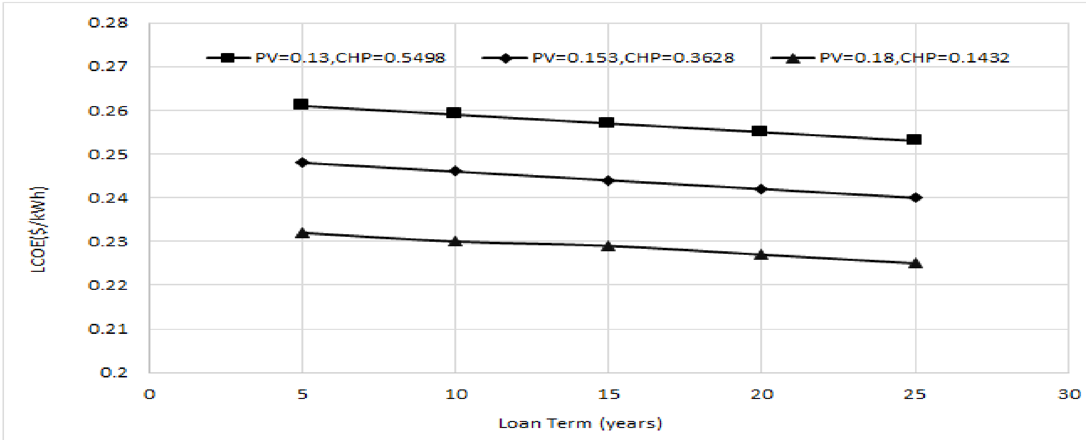

Figure 6: LCOE of the system for varying the capacity factor of PV module (13%,15.3%,18%) and hence the capacity factor of the CHP module (55%, 36%, 14%). Assumptions included loan term is 25 years, degradation rate=0.5%/year, installation cost of PV=$4.00/W, capital cost of CHP=$1400/kW,
total energy output=14,000Wh/year, discount rate=3% and interest rate=2%.

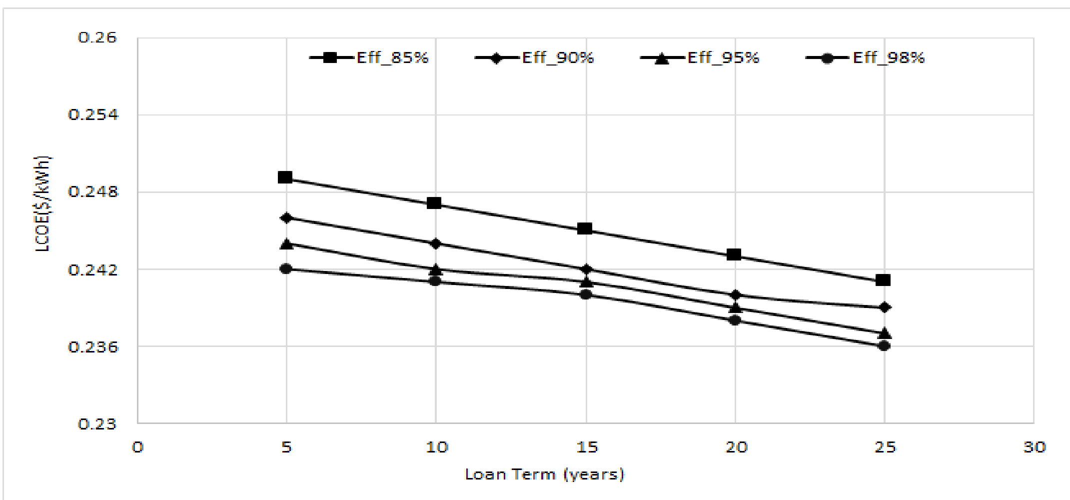

Figure 7: LCOE of the system for varying the efficiency of the CHP module(85%, 90%, 95%, 98%) for a loan term of 25 years. Assumptions included degradation rate of 0.5%/year, installation cost of PV is $4.00/W, capital cost of CHP is $1400/kW, total energy output is 14,000Wh/year, discount rate is 3% and interest rate of 2%.

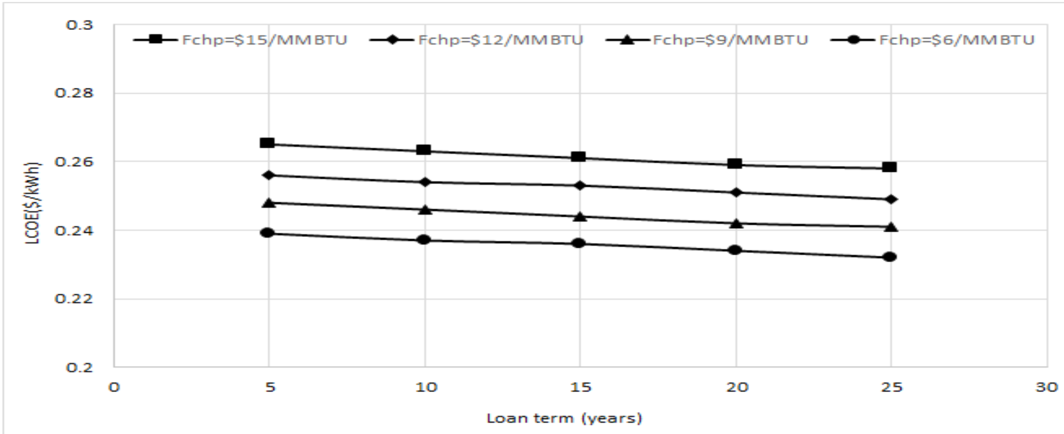

Figure 8: LCOE of the system for varying the rates of the natural gas ($15, $12, $9, $6 per MMBTU) used by CHP for a loan term of 25 years. Assumptions included degradation rate of 0.5%/year, installation cost of PV is $4.00/W, capital cost of CHP is $1400/kW, total energy output is 14,000Wh/year, discount rate is 3% and interest rate of 2% .

2.5 Discussion

A simple methodology for calculation of LCOE of hybrid PV, battery and CHP system has been presented. The methodology was used to determine the LCOE for the hybrid system which can be installed in Houghton, Michigan, US. The results of the case study are present in Figures 3-8, which provide a quantitative view of the effects on the LCOE with changes in various input factors.

The high initial installation cost of the hybrid system can be an obstacle in its installation in this region with an immature market for both PV and CHP systems. However, it can be observed that with lower interest rates, long term loans, high discount rate and a reasonable degradation rate, such a system will be profitable and may be preferred to maintaining grid dependence. It can be seen from Figure 5A-C that the LCOE of the system was greatly affected by the installation cost of PV and the capital cost of the CHP. The largest contributions of the PV subsystem costs are the PV module cost and the inverter cost, although it is clear in comparison with regions with more mature markets that if the BOS cost is reduced then the installation cost of PV module can be significantly further reduced. Moreover, Figure 5D shows with the reduction in the battery cost the LCOE of the system can further be reduced, but the cost of the battery has a relatively small impact on the LCOE for the entire system.

The interest rates and discount rates also affects the LCOE of the system. This can be seen by comparing the results in Figure 4A-4F. When both of these financing terms are high the impact is severe and raises the LCOE outside of the range of profitability. Using current low interest rates result in a competitive LCOE even with inflated initial costs. Figure 4A shows 0% interest rate with long loan term results into lowest LCOE value for any given starting condition.

The capacity factor of the PV as well as CHP also affects the LCOE of the system. This can be seen from Figure 6. As the capacity factor of PV increases the energy generated at the output of the PV also increases. The total energy at the output of the system is maintained constant so as it is sufficient to satisfy the electrical load demand of the house, and thus the energy at the output of the CHP can be reduced by reducing the capacity factor of the CHP. As the capacity factor of the CHP declines the number of hours the CHP module operates in a year is reduced resulting in less fuel consumption and improving the LCOE of the hybrid system. As can be seen in Figure 6 this effect is relatively minor.

The efficiency of the CHP was also varied between 75% to 98%. As the efficiency of the CHP increases the fuel consumption is reduced, reducing the fuel cost and improving the LCOE as can be seen in Figure 7. As CHP units are already relatively efficient the relative impact on the LCOE is a minor one.

Although in recent years in the U.S. as a whole (and in the case study region of MI in particular) the natural gas retail prices have been declining as seen in Table 3, the natural gas rates can even increase or decrease over the next 25years. Thus, the cost of the fuel utilized by the CHP will be affected, and hence the LCOE of the system. The impact of natural gas prices on the hybrid system can be seen in Figure 8. Lowering the natural gas rates reduces the LCOE of the system, but large changes in the fuel costs have relatively minor impacts on the LCOE of the whole system.

The results of both the initial case study (Figure 4) in Houghton, MI and the sensitivity (Figures 5-8) provide decision makers with clear guides to the LCOE of distributed generation with off-grid PV+battery+CHP systems. The lower LCOE costs of the hybrid off-grid system (Figures 4-8) as compared to grid costs with even modest escalation rates (Figure 3) offer support to preliminary analysis that indicated a potential increase in grid defection in the U.S. in the near future [94].

Tables

Table 1: Summary of Average Residential PV Installed System Costs [67,73,74].

Solar PV Installation year	Size of the system (kW)	Installed Cost($/W)
2012 (US)*	2-5	5.2
2012 (Germany)*	2-5	2.6
2012(Australia)*	<5	3.1
2012(Italy)*	2-3	3.1
2012(France)*	<3	4.8
2012(Germany)**	2-5	2.3
2012(US)**	2-5	5
2013(US)	<10	4.72

2014(US)	<10	3.5

*-Excluding Tax

**-Including Tax

Table 2 : Electrical output, efficiency and total system efficiency for various CHP product available in market for residential use[61].

Product	**Technology**	**Electrical output (kW)**	**Electrical Efficiency(%)**	**Total Efficiency(%)**
Baxi-cogen	Stirling	1	15	91
Honda Eco-	ICE	1	26	92
PanasonicEne	Fuel cell	1	35	85
CFCL Blue-	Fuel cell	1.5	60	<85

Table 3 :CHP capital, engineering cost and efficiency depending on the technology [77,68].

CHP technology (prime-mover)	Typical Capacity	Installed cost($/kW$_e$)	Efficiency (%)
Gas Turbine	500kWe-300MWe	1,200-3,300 (5-40 MW)	66-71%
Steam Turbine	50kWe to several hundred MWe	$670-1,100	Nearly 80%
Microturbine	30 kWe to 250 kWe with multiple unit packages up to 1,000 kWe	2,500-4,300	63-70%
Internal-combustion engine	1 kWe to 10 MWe in DG applications	1,500-2,900	75-80%
Fuel Cell	5 kWe to 2 MWe	5,000-6,500	55-80%

e: Electrical output from the CHP module.

Table 4 : Natural gas rates for various years in MI, US [46].

Natural Gas rates Michigan State($/MMBTU)	Year
11.37	2009
11.32	2010
10.47	2011
9.95	2012
9.09	2013

Table 5 : Natural gas rates variation in year 2014 for MI, US [46].

Month year-	**Michigan state Natural gas rates ($/MMBTU)**
July	14.00
August	14.57
September	12.48
October	10.04
November	8.85
December	8.99

Table 6: Capacity factor for PV and CHP module.

Capacity factor PV	**Capacity factor CHP**
13% (minimum of 3.3	55%
15.3% (Houghton from	36%
18% (maximum 4.1-4.4	14%

2.6 References

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Chapter 3[2]

A Review of Technical Requirements for Plug-and-Play Solar Photovoltaic Microinverter Systems in the United States

[2] --under review (Journal-Energies)

Abstract

The average American is highly supportive of solar photovoltaic (PV) technology and has the opportunity to earn a high ROI from a PV investment for their own home. Unfortunately, the average American does not have easy access to capital/financing to install a PV system able to meet their aggregate annual electric needs. One method to overcome this challenge is to allow 'plug-and-play solar', which is defined as a fully inclusive, commercial, off-the-shelf PV system (normally consisting of a PV module and microinverter), which a prosumer can install by plugging it into an electric outlet and avoiding the need for significant permitting, inspection and interconnection processes. Many advanced countries already allow plug-and-play solar, yet U.S. regulations have lagged behind. To assist US policy makers in overcoming regulatory obstructions to greater PV penetration, this article first reviews the relevant codes and standards from the National Electric Code, local jurisdictions and utilities for PV with a specific focus on plug-and-play solar. Next, commercially available microinverters and alternating current (AC) modules are reviewed for their technical and safety compliance to these standards and all were found to be compliant. The technical requirements are then compared to regulatory and utility requirements using case studies in Michigan, which were found to create arbitrary non-technically-valid barriers to grid entry. The analysis also exposed the redundancy of the utility accessed AC disconnect switch for residential and small commercial grid connected solar PV. It is clear that the AC disconnect switch is not technically necessary and thus imposing it is an economic barrier to grid entry for solar PV systems with UL (Underwriters Laboratory) certified microinverters. To reduce consumer and utility workload and the concomitant soft costs, this article provides a streamlined application with only technical requirements and free and open source software to ease utility implementation. Finally, the advantages of supporting plug-and-play solar PV with UL certified microinverters include greater PV system performance, faster uptake and higher PV penetration levels, improved prosumer economics, and more environmentally responsible electric generation.

Keywords: AC disconnect switch; distributed generation; net metering; net metering application; photovoltaic; plug and play solar; prosumer; renewable energy; solar energy;

PACS: 88.05.-b, 88.05.Lg, 88.40.-j, 8.40.fc, 88.40.H-, 88.40.hm, 88.40.M-, 88.40.mp, 88.80.-q, 88.20.tf

Abbreviations

The following abbreviations are used in this manuscript:
AC: alternating current
AHJ: authorities having jurisdiction
BOS: balance of system
C_S: average solar PV system cost ($)
DC: direct current
D_f: derate factor rate

DR: distributed resources
E_l: average electricity load demand (kWh)
EPS: electric power system
FIT: feed-in-tariff
GFDI : Ground-Fault Detection and Interruption
IBC: International Building Code
IEEE: Institute of Electrical and Electronics Engineers
I_{cont}: continuous current
I_{max}: maximum current
LCOE: levelized cost of electricity
M_S: average solar PV installation cost per Watt ($/W)
NEC: National Electric Code
OCPD: over current protective devices
P_{ave}: average installed PV Power (kW)
PD: Project Developer
POA: Parallel Operating Agreement
P_S: solar PV power (kW)
PV: photovoltaic
RET: renewable energy technology
ROI: return on investment
RPS: renewable portfolio standards
S_H: solar irradiance
UEDS: utility external disconnect switch
UL: Underwriters Laboratories

3.1 Introduction

Technical improvements [1-4] and scaling [1, 5] have resulted in a significant reduction in solar photovoltaic (PV) module costs, which has catalyzed PV industry growth both globally as well as in U.S [6]. As the demand for PV installations continues to increase, the costs continue to decline further [7-15]. This has enabled the solar levelized cost of electricity (LCOE) [16] to sometimes surpass grid parity (equal to or drop below the price of grid supplied electricity) [17] and now small-distributed on-grid PV systems are competitive with conventional utility electrical rates in many instances [18]. This has led to a surge of distributed generation, with PV installations up by 30% in 2014 over 2013, reaching 6.2GW of cumulative solar photovoltaic electric capacity [19]. According to SEIA, by the second quarter of 2015, 22.7GW of total installed solar electric capacity was operating in U.S., which is enough to power 4.6 million American homes [20]. There is a popular support for solar energy in the U.S. [21-23]. Globally, such popular support often leads to political support [24] and a mix of pro-solar policies [25-28] such as net metering [29-31], renewable portfolio standards (RPS) [29,32-33], strong statewide interconnection policy [29,34], and financing policy [29,35-36]. This has made solar energy generation the fastest growing energy source over the past decades, having more than tripled globally in the past 5 years [37-39]. In addition, many of the world's governments are carrying out steps to provide policy-supported financial incentives programs such as feed-in-tariffs (FITs) [40]. A FIT is set to be a financially rewarding rate the utility pays for electricity being generated by the local renewable energy generators. Many countries who have adopted this mechanism have experienced the largest renewable energy technology (RET) deployments [29,40-46]. However, even with the popularity and steps taken by various state and federal governments to support solar PV, it is contributing only 0.54% of the electricity generation in the U.S. by April of 2015 [47-48]. This is far less than economics would presume.

PV can earn individuals a significant return on investment (ROI) throughout the U.S. even in sub-optimal locations such as the relatively snowy [49] Houghton, MI [50-51]. Yet, why has the growth in solar failed to reach market saturation, a situation that would be characterized by most southern facing rooftops generating solar energy? This puzzle can in part be explained by simple lack of capital and the requisite financing amongst the general population [41,52-56]. Installing a solar PV system is expensive for an average homeowner [57] and many simply lack access to credit [41,52]. Although the median net worth of U.S. households was $81,400 [58], the majority of the wealth (89%) has been aggregated in the top 20% (of which the top 1% holds 35% of the wealth [59]), indicating that the majority of Americans may not have the capital to invest in full PV power for their households. This can be quantified with the following assumptions. If the average family needs approximately 10,000 kWhrs per year [60], and the average solar hours per day in U.S. is approximately 4.5hrs [61], the installed PV power (Pave) is about 8.2kW for the average family determined by:

$$P_{ave} = \frac{E_l}{365 * S_H * D_f} \tag{1}$$

where E_l is the annual load demand (kW h), S_H is the peak average solar hours per day, and D_f is the derate factor, which is considered here to be 75% [62]. The median installed cost for a (P_S) ≤10kW PV system in 2014 was at (M_S) $3.83/W [63] and so the average U.S. family would need to invest approximately (C_S) $32,000 for their PV array. This is a significant fraction of the average American's wealth that includes home ownership, but it also represents significantly more than the average wealth for African Americans (at $11,000) and Hispanics (at $13,700) [64], which make up 13.2% and 17.4% of the U.S. population, respectively [65]. In addition 35% of the U.S. population rents rather than owns their houses [66] and even those that do own their homes are likely to move approximately 11.4 times on an average in their life [67]. Thus, the average American family cannot wait for a long payback at a given location and many cannot simply afford to invest in a PV systems to offset all of their electrical consumption despite the fact that it would result in a positive economic return.

One method to overcome this challenge is to allow plug-and-play solar, which is defined here as a fully inclusive, commercial, off-the-shelf PV system, which is able to be installed by an average prosumer. A prosumer can buy and install the system (one PV module and microinverter or a pre-packaged alternating current (AC) module, mount it on a low-cost temporary fixture using commonly available tools and without the need for training or special skills, ground it and then plug it into a conventional house electric outlet. The system can be installed and commissioned without the need for significant permitting, inspection and interconnection processes. By removing these sources of "soft" costs, residential solar PV systems will be more cost competitive and attractive to consumers, accelerating U.S. solar adoption and production [68-69]. In some countries like the United Kingdom [70-71], Netherlands, Switzerland and Czech Republic [72] this is already permitted. Yet the U.S. regulations have lagged behind creating, substantially higher soft costs than more mature markets, such as those in Germany [73-76].

In order to assist U.S. policy makers in overcoming the regulatory obstructions to greater PV penetration, this article first reviews the relevant codes and standards from the U.S. National Electric Code (NEC), American local jurisdictions and U.S. utilities for PV with a specific focus on plug-and-play solar. Next, commercially available microinverters and AC modules are reviewed for their technical and safety compliance to these standards. The technical requirements are then compared to utility regulatory requirements using case studies in Michigan. A streamlined application is generated and methods of implementing it are provided to reduce consumer and utility workload and the concomitant soft costs. A sensitivity analysis is performed based on tolerable kW capacity of potential future regulations on the U.S. market. The results are discussed and recommendations are made for national level policy normalization.

3.2 A Review of PV Codes, Standards and Utility Grid-Interconnection Application

3.2.1. U.S. National Electrical Codes

The solar industries growth and success requires PV system safety and thus PV systems are to be designed and installed to meet the standards set forth by NEC [77] and standards stated in the National Fire Protection Association-70 [78]. Article 690 'Solar Photovoltaic Systems' and Article 750 'Interconnected Electric Power Production Sources', are of particular interest to PV system designers and installers [78]. The following are relevant technical details to the NEC 2014 code for plug-and-play PV systems [77-81] and will be reviewed in detail here: 1) ground fault protection, 2) overcurrent protection, 3) arc fault circuit protection, 4) disconnecting means, 5) disconnecting type, and 6) grounding.

3.2.1.1. Section 690.5: Ground fault protection

According to NEC 2014 grounded DC PV arrays must be provided with DC ground-fault protection meeting the requirements of 690.5(A) and (C) to reduce fire hazards

(A) Ground-Fault Detection and Interruption (GFDI) The ground fault protection must:
- (1) Be capable of detecting a ground fault in the PV array DC current-carrying conductors and components, including any intentionally grounded conductors,
- (2) Interrupt the flow of fault current,
- (3) Provide an indication of the fault, and,
- (4) Be listed for providing PV ground-fault protection.

(C) A warning label that is not handwritten and is of sufficient durability to withstand the environment involved, must be permanently affixed on the utility interactive inverter at a visible location stating the following [77,79]:

WARNING: ELECTRIC SHOCK HAZARD-IF A GROUND FAULT IS INDICATED,

NORMALLY GROUNDED CONDUCTOR MUST BE UNGROUNDED OR ENERGIZED.

3.2.1.2. Section 690.9: Overcurrent protection

According to NEC 2014 the overcurrent risk in PV systems is associated with the parallel-connected circuit as the PV modules and utility-interactive inverters are inherently current limited. To clarify, on the DC side of the system, there is a risk from PV source or output circuits that are connected in parallel. However, in a plug-and-play PV system each individual module is directly connected to an inverter so this is not an issue. On the AC side of the system, the risk comes from the utility grid or the inverter output circuits in parallel. Thus, the AC circuit must be protected at the source of significant higher current. In this case no combiner box is used and thus no protection of it is necessary.

3.2.1.3. Section 690.11: Arc Fault Circuit Protection (Direct Current)

PV arc faults in ground-mounted PV arrays can result in grass and brush fires. Such fires can result in deaths and significant property damage, which can be prevented with PV arc-fault protection. An arc-fault protective device must be listed for use in DC PV systems. The applicable product safety standard is UL 1699B, "Photovoltaic (PV) DC Arc-Fault Circuit Protection".

3.2.1.4. Section 690.12: Rapid Shutdown of PC Systems on Buildings

The NEC 2014 code requires that conductors associated with a PV system, whether AC or DC, be able to be de-energized on demand, so that any portion of the conductors that remain energized do not extend more than 10 feet from the PV array or more than 5 feet within a building. The rapid shutdown initiation methods shall be labeled in accordance with 690.56(B). Equipment that performs rapid shutdown must be listed and identified. It should be noted that the code does not specify where the control point for the rapid shutdown is to be located.

3.2.1.5. Section 690.14: Disconnecting means

The NEC 2014 code also has a separate section (690.14) directly relevant to microinverters, which is the most relevant for plug-and-play PV and includes all the prior requirements [82]. Specifically, PV disconnecting means shall comply with 690.14(A) through (D).

(A) The disconnecting means shall not be required to be suitable as service equipment and shall comply with 690.17.

(B) Equipment such as photovoltaic source circuit isolating switches, overcurrent devices, and blocking diodes shall be permitted on the photovoltaic side of the photovoltaic disconnecting means.

(C) Requirements for Disconnecting Means. Means shall be provided to disconnect all conductors in a building or other structure from the photovoltaic system conductors.

(1) Location. The photovoltaic disconnecting means shall be installed at a readily accessible location either on the outside of a building or structure or inside nearest the

point of entrance of the system conductors. Exception: Installations that comply with 690.31(E) shall be permitted to have the disconnecting means located remote from the point of entry of the system conductors.

(D) Utility-Interactive Inverters Mounted in Not-Readily-Accessible Locations. Utility-interactive inverters shall be permitted to be mounted on roofs or other exterior areas that are not readily accessible. These installations shall comply with (1) through (4):

(1) A direct-current photovoltaic disconnecting means shall be mounted within sight of or in the inverter.

(2) An alternating-current disconnecting means shall be mounted within sight of or in the inverter

(3) The alternating-current output conductors from the inverter and an additional alternating-current disconnecting means for the inverter shall comply with 690.14(C)(1).

(4) A plaque shall be installed in accordance with 705.10.

3.2.1.6. Section 690.17: Disconnect Type

Section 690.17 gives the details of allowable types of manually operable disconnecting means for ungrounded PV conductors. The list of devices allowed when specifically *marked* for use in PV systems includes industrial control switches (the subject of UL 98B), molded-case circuit breakers and switches (the subject of UL 489B), and enclosed and open-type switches (the subject of UL 508I). The disconnecting means for ungrounded conductors shall consist of a manually operable switch(es) or circuit breaker(s) complying with all of the following requirements.

(1) Located where readily accessible

(2) Externally operable without exposing the operator to contact with live parts

(3) Plainly indicating whether in the open or closed position

(4) Having an interrupting rating sufficient for the nominal circuit voltage and the current that is available at the line terminals of the equipment.

There is an exception listed to allow a connector as a disconnecting means if it meets the requirements of 690.33, but a standard plug does not do so. This means prosumers would need to plug the inverter into an extra switch or have it packaged in the plug-and-play product

3.2.1.7. NEC 690.8: PV Circuit Sizing and Current Calculation

This section deals with PV circuit sizing and current calculations, and defines how to calculate four maximum circuit current values.

(1) PV source circuit: **These** are conductors between the modules, and from modules to a common point of connection, typically a junction box or combiner box

(2) PV output circuit: These are the circuit conductors after a combiner box to the inverter or charge controller.

(3)Inverter input circuit: These are the conductors between the inverter's integrated DC disconnect and the inverter's DC input connection.

(4)Inverter output circuit: These are the AC conductors from the inverter to the ultimate connection to the AC distribution system for either stand-alone or utility-interactive systems.

According to NEC 690.8 (B) over current protective devices (OCPDs) shall be sized to carry not less than 125% of the maximum current as calculated in 690.8(A). To determine the minimum OCPD, multiply the maximum current (I_{max}) for a given conductor run by 1.25. The resulting continuous current (I_{cont}) is the minimum OCPD required to protect the conductor in the circuit and the minimum rating of all terminals used to make the wiring connections. Plug-and-play PV is limited by the amperage of the branch circuit supplying the receptacle that the prosumer is plugging into. To be safe the I_{max} value can be assumed to be 15 amps. Thus if the over current protective device shall be the inverter continuous output rating multiplied by 125%. So the plug-and-play system is limited to 1,440 Watts (12A X 120V).

3.2.1.8. NEC 690.46: PV Array Equipment Grounding Conductors

NEC 690.46 requires that equipment grounding conductors for PV modules smaller than 6 AWG shall comply with 250.120(C), which requires them to be protected from physical damage [83]. This is particularly important if conductors are a potential a trip hazard. This may include the back of an array, even on rooftops, according to some authorities having jurisdiction (AHJs) [84]. AHJs should consider the circumstances for a plug-and-play PV system carefully to ensure that such rulings are appropriate for the context. In some commercialized plug and-play solar systems the DC voltage generated is around 50V and the microinverters used are frame grounded via a pre-fabricated 6 AWG ground wire [85]. Plug and play solar units are generally provided with ground lugs, which can be used to connect the system to ground using a 6AWG EGC. Suppliers should also considering providing the grounding wire in kit forms. Thus, use of frame grounding ensures ground safety.

3.2.2 State and Community Codes

Along with the NEC codes and standards each state and community has its own sets of codes and regulations to add a small renewable energy system homes and small business [86]. To illustrate the challenges with these local codes a case study is presented for Michigan.

3.2.2.1. Case Study: Michigan Electric Utility-Interconnection Procedure and Requirements

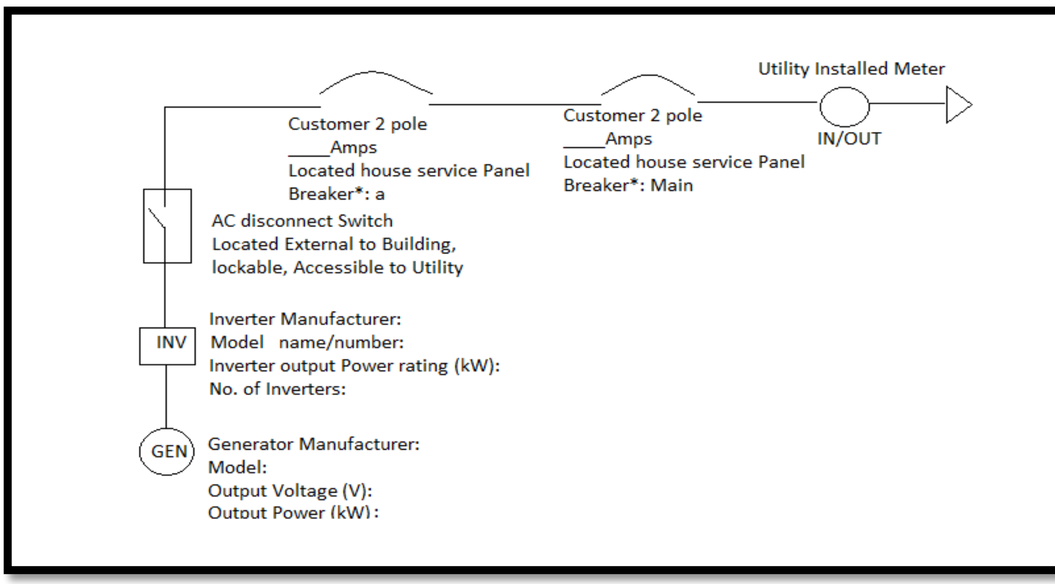
The data is provided by references [87-88]: An inverter based project less than 20kW falls under category 1, which would be the case for all plug-and-play PV systems. Thus, the equipment used must be certified by a nationally recognized testing laboratory to IEEE1547.1 testing standards.

1. Technical Requirements:

(a) Major Component design requirements: The data required is summarized in Figure 9 for all major equipment and relaying proposed by the Project Developer (PD) must be submitted as part of the initial application for review and approval by the Utility. The Utility may request additional data be submitted as necessary during the study phase to clarify the operation of the Project.

(b) Data requirements: The data required by the Utility to evaluate the proposed interconnection is documented on one-line diagram as shown in Figure 9 site plan, one-line diagrams, and interconnection protection system details of the Project are required. The generator manufacturer supplied data package should also be supplied.

Figure 9. Technical requirements and sample line diagram



(c) Isolation Device:
This device can be circuit breaker, circuit switcher, pole top switch, load-break disconnect, etc., depending on the electrical system configuration. After review this may not be required by the utility. This device should be placed at point of common coupling.
(d) Interconnection Lines: Any new interconnection lines required to connect the system or project to the grid will be undertaken by the Utility.

2. Relaying Design Requirements:
The interconnection, for simplicity for all Projects in this capacity rating range, the interconnection relaying system must be certified by a nationally recognized testing laboratory to meet IEEE standard 1547.
(a) Auto reclosing: The Utility employs automatic multiple-shot reclosing on most of the Utility's circuit breakers and circuit reclosers to increase the reliability of service

to its customers. Automatic single-phase overhead reclosers are regularly installed on distribution circuits to isolate faulted segments of these circuits.
(b) Single Phase Sectionalizer: The Utility also installs single-phase fuses and/or reclosers on its distribution circuits to increase the reliability of service to its customers. Three-phase generator installations may require replacement of fuses and/or single-phase reclosers with three-phase circuit breakers or circuit reclosers.

3. Inverter Project Requirements:

(a) Inverter Projects: No isolation transformer is required between the generator and the secondary distribution connection.
(b) Maintenance and Testing: The Utility reserves the right to test the relaying and control equipment that involves protection of the Utility's electric system whenever the Utility determines a reasonable need for such testing exists.

4. Miscellaneous Operation Requirements:

(a) Operating in Parallel: Voltage fluctuation at the PCC during synchronizing is limited by IEEE standard 1547. These requirements are directly concerned with the actual operation of the Project with the Utility:

(i) The Project may not commence parallel operation until approval has been given by the Utility. The completed installation is subject to inspection by the Utility prior to approval. Preceding this inspection, all contractual agreements must be executed by the PD.

(ii) The Project must be designed to prevent the Project from energizing into a de-energized Utility line. The Project's circuit breaker or contractor must be blocked from closing in on a de-energized circuit.

(iii) The Project shall discontinue parallel operation with a particular service and perform necessary switching when requested by the Utility.

5. Revenue Metering Requirements:

The Billing equipment will be owned, operated and maintained by the utility.
(a) Non-Flow-back Projects: A Utility meter will be installed that only records energy deliveries to the Project.
(b) Flow-back Projects: Special billing metering will be required. The PD shall provide the Utility access to the premises at all times to install, turn on, disconnect, inspect, test, read, repair, or remove the metering equipment. The metering installations shall be constructed in accordance with the practices, which normally apply to the construction of metering installations for residential, commercial, or industrial customers.

6. The Application process and time consumed for the activation [87-88].

The flow chart of this application process is provided shown in Figure 10 and described below. Interconnection Application:

1. The PD must first submit an Interconnection Application to the Utility: A completed Interconnection Application consists of: (1) an application with all

relevant data fields populated, Site Plan and One-line diagram provided, and (2) a $75 filing fee. The Utility will notify the applicant within 10 working days after the application has been received. If any portion of the Interconnection Application, data submitted (a site plan and the one-line diagrams), or filing fee is incomplete and/or missing; Utility will return the application, data, and filing fee to the Applicant with explanations.

2. Engineering Review and Distribution study:
   Once the Utility has accepted an Interconnection Application, the Utility must determine whether an Engineering Review (Additional Study) is required (e.g. Inverter Based Generators with UL certification 1741 Scope 1.1A meeting IEEE 1547-2003 and 1547.1-2005 usually do not require a review). After the Engineering review is complete, the Utility will determine if a distribution study is required (e.g. Inverter Based Generators with UL certification 1741 Scope 1.1A meeting IEEE 1547-2003 and 1547.1-2005 usually do not require a study). This process take around 10 business days and the utility will notify the applicant if any further additional studies is needed or not.

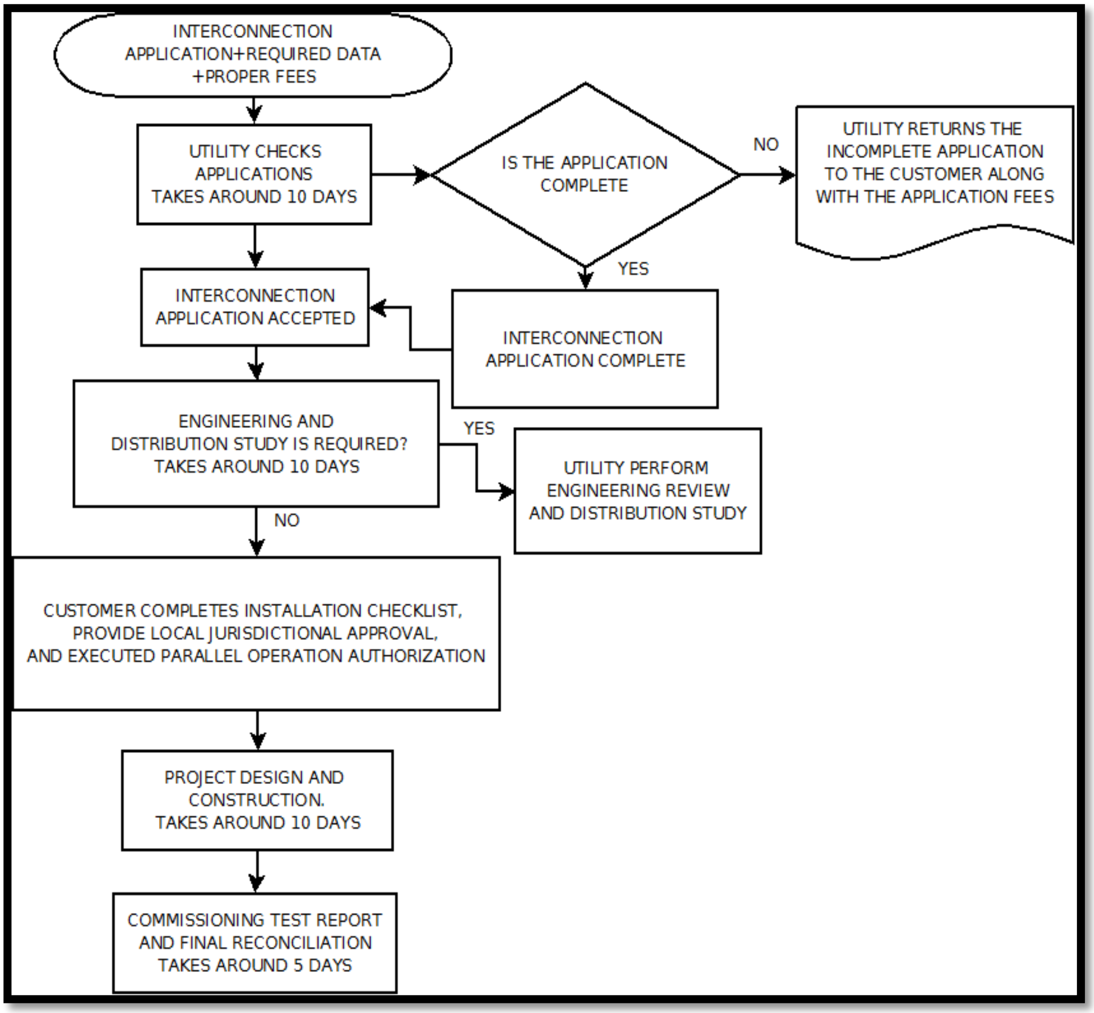


Figure 10. Flow chart of the Interconnection Application process.

3. Customer Install and Parallel Operating Agreement (POA):
The applicant shall notify the Utility when an installation and any required local code inspection and approval is complete.

4. Project Design & Construction:
Upon receipt of the local code inspection approval and POA executed by the applicant, utility will schedule the meter install, testing, and inspection. Utility shall notify the applicant of its intent to visit the site, inspect the project, witness or perform the commissioning tests, or of its intent to waive inspection within 10 working days after notification that the installation and local code inspections have passed.

5. Commissioning Test Report & Final Reconciliation:
Within 5 business days of receiving a completed commissioning test report, the Utility will notify Applicant of its approval or disapproval of the interconnection. If approved,

the Utility will provide a written statement of final approval, cost reconciliation and a Generator Interconnection & Operating Agreement. Table 7 gives the probable business days needed to install the project using current rules, which amount to more than a month at minimum.

Table 7. Application Time-Business days [87-88]

Steps	Time(Business days)
Application Complete	10
Application Review	10
Engineering Review and Distribution Study	If needed
Distribution Upgrades	If needed
Project Design and Constructions	10
Commissioning Test Report and Final Reconciliation	5
TOTAL	35

3.3 Results

3.3.1 Microinverters and AC module Compliance

A microinverter is a device that is used in a solar PV system to convert DC generated by a solar module to AC using power converter topologies [89-91]. In a PV system using microinverters, each PV module is coupled with an individual microinverter, which enhances the output power efficiency of the solar PV system [91], while also enabling solar PV to be used as plug-and-play device [92]. The output from each single PV module or several microinverters can be combined together and fed into electric grid [91]. Interconnection equipment (in this case is the microinverter) that connects distributed resources (DR) (in this case is a solar PV module) to an electric power system (EPS) must meet the requirements specified in IEEE Standard 1547.1 [93-95]. Standardized test procedures are necessary to establish and verify compliance with those requirements [94]. These test procedures must provide both repeatable results, independent of test location, and flexibility to accommodate a variety of DRs (in this case PV module technologies) [94]. In the event of electric grid failure it is required that any independent power-producing inverters attached to the grid turn off in a short period of time (2 seconds) [95-96] to prevent the inverters from continuing to feed power into small sections of the grid, known as “islands.” Powered islands present a risk to workers who may expect the area to be unpowered, and they may also damage grid-tied equipment. Thus UL1741 safety testing of the inverters including anti-islanding requirements has been standardized and is harmonized by IEEE1547 [95-96].

Table 8. Microinverters available on the U.S. market and their safety standard and grid connection standard compliance [97-103].

Company [Source]	**Product**	**Safety Standard Compliance**	**Grid Connection Compliance**
Apparent	MGi-220 Grid-connected Micro-inverter	UL 1741 : 1999 R11.05 CSA C22.2.107.1-01	IEEE 1547
APS Microinveters	YC500A Micro-inverter	UL 1741 , CSA C22.2, No. 107.1-01,NEC2014 690.12	IEEE 1547
APS Microinveters	YC1000-3A Microinverter	UL1741xCSA C22.2 No.107.1-01	IEEE 1547
Chilicon Power	CP-250 Micro-inverter	UL1741. CSA C22.2 NO. 107.1	IEEE 1547
Solar Panel Plus	MI-250-240A Micro-inverter	UL 1741 CSA C22.2 No. 107.1	IEEE 5047
Enphase	M215 Micro-inverter	UL1741. CAN/CSA-C22.2 NO. 0-M91, 0.4-04, and 107.1-01	IEEE 1547
Enphase	M250 Micro-inverter	UL1741. CAN/CSA-C22.2 NO. 0-M91, 0.4-04, and 107.1-01	IEEE 1547
Enphase	C250 Micro-inverter	UL1741. CAN/CSA-C22.2 NO. 0-M91, 0.4-04, and 107.1-01	IEEE 1547
Enphase	S230 Micro-inverter	UL1741. CAN/CSA-C22.2 NO. 0-M91, 0.4-04, and 107.1-01	IEEE 1547
Enphase	S280 Micro-inveter	UL1741. CAN/CSA-C22.2 NO. 0-M91, 0.4-04, and 107.1-01	IEEE 1547
Siemens	SMIINV215R60XX Micro-inverter	UL1741, CAN/CSA-C22.2 NO. 0-M91, 0.4-04, and 107.1-01	IEEE 1547

An AC module is a photovoltaic module which has a small AC inverter mounted on the back that produces AC power without any external DC [104]. Table 9 summarizes the safety and module compliance of many of the AC module available in U.S. market.

Table 9. AC modules available in U.S. market and their safety and module compliance [105-107].

Company	**Product**	**Micro-inverter Compliance**	**Module Compliance**
Phono Solar	PS250P-AC	UL1741/IEEE1547, FCC Part 15 Class B, CAN/CSA-C22.2 NO. 0-M91, 0.4-04, and 107.1-01	UL1703
LG	MonoXAcE LG-300A1C-B3	UL1741, IEEE 1547, FCC Part 15 Class B, CAN/CSA-C22.2 NO. 107.1-01	UL1703
ET AC Module	ET-P660245WBAC/ ET-P660245BBAC/ ET-P660250WBAC/ ET-P660250BBAC	UL1741/CSA 107.1 FCC Part 15 Class B	UL1703

As can be seen by Tables 8 and 9, all of the commercial systems from the survey of available plug-and-play solutions in the U.S as of Nov. 2015 (both PV + microinverter and AC modules) are compliant with safety, grid connection, inverter and module requirements.

3.3.2 External AC Disconnect Switch: a Redundant Device

The utility-accessible AC external disconnect switch for distributed generators, including PV systems, is a hardware feature that allows a utility's employees to manually disconnect a customer-owned generator from the electricity grid. The main purpose of installing such an AC disconnect switch is to keep workers safe when they make repairs to the electric grid [108]. Thus, a utility external disconnect switch (UEDS) is a disconnect device that the utility uses to isolate a PV system to prevent it from accidentally sending power to the utility grid during routine or emergency maintenance [109 Sheehan, 2008]. For decades there has been a debate about UEDS among utilities, state public utility commissions and PV system installers as many utilities requires the AC external disconnect switch installed within the sight of the revenue meter [108]. Underwriters Laboratories (UL) Standard 1741 covers inverters, which convert DC power to alternating-current (AC) power for use by the customer or utility [108]. The Institute of Electrical and Electronics Engineers (IEEE) Standard 1547 provides interconnection requirements for PV systems at the point of common coupling and is referenced in the utility connection requirements of UL 1741 [108]. IEEE 1547, UL 1741, and the NEC do not require the use of customer-owned external AC disconnect switch for PV systems [108]. According to IEEE 1547 External AC disconnect switch is not a universal requirement, but the utility may desire it for its own use [108]. All the above mentioned codes and standards require that PV systems automatically disconnect from the grid in the event of an electric outage. However, many utilities require a redundant utility-accessible external AC disconnect switch for grid-related problem. Moreover, It is important to note that all grid interactive inverters installed in the U. S. have been tested to the UL 1741 and IEEE 1547 standards that include passing the Unintentional Islanding Test, which verifies that the inverter does not operate independent of the utility. This evaluation also tests that these inverters cease to export power when the utility is de-energized [109]. The NEC requires all buildings to have switches or breakers capable of disconnecting them from all sources of power. The switches must be manually operable without exposing the operator to contact with live parts and must be readily accessible. NEC 690.13 states that Means shall be provided to disconnect all current carrying conductors of a photovoltaic power source from all other conductors in a building or other structure [109 Sheehan, 2008]. Moreover, the NEC does not require that these disconnects be lockable or that they provide a visible-break separation [109]. There are three core issues encountered if an external AC disconnect switch is mandated:

1. Operational issues [108-109]:

   Firstly, as the number of PV systems increases, the work and time needed to troubleshoot an outage on a distribution circuit with PV systems (and external AC disconnect switches) will increase. Second, if utility line workers are required to use a group of external AC disconnect switch on a line section, they must be incorporated into switching orders. Third, the geographic information system departments at utilities will need to maintain accurate and timely maps to help dispatchers and line workers locate the external AC disconnect switch during emergencies. And fourth, as the time needed to turn off all of these redundant switches causes line workers to ignore them, utilities may face liability in the event of injury or equipment damage.

2. Cost issues [109-110]:

Many of the commercially available small generator systems that use inverters cost from $4-8,000/kW installed. Several PV installers have estimated the typical incremental cost of installing an external AC disconnect switch to be in the range of $200 to $400. This represents only five to ten percent of the installed cost of a one kilowatt system although these costs can be much higher. For example, the estimated cost by Progress Energy (now Duke Energy) of the external AC disconnect switch is to be around $1200 per customer [111]. Thus, for plug-and-play PV systems the UEDS may actually cost more than the PV system itself.

3. Legal and Jurisdiction issues [109]:
The utility requires the line worker to operate the UEDS even though it is located outside the utility's jurisdiction. In other words the external AC disconnect switch is located on the customer side and its the property of the customer.

A number of states have allowed utilities to require external disconnect switches, but specified that the utility must reimburse applicants for the cost of the switch. Several states have specified that an external disconnect switch may not be required for smaller inverter-based generating facilities [112]. Among the 35 U.S. States with specific rules, 18 states requires the external AC disconnect switch, 8 states have waived the requirement for small systems (that meet specific technical requirements), and 9 states have left the decision to utilities. PG&E (Pacific Gas and Electric) has the most interconnected PV systems in U.S. and SMUD (Sacramento Municipal Utility District) is one of the most fast pacing adopters of PV technologies, both of which have changed their policy for the utility grid connected PV system, and eliminated the installation of external AC disconnect switch [113-114]. This policy change was based on the expected cost and time saving for utilities as well as the customers [108-109]. This is becoming more common, as for example, another utility that has adopted the same policy is SDGE (San Diego Gas and Electric) [115]. Thus, the utility accessed AC disconnect switch issue is addressed by the IEEE 1547 and UL 1741 and requirements for another switch are thus redundant and unnecessary. By eliminating the requirement locally, administrative burden and the cost associated with AC disconnect switch will be reduced and utility interactive PV systems with effective and UL 1741 listed inverters will increase. This will assist in increasing the PV installation rates to meet targets at the state level or national level.

3.3.3 Streamlining the U.S. Grid-Tied PV Application Process:

As can be seen in Section 2, the current PV application process is unduly time consuming and costly for a plug-and-play PV system. The application form to be submitted to the utility for plug-and-play PV grid interconnection should be well organized and should be presented in a logical manner. The form should shorten the time of the process so that the time required to process the application and giving the permit for the same is minimized.

3.3.3.1. Streamlined Interconnection Application

The form should include customer information along with the electric service account number and meter number. Then depending on whether the system being installed by the customer is a Section A-plug and play solar kit or Section B-discrete equipment's integration, a customer can fill in the required information of that desired section. Section A includes the plug and play module kit number, testing standards criteria, number of modules being installed and the AC operating voltage. Section B includes the inverter information such as power-rating, quantity, AC output voltage; it also includes solar panel information such as AC output rating, number of solar panels and few testing standards for inverter and the solar panel. A streamlined interconnection application is shown below in Table 10. It is comprised of three parts. The first is for customer information. Then the user chooses to fill out either section A for a plug and play kit or a section B or the second for PV and microinverters a la carte.

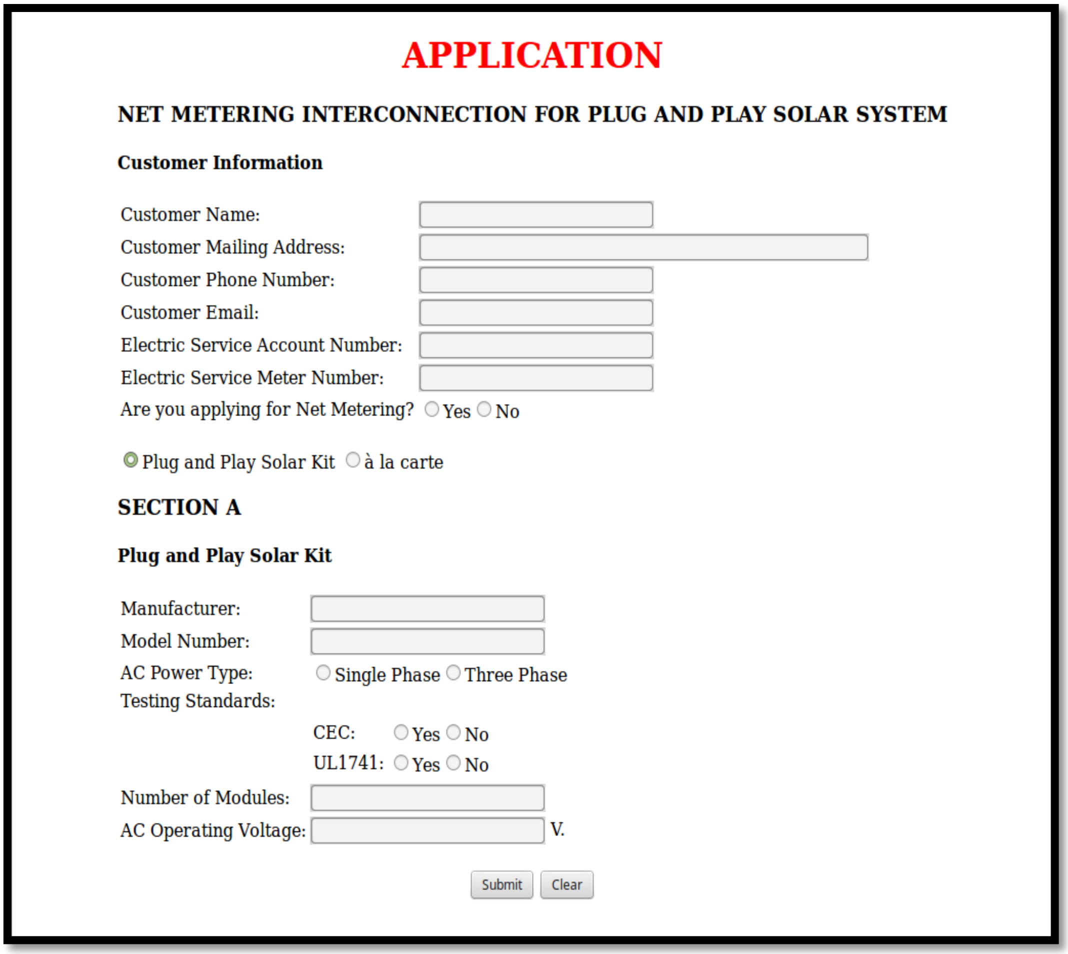
Table 10. Net metering interconnection application for plug and play solar system

CUSTOMER INFORMATION
1. CUSTOMER NAME: 2. CUSTOMER MAILING ADDRESS: 3. CUSTOMER PHONE NUMBER: 4. CUSTOMER EMAIL: 5. ELECTRIC SERVICE ACCOUNT NUMBER: 6. ELECTRIC SERVICE METER NUMBER: 7. ARE YOU APPLYING FOR NET METERING: YES NO
SYSTEM INFORMATION (IF PLUG AND PLAY SOLAR KIT REFER SECTION A IF DISCRETE EQUIPEMENTS REFER SECTION B)

SECTION A **PLUG AND PLAY SOLAR KIT** 1. MANUFACTURER: 2. MODEL NUMBER: 3. AC POWER TYPE: SINGLE PHASE [Y/N] THREE PHASE[Y/N] 4. TESTING STANDARDS: CEC YES NO UL 1741 YES NO 5. NUMBER OF MODULES: 6. AC OPERATING VOLTAGE:_______V
SECTION B **INVERTER AND SOLAR PANEL INFORMATIION** 1. INVERTER MANUFACTURER: 2. INVERTER MODULE NUMBER: 3. INVERTER POWER RATING (kW/unit): 4. NUMBER OF INVERTER UNITS: 5. AC OUTPUT VOLATGE:_____V 6. SOLAR PANEL AC OUTPUT RATING:____kW/unit. 7. NUNBER OF SOLAR PV PANELS: 8. AC POWER TYPE: SINGLE PHASE [Y/N] THREE PHASE[Y/N] 9. UL1741 STANDARD TESTING: YES NO 10. UL1703 STANDARD TESTING: YES NO IF YES THEN CERTIFIED TESTING RECORD NUMBER:

3.3.3.2 Net Metering Interconnection for Plug and Play Solar System Application

Webpage



APPLICATION

NET METERING INTERCONNECTION FOR PLUG AND PLAY SOLAR SYSTEM

Customer Information

Customer Name:
Customer Mailing Address:
Customer Phone Number:
Customer Email:
Electric Service Account Number:
Electric Service Meter Number:
Are you applying for Net Metering? Yes No

Plug and Play Solar Kit à la carte

SECTION A

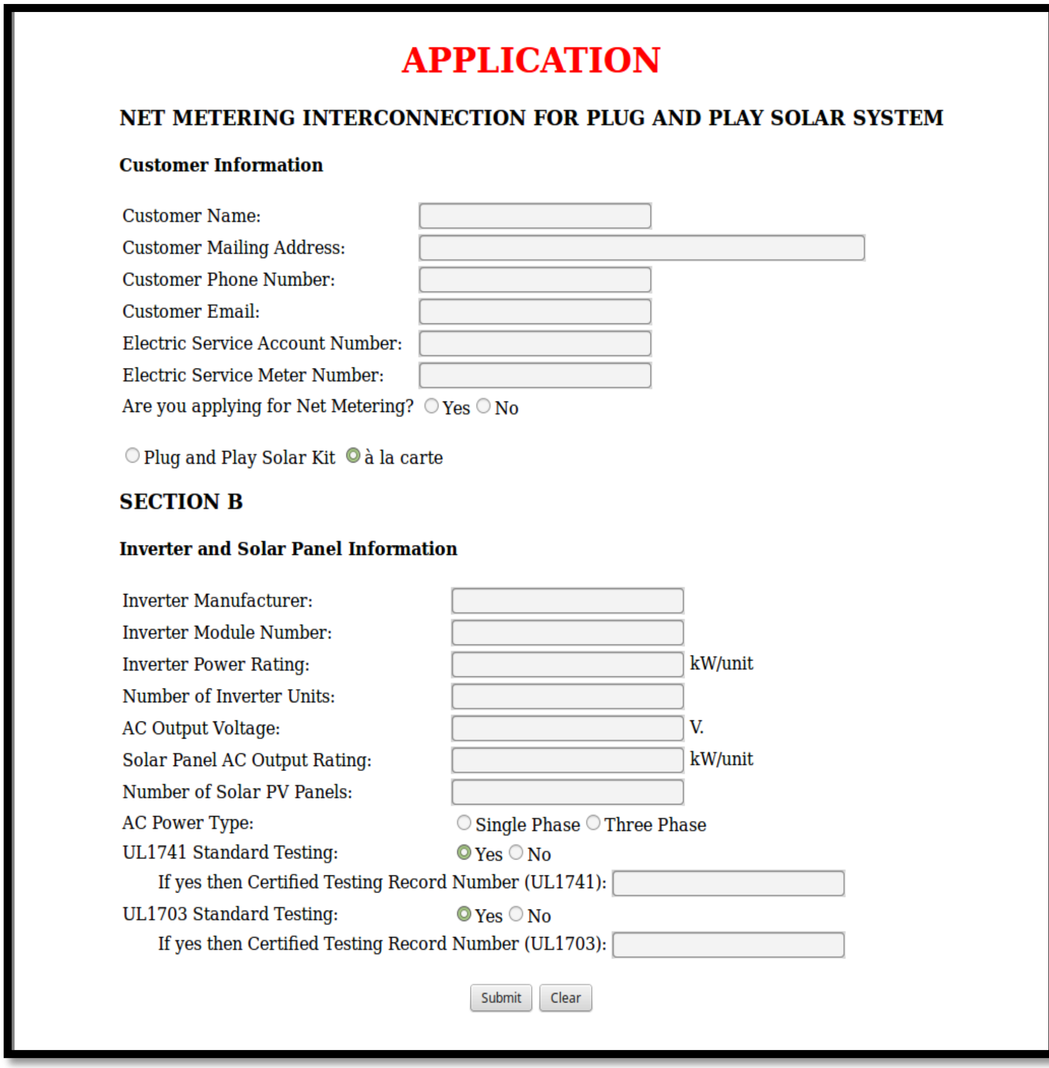
Plug and Play Solar Kit

Manufacturer:
Model Number:
AC Power Type: Single Phase Three Phase
Testing Standards:
CEC: Yes No
UL1741: Yes No
Number of Modules:
AC Operating Voltage: V.

Submit Clear

Figure 11. Streamlined net metering application for plug-and-play solar kit.

In order to streamline the process for the utilities a free and open source web application for 'Net metering Interconnection for Plug and Play Solar System Application' was created based on the required information for the application from in Table 10 [116]. Text boxes and radio buttons were used to receive data input by a user (utility customer). The web page of the system is shown in Figures 11 and 12 for a plug-and-play PV system and PV and microinverters a la carte systems, respectively.



APPLICATION

NET METERING INTERCONNECTION FOR PLUG AND PLAY SOLAR SYSTEM

Customer Information

Customer Name:
Customer Mailing Address:
Customer Phone Number:
Customer Email:
Electric Service Account Number:
Electric Service Meter Number:
Are you applying for Net Metering? ○ Yes ○ No

○ Plug and Play Solar Kit ◉ à la carte

SECTION B

Inverter and Solar Panel Information

Inverter Manufacturer:
Inverter Module Number:
Inverter Power Rating: kW/unit
Number of Inverter Units:
AC Output Voltage: V.
Solar Panel AC Output Rating: kW/unit
Number of Solar PV Panels:
AC Power Type: ○ Single Phase ○ Three Phase
UL1741 Standard Testing: ◉ Yes ○ No
If yes then Certified Testing Record Number (UL1741):
UL1703 Standard Testing: ◉ Yes ○ No
If yes then Certified Testing Record Number (UL1703):

Submit Clear

Figure 12. Streamlined net metering application for PV and microinverters chosen a la carte

In order to host the web application, a server machine with a web server (Apache HTTP server), PHP interpreter, and MySQL database installed is needed. Then the web application (application.php) and the SQL code (nmifpapss.sql) can be download from https://github.com/mtu-most/Net-Meter-Solar-App. On the server machine, utilities may use phpmyadmin or other MySQL clients of their choice to create a database and tables by running the SQL file. After that the 'appplication.php' should be copied to the public folder of the Apache web server, usually at '/var/www/html' on Linux machines. The default user name and password for MySQL server are 'root' and 'password!', respectively. If the different user name and password were set up, then utilities can change them in the 'application.php' by finding the line:

$db_conn = new mysqli("localhost", "root", "password!", "nmifpapss"); and changing it to their new user name and password. On the server machine, the application page can be accessed from the url: 'localhost/application.php'. On other machines, the IP address or the domain name of the server is needed to access the page through them, for example, '192.168.2.7/application.php' or 'mydomain.com/application.php'. On the page, users can fill in all the data according to the form then click the submit button. The page will notify users if the submission has succeed and the data will be saved to table named 'application' in the database named 'nmifpapss', which can then be used by utilities for planning and service purposes.

3.4 Barriers and Solutions to Plug-and-play PV

In summary, according to workshop held by DOE the Plug and Play Solar technology has several barriers, which need to be overcome for widespread use [68; 116] including structural permitting and inspection, electrical permitting and inspection and utility interconnection and reliability.

1. Structural Permitting and Inspection:

   Based on documents like the International Building Code (IBC), AHJ’s generally require structural inspections in order to ensure the safety, health, and welfare of the public as affected by building construction, as well as the life and property of occupants. Generally most solar PV systems require a permanent mount, usually on the roof, which would require a substantial change to a building. However, this is inappropriate for temporary mobile plug-and-play PV systems, which is mechanical functionally equivalent to installing a beach umbrella, and thus there is no need of a building permit for such a system.

2. Electrical Permitting and Inspection:

   Based on provisions in the NEC, AHJ’s generally require permits and inspections in order to safeguard persons and property from hazards arising from the use of electricity. A plug-and-play systems has the potential to eliminate electrical inspections include developing one listing for the entire PV system eliminating the need for inspection, developing a standard PV plug at the utility meter or elsewhere, installing an external AC disconnect switch if mandated, and developing smart, PV-ready circuit breakers. However, installation of a plug-and-play PV system is equivalent to plugging in a bug zapper into an electric outlet and thus does not necessitate an electrical permit and inspection.

3. Utility Interconnection and System Reliability:

   Without adequate communications between plug-and-play PV systems and the utility, grid reliability could be jeopardized in high penetration scenarios. When plugged in, the PV system should automatically connect with the grid, perform self-diagnostics, and communicate to the utility the pertinent information required to ensure that it does not interfere with the normal operation of the grid. The current microinverters available in the market does not have the communication feature available. Moreover, a few microinverter companies also manufactures communication gateways to monitor the microinverter connected to the PV modules (eg. Enphase Envoys, Enphase Envoy collects energy and performance data from the microinverters over on-site AC power lines and then forwards that data to Enphase Enlighten, via the Internet, for statistical reporting). This is not needed for plug and play PV system for systems less than or equal to 1kW.

3.5 Discussion

A circuit breaker panel (also called as load center, service panel, electrical panel or breaker box) holds multiple circuit breakers that distribute power throughout a building. Circuit breakers protect wiring from damage by "tripping" when an electrical short or overcurrent occurs. According to NEC Codes and Standards, a circuit breaker is a device designed to open and close a circuit by non-automatic means, and to open the circuit automatically on a predetermined overcurrent without damage to itself when properly applied within a given rating [118]. The NEC defines overcurrent as any current in excess of the rated current of the equipment or the ampacity of a conductor. Overcurrent (or excessive current) are resultant of defective conductor insulation, defective equipment, or an excessive workload burden placed upon the utilization equipment and its electrical circuit. Fuses and circuit breakers provide a level of safety against overcurrent conditions in electrical circuits. Thus, they are generally termed as overcurrent protective devices (OCPD). An OCPD opens a circuit to prevent excessive heat from damaging conductors and related equipment [119]. NEC codes that are applicable for proper selection of an OCPD are stated below. According to 210.20(a) and 215-3 the over-current protective devices must be sized not less than 100% of the non-continuous load and not less than 125% of the continuous load [119]. Moreover, the section 240.6(a) provides with the list of standardize over-current devices sizes in amperes is 15A, 20 A or 30 A [119-120]. Thus, the minimum circuit breaker rating that is permitted by NEC standards is 15A. On of the commercially available grid-tied Solar-Pods has a dedicated 20A rated Circuit breaker with four solar PV modules generating 1000W, costs around $2,800 along with additional Federal Tax and some local incentives [85]. Even if an average American budget is considered, where the average American annual household earning is around $51,000 excluding taxes [121]; after excluding all the expenses an average annual saving will be more than 5% of the annual income [121] (historically it was higher with the saving rate on an average of an American of 9.8% from 1913-2013 [122]). This provides over $2,500/month in average yearly savings and indicates the average American could afford a plug-and-play PV system that will have a higher ROI than their other investments or the cost of borrowing money.

3.5.1 Advantages of Micro-inverter over Traditional Inverters

Microinverters are plug and play ready and can be easily installed without professionals, however, they have several other attributes that make them particularly appealing for prosumers. Microinverters optimize each PV module independently unlike that of traditional inverters which optimize the whole PV system providing an advantage [123], particularly under partial shading conditions. For example, even 9% shading of a PV system connected to central inverter can reduce the power output by 54%, whereas if micro-inverters are used partial shading of the modules in a system only effect those shaded modules and do not drag down the performance of the whole PV system [124]. In addition, microinverters optimize the power of a system, which results in increasing the power output per PV module by 15% [125] and hence the whole solar system [91;123]. Microinvereters also possess a significantly longer lifetime than that of central inverters as they are not exposed to as high of power and heat loads as central inverters, which results in a life time of 20 to 25 years for microinverters [124-125]. Unlike in case of traditional inverters restringing or installing a second central inverter is required [91,126], expanding with microinverters is easy as each module has a dedicated micro-inverter. Finally, micro-inverters eliminate the use of wiring with high DC voltages, which results in safety for both installers as well as home-owners [89,124-125].

3.5.2 Advantages of Plug and Play Solar

The greatest advantage of plug-and-play PV systems is the ability to produce power output from the PV modules by simply plugging in an extension cord, followed by a short applications to request net metering [127,128]. Plug-and-play PV kits will not only eliminate the relatively high cost required during installation and wiring by a professional electrician [127,128], but also provides the potential to streamline permits, inspections and utility interconnect requirements [73]. In recent years the soft costs of a PV system, which includes the balance of system (BOS) costs, permitting, inspection, interconnection accounts for a growing percentage of the PV system installation cost due to radical declines in the PV module costs [129]. Also the regulatory requirements, the permit process takes a substantial amount of time and money, which is again considered under the soft cost [73]. Installing Plug and Play solar PV system and modifying the Standards and local jurisdiction will reduce the soft cost involved by considerable amount [73,127].

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Chapter 4[3]

U.S. Market for Solar Photovoltaic Plug-and-Play Systems

[3] --under review (Journal-Renewable Energy)

Abstract

Plug and play solar photovoltaic (PV) systems are affordable, easy to install and portable grid-tied solar electric systems, which can be purchased and installed by an average prosumer (producing consumer). The combination of recent technical/safety analysis and trends in other advanced industrialized nations indicate that U.S. electrical regulations may allow plug and play solar in the future. Such a shift in regulations could radically alter the current PV market. This study provides an estimate of this new U.S. market for plug and play PV systems if such regulations are updated by investigating personal financial decision making for Americans. The potential savings for the prosumer are mapped for the U.S. over a range of scenarios. The results show the total potential U.S. market is over 57 GW, which represents an opportunity for sales for retailers from \$14.3–\$71.7 billion depending on the capital cost of plug and play solar systems (\$0.25-\$1.25/W). These systems would generate ~108,417,000 MWh/year, which is 4 times the electricity generated from U.S. solar in 2015. This distributed solar energy would provide prosumers approximately \$13 billion/year in cost savings, which would be expected to increase by about 3% per year over the year lifetime of the systems.

Keywords: electricity market; distributed generation; levelized cost of electricity; photovoltaic; plug and play solar; prosumer

Nomenclature

AC-Alternate Current

BNEF- Bloomberg New Energy Finance

BOS-Balance of System

C_g - Electricity cost on grid (\$/kWh)

d- Degradation rate (%/year)

DOE- Department of Energy

E- total potential electricity generated from appropriate plug and play PV systems in the U.S. (kWh)

ECD- Esource Customer Direct

EIA- U.S. Energy Information Administration

EURAC- European Academy of Bozen/Bolzano

E_{pv} - Electricity generated by AC PV module (kWh)

GTM- Greentech Media Company

h- U.S. average Household size (%)

h_s - appropriately oriented households in a state

I- Installation cost of the plug and play solar photovoltaic system

IEA- International Energy Agency
IEEE- Instititute of Electrical and Electronics Engineering.
IFC- Internation Finance Corporation
IRENA- International Renewable Energy Agency
LCOE- Levelized cost of Electricity ($/kWh)
M- Total U.S. Market value for plug and play solar PV system (W)
NMCH- National Multi-Family Housing Council
NREL- National Renewable Energy Laboratory
NSJC- National Solar Job Census
O- Total amount of power of plug and play PV that can be installed by households that owns their homes/apartments (W)
O_o - Orientation in the class of housing for owners (%)
O_R - Orientation in the class of housing for renters (%)
OMB- Office of Management and Budget
p- Households that can install plus and play solar PV system
P_o – Total population that own their housing (%)
P_R - Total population that rent their housing (%)
P_S- solar PV system size (kW)
P_{cf} - Capacity factor of the solar PV (%)
PV- Photovolatic
R- Total amount of power of plug and play PV that can be installed by households that rent their homes/apartments (W)
r- Discount rate (%)
S_H – Percentage shading (%)
SEIA- Solar Energy Industries Association.
SPS- Solar Power Station
T- Life time of the technology (years)
Treasury- U.S. Department of Treasury
u_s – solar flux per unit area per day for a state (kWh/m^2/day or 1 sun hours)
WNA- World Nuclear Association
Z- Size of the system (kW)

4.1 Introduction

In the United States there is widespread support for solar energy from all political groups (Shahan, 2012; Riffkin, 2015; SEIA, 2015). Historically, the enormous potential of solar photovoltaic (PV) (Pearce, 2002) has only been held back from extensive use (and even dominance in the electrical generation market) by economics (Wilkins, 2002; Beck & Martinot, 2004; Pietruszko, 2006; IFC, 2007; Branker, Shackles, & Pearce, 2011; Alafita & Pearce, 2014). However, solar PV module costs have declined sharply (SEIA&GTM Q2, 2012; SEIA&GTM Q3, 2015) resulting in sustained and rapid growth of the solar PV market (SEIA&GTM, 2015; IRENA, 2015; SEIA&GTM-Q3, 2015). For example, solar PV module prices have declined by 75% between 2009 and 2014 (IRENA, 2015) and overall residential scale PV systems costs declined by 45% since 2010 (IRENA, 2015; SEIA&GTM, 2015). This resulted in cumulative 41 GWdc of U.S. solar PV installations from 2007 to 2016, of which 41% were residential (SEIA&GTM, 2015).

As the cost of fossil fuels increases due to reduced conventional sources (Payne, Dutzik & Figdor, 2009; IEA, 2014; WNA, 2016) and greenhouse gas emission liability increases (Short et.al., 2013; Cooper& Rosin, 2014; Heidari & Pearce, 2016), the demand for PV installations will continue to increase, resulting in further declines in PV manufacturing costs, which will continue to drive more demand (McDonald & Schrattenholzer, 2001; Van der Zwaan & Rabl, 2003; Watanab, Nagamatsu & Griffy-Brown, 2003; Nemet, 2006; Candelise, Winskel, & Gross, 2013 Parkinson, 2014; Barbose, et al., 2015; Rubin, et al., 2015; WNA, 2016). Reductions in solar PV module costs reduces the levelized cost of electricity (LCOE) of solar (Branker, Pathak & Pearce, 2011; Parkinson, 2014) and helps expand the solar PV markets to achieve or surpass grid parity (equal to or drop below the price of grid supplied electricity) (Christian & Gerlach, 2013). Many economically beneficial PV markets already exist. The cost of electricity generated by small-distributed on-grid PV systems is comparable with the conventional electricity rates in various locations (Branker, Pathak & Pearce, 2011; Stefan and Yorston, 2013).

Despite the popularity of solar energy technology and ability to achieve positive economic returns, solar PV contributes only 0.54% to the total electricity generation in U.S. as of April 2015 (EIA, 2015a; EIA, 2015b). Primary barriers for rapid growth of solar PV among the general population include the lack of initial capital and inappropriate financing mechanisms (Wilkins, 2002; Beck & Martinot, 2004; Pietruszko, 2006; IFC, 2007; Branker, Shackles, & Pearce, 2011; Alafita & Pearce, 2014). While the U.S. is a wealthy country, with a total net worth of $84.9 trillion in June 2015, (Poppick, 2015), the top 20% of the population possesses 89% of the wealth (of which top 1% owns 35% of the wealth) (Wolff, 2012). The median net worth of U.S. households is only $81,400 (Lubin, 2013). Thus, obtaining a solar PV system capable of providing all electrical consumption is relatively expensive for the average American homeowner (Wilkins, 2002; Pietruszko, 2006; ECD, 2008).

One method to overcome this challenge is to allow installation of “plug and play” solar PV systems for residential purpose and small-commercial use (Mundada, Nilsiam & Pearce, 2016). Plug and play PV systems are affordable, easy to install, and portable grid-tied solar PV systems, which can be purchased and installed by an average prosumer (producing consumer). A prosumer can buy such a pre-configured and pre-certified grid-tied AC module (consisting of PV modules, microinverters, and wires) and can install it by plugging it into a household outlet to produce solar electricity. This can be accomplished using commonly available tools and without assistance of a trained licensed technician or concomitant overhead and soft costs. Additionally, plug and play solar systems are portable, allowing easy transport for people who relocate to own solar. The United Kingdom (Kennect 2012; SPS 2015), Switzerland, Netherlands and the Czech Republic (Movellan, 2014) currently permit and install plug and play solar without any technical issues. A recent technical review of plug and play solar indicated that it is technically viable and safe for U.S. adoption as well (Mundada, Nilsiam & Pearce, 2016).

Based on technical analysis and the trends in other advanced industrialized nations, expanding U.S. electrical regulations to allow/or include plug and play solar is viable. Such a shift in regulations could radically alter the current PV market. This study provides an estimate on a potential new market for plug and play PV systems in the U.S. if such regulations are updated. This is accomplished by investigating personal financial decision making for Americans using plug and play solar PV as an investment. First, the LCOE calculation is made for all the States in the U.S. based on solar flux using a sensitivity analysis on the cost of a system. Next, the current residential retail electricity rate is determined for the entire U.S. The potential savings for the prosumer are then mapped for the U.S. over a range of scenarios and escalation rates. Finally, demographic data is correlated with the GIS date to extract the total market in the U.S. These results are presented and discussed.

4.2 Methodology

LCOE can be determined by summing up all the costs incurred for the generation of electricity by a PV-based technology in a time span divided by the total energy generated by the technology during that time span (Branker, et al., 2011 ; Mundada, Shah & Pearce, 2016). LCOE is expressed in $/kWh, which can be compared directly to residential electric rates. There has been various methods to determine LCOE of solar PV technologies (Short, Packey, & Holt, 1995; Cambell, 2008; Grana, 2010; Velosa III, 2010; Darling, et al., 2011), however, this analysis will use the simplified version of the comprehensive review of LCOE by Branker et al. (2011). The LCOE of a plug and play solar PV depends on the following inputs:

1. Capital cost of the AC PV module (I)
2. Discount rate (r)
3. Degradation rate (d)

4. Electricity generated by AC PV module (E_{pv})

5. Life time of the technology (T), which is normally taken as the warranty life.

The LCOE from plug and play PV, C_{pnp}, is thus determine by:

$$C_{pnp} = \frac{I}{\sum_{n=1}^{T} \frac{\left(\frac{8760hrs}{years}\right)*P_S*P_{cf}*(1-d)^n}{(1+r)^n}} \qquad \frac{\$}{kWh}$$

(1)

where P_S is the solar PV system size (kW) and P_{cf} is the capacity factor of the solar PV (%), which is the ratio of full sun hours (defined as 1000W/m^2) to 24 hours in a day. The electricity generated by the plug and play solar PV module is location dependent, relying directly on the capacity factor of the solar PV module, and the solar flux (kWhr/m^2/day) of the region. The solar flux available in the United States ranges from 3 kWhr/m^2/day to 9 kWhr/m^2/day (NREL, 2007).

The savings, S, which prosumers can obtain from installing a plug and play PV system is given by:

$$S = C_g - C_{pnp} \qquad [\$/kWh] \qquad (2)$$

where C_g is the cost of electricity on the grid in [$/kWh]. Any positive S, indicates a positive return for the prosumer.

In this study a sensitivity analysis is run on the three primary variables in the LCOE calculation: 1) the capital cost of the AC PV module is varied from $0.25/W to $1.25/W, 2) the discount rate is analyzed at 1% and 7% and 3) capacity factor is varied from 13% to 28%. The justification for this sensitivity and the values of the other core variables are explained below.

4.2.1 Theory and calculations for determining LCOE of plug and play solar PV microinverter system

4.2.1.1 Capital cost of the AC Solar PV module

A solar plug and play PV module consists of solar PV module, microinverter, mounting materials, and electric cables. As homeowners can install the systems themselves, the installation cost of the plug and play solar PV module includes only the capital cost of the hardware, which is dominated by the AC PV module (plug and play solar can be made up of a PV module and a microinverter or an AC PV module that integrates the microinverter into the module). Other factors that normally accompany PV installations such as labor costs, electrical BOS costs, structural BOS costs, engineering & permitting, inspection, and interconnection cost are excluded. This represents a substantial savings as labor cost and BOS of a solar PV system adds up to more than 50% of the system cost (Barbose, Darghouth, & Wiser, 2010) and is increasing as a percentage as PV module prices have declined. It should be pointed out here, that because of this, the plug and play PV systems reverse the trend observed in the rest of the PV industry: the larger the system the smaller the cost per unit power no longer holds. Reports show, since 1998, the overall installation cost of solar PV system is declining on average by 6%-8% every year in all the sectors (residential, commercial and utility scale) (Feldman, et al., 2014). From 2012-2013 the solar PV market realized a decline of 12% in the installation cost of solar PV system of <10kW (Feldman, et al., 2014). The solar PV module cost decreased sharply from $1.85/W in 2010 to $0.65/W in 2013 (BNEF, 2013; SEIA&GTM, 2014). Additionally there has been noticeable decline in the inverter cost of 6% (i.e. $0.42/W to $0.25/W from 2010-2013) (BNEF, 2013; Davidson, et. al., 2014). In year Q1-2014 to Q1-2015 the solar module cost around $0.64/W to $0.75/W and the inverter cost around $0.23/W to $0.34/W (SEIA-&GTM- Q1, 2015). In addition, capital costs for PV modules drop below $0.50/W when purchased in bulk from wholesalers. For example: Sunvia solar modules currently cost $0.45/W (Sunvia, 2016). Thus, for determining the LCOE the capital cost of the AC solar PV module is considered to be $1.00/W. For sensitivity analysis the capital cost of the AC PV module is varied from $0.25/W to $1.25/W, representing near and medium term potential costs to prosumers.

4.2.1.2 Degradation rate

The degradation in performance of solar PV module is an important variable for predicting lifetime output and is influenced by chemical and material processes such as weathering, oxidation, corrosion and thermal stress (Jordan & Kurtz, 2012). Researchers conducted standardized tests to determine a degradation rate of solar PV modules (Osterwald et.al., 2002; Pinge et al., 2010; Jiang, Lu, & Sun 2011) and the degradation rates for amorphous silicon PV is 0.5-1.0%/year, for crystalline silicon it is 0.1-0.5%, for polycrystalline silicon PV it is 0.1-1.0% and for cadmium telluride 0.1-0.5%/year (Osterwald et.al., 2002; Jordan et.al., 2011; Belluardo, Ingenhoven, & Moser, 2013). A median degradation rate for solar PV module is 0.5%/year (Jordan and Kurtz, 2012) and thus the degradation rate considered for determining LCOE in this case is 0.5%/year following Branker et al. (2011).

4.2.1.3 Life span of the Plug-and-Play PV System

The lifespan of solar PV module is beyond 25 years (Czanderna & Jorgensen, 1999; Realini, 2003; Dunlop, Halton, & Ossenbrink, 2005; Skoczek, Sample, & Dunlop, 2009; Holladay, 2010). Although a lifespan of 30 years or more is expected for a solar PV module (Harrabin, 2009), the financial lifespan is normally taken as the warranty period, which is 20-25 years (Wohlgemuth, 2003; Brearley, 2009). In addition, a service life-time of over 25 years is expected for certified, microinverters available on the market (Nahi, 2009). The life-time of plug and play solar PV system depends on the life-time of the PV and microinverter, thus, the life span, T, of the system is considered to be 25 years. Table 11 summarizes the commercially available microinveretes on the U.S. market and their warranty period.

Table 11. Microinverters available on the U.S. market with their lifespan warranty period and certified standards.

Company [Source]	Warranty Period (Years)	Product	Safety Standard Compliance	Grid Connection Compliance
Chilicon Power	25	CP-250 Micro-inverter	UL1741. CSA C22.2 NO. 107.1	IEEE 1547
Solar Panel Plus	25	MI-250-240A Micro-inverter	UL 1741 CSA C22.2 No. 107.1	IEEE 1547
Enphase	25	M215 Micro-inverter	UL1741. CAN/CSA-C22.2 NO. 0-M91, 0.4-04, and 107.1-01	IEEE 1547
Enphase	25	M250 Micro-inverter	UL1741. CAN/CSA-C22.2 NO. 0-M91, 0.4-04, and 107.1-01	IEEE 1547
Enphase	25	C250 Micro-inverter	UL1741. CAN/CSA-C22.2 NO. 0-M91, 0.4-04, and 107.1-01	IEEE 1547
Enphase	25	S230 Micro-inverter	UL1741. CAN/CSA-C22.2 NO. 0-M91, 0.4-04, and 107.1-01	IEEE 1547
Enphase	25	S280 Microinveter	UL1741. CAN/CSA-C22.2 NO. 0-M91, 0.4-04, and 107.1-01	IEEE 1547
Siemens	25	SMIINV215R60XX Microinverter	UL1741, CAN/CSA-C22.2 NO. 0-M91, 0.4-04, and 107.1-01	IEEE 1547

4.2.1.4 Capacity factor

Capacity factor is the total energy a technology can produce in a duration of time compared to that of the total energy it could have generated to its full capacity. The capacity factor of solar PV module is a function of the solar irradiation at the location, the orientation of the solar PV module, the performance (or efficiency) of the solar PV module, the electrical efficiency of the system (Campbell et al., 2009; Hossein et al., 2012; NREL, 2013). For the case studies in this paper the capacity factor is varied from 13.08% (IL, Chicago, average sun hours/day 3.14 hrs/day) to 28.2% (NM, Albuquerque, average sun hours/day 6.77 hrs/day) (SolarDirect, 2016; Alternate Energy sources, 2016) depending on the solar irradiation (3 kWhr/m^2/day to 9 kWhr/m^2/day) (NREL, 2007) received at different states in U.S.

4.2.1.5 Discount rate

Discount rates are used to determine the discounted cash flows, which takes into account time value for money and risk or uncertainty involved in the future cash flows. The U.S. Department of Energy (DOE) establishes technologically feasible energy efficiency standards for many appliances used daily in American households (i.e. microwaves, clothes dryers, and air conditioners). To determine if the investments in reduced electrical consumption are economically justified, the DOE performed a sensitivity analysis on consumer purchase of energy by varying the discount rate from 3% and 7% (OMB, 1992). These values were chosen by the OMB based on the following logic: On the low end, the OMB recommends using a "social rate of time preference" of approximately 3 percent, which approximates average saving rates using the real rate of return on long-term government debt, such as 10-year Treasury notes (OMB 2003, 33), and thus can act as a proxy of how consumers value future consumption against current consumption. On the high end, a 7% discount rate is appropriates the marginal pretax rate of return on an average investment in the stock market (OMB 1992, 9). Both of these values can be viewed as overly conservative. First, on the low-end the daily long term-real treasury rate for more than 10 years for 2015 was around 1% (Treasury, 2016). On the high end, 7%, may be the average rate of return on the stock market before taxes, but both energy efficiency and solar generated offsets of electricity consumption for consumers can be viewed as after tax savings. For high income households this number decreases significantly, but for the lowest income households 7% can be seen as the maximum valid discount rate. Thus, in this study 1% and 7% will be used in the sensitivity analysis.

It should be noted that discount rates are often points of contention in the literature. Various studies have attempted to determine "implicit consumer discount rates" based on purchasing preferences using appliances and finding large variances and in some cases extremely high (triple digit) discount rates (Ruderman et al., 1987; Hausman, 1979;

Dermot, 1980; Frederick et al., 2002; Harrison et al., 2005; Andersen et al., 2006; Newell & Siikamäki, 2015). It has been well established that discount rates for consumers varies according to income, race, education (Newell & Siikamäki, 2015). For example, as the education of consumers increases the discount rates they use for decision-making decreases (Newell & Siikamäki, 2015). It has been pointed out that observed discount rates are so high because of lack of information and inability to adequately understand available information related to energy consumption (Frederick et al., 2002). Stated simply, un-educated or poorly educated consumers make irrational economic decisions. Unfortunately, some older studies such as (Hausman, 1979) have erroneously argued that low discount rates should only be used for efficiency standards for high-income households and are not suitable for low or median-income households that have implicit discount rates that are much higher. Sadly, even some contemporary studies have mistakenly argued for government policy for low and median-income households to use implicit discount rates (e.g. 27% to 102%) (Miller, 2015). Such policy recommendations are simply incorrect and if adopted would perpetuate ignorant economic errors commonly observed in American middle and lower class. No low- or median-income household, for example, has standard legal low-risk investment opportunities available to them to reach triple digit returns. Yet as many studies have shown they pass up energy efficiency investments as if they do. Considerations for economic education will be presented in the discussion, but for the present case studies in this paper the discount rates considered is 1% and 7%.

4.2.2 GIS Analysis

A shapefile of the United States was obtained from the ArcGIS database (Fitzpatrick, 2012). The electricity rate of each state was obtained from the U.S. Energy Administration database (EIA 2016). Savings for each state were calculated utilizing a 1% and 7% discounted LCOE at $1.25/W capital cost. Average electricity rate for each state was subtracted from this value. Average savings across the United States were transcribed to a map utilizing ArcMap version 10.3.1.

4.2.3 U.S. Market Analysis

To estimate total market for plug and play, several assumptions and factors that affect solar plug and play market size are included. The average family will require a 1kW plug and play installation to satisfy electrical needs. There are about 117,259,427 U.S. households and approximately 37% of U.S. households (43,267,432) are renter occupied (h_r) and 63% (73,991,995) are owner occupied (h_o) (NMHC, 2014). As the number of occupants within a household is correlated with varying electrical consumption (Kavousian, 2013), it is expected that larger households will consume greater amounts of electricity. However, for the maximum plug and play PV system size considered here (1kW), even the smallest households (e.g. 1 person) are expected to have a demand above what can be provided by the PV system alone. This, thus, does not affect the potential market for plug and play solar.

It is assumed that the average U.S. utility rates will remain static or rise, allowing for the market penetration of plug and play solar determined in this study to be considered a base. This is a conservative assumption as the real electricity price escalation for the residential market has historically increased (e.g. on average 3.6% per annum in the years 2000 to 2006 in the U.S. (EIA, 2016)). In addition, it is assumed that the median U.S. household incomes will remain at roughly $52,250 (Noss, 2014) indicating that the economic situation that favors plug and play over larger-scale residential PV remains intact.

Factors such as orientation, shading, and neighborhood configurations will affect customers who can optimally utilize plug and play solar technology Orientation of homes or rental units in a direction other than south, southwest, or southeast will affect solar plug and play performance and should be accounted for in calculations (Hachem et al 2013). For single family homes the size of the plug and play systems remove restrictions on orientation as it could be located on the southernmost facing facade. However, for those that rent, a fraction of 50% is used for appropriate orientation. This assumes a random orientation of the rentals with roughly half facing south in some capacity. Previous conservative estimation for unshaded roof in cities was taken as 30% for all locations (Wigington, et al., 2010) as shading due to trees, multiple facades on the home, or proximity to other residences can reduce PV performance (Norton et al., 2011). In this study because the prosumer would have the option to move the relatively small footprint (1kW is only 3 to 4 modules) of the plug and play solar to unshaded rooftop, porches, or yard locations this study assumes the unshaded percent is doubled to 60%. These factors and assumptions are considered when determining the total U.S. market, M, value for plug and play solar given by:

$$M = O+R \qquad [W] \tag{3}$$

Where O is the total power [W] of plug and play PV that can be installed by households that own their homes and is given by:

$$O = h_o*p*Z*s_h*o_o \qquad [W] \tag{4}$$

and R is the total number of power [W] of plug and play PV that can be installed by households that rent their homes/apartments and is given by:

$$R = h_r*p*Z*s_h*o_r \qquad [W] \tag{5}$$

Where p is the percent of U.S. households that can economically and technically install a plug and play PV system, Z is the size of that system based on power in W, s_h is the percent of unshaded residences and o_o and o_r is the appropriately oriented in that class of housing for owners and renters, respectively.

The average U.S. household size in 2015 was 2.54 (U.S. Census, 2015a). This value was used to estimate the number of households in each state given the state populations (U.S. Census, 2015b).

The potential energy generated from plug and play solar in the U.S. is then given by:

$$E = \Sigma_{states} (h_s * Z * u_s * 365 \text{ days/year} * s_h) \quad \text{(kWh)} \qquad (6)$$

Where h_s is the appropriately oriented households in the state, which assumed the same ratio of renters and owners nationally resulting in a value of 0.8155), and u_s is the kWh/m^2/day (1 sun hours) for the state from Table 12.

4.3 Results

A case study is performed for residential sectors in all the states with average solar hours and average electricity rate as represented in Table 12.

Table 12: The average 1 sun (1000W/m^2) solar hours and the average electricity rates during Dec. 2015 for residential sector in United States (EIA, Dec 2015; Solar Direct, 2016; Alternate Energy Source, 2016):

Census Division and States	Average sun hours (hrs/day)	Average Electricity rate (cents/kWh)
New England		
Connecticut	4.30	19.43
Maine	4.19	15.52
Massachusetts	3.79	19.60
New Hampshire	4.60	18.00
Rhode Island	4.23	19.88
Vermont	4.40	17.17
Mid Atlantic		
New Jersey	4.21	15.54
New York	3.16	17.53
Pennsylvania	3.28	14.12
East North Central		

Illinois	3.14	11.81
Indiana	4.21	11.11
Michigan	4.00	14.58
Ohio	3.94	12.61
Wisconsin	4.295	13.83
West North Central		
Iowa	4.40	10.61
Kansas	4.57	12.29
Minnesota	4.53	11.77
Nebraska	4.79	9.68
North Dakota	5.01	8.84
South Dakota	5.23	10.27
Missouri	3.78	10.39
South Atlantic		
Delaware	4.00	13.45
District of Columbia	4.23	13.34
Florida	4.99	11.49
Georgia	4.74	10.22
Maryland	4.47	14.67
North Carolina	4.71	10.96
South Carolina	5.06	12.05
Virginia	4.31	10.98
West Virginia	3.65	10.43
East South Central		
Alabama	4.23	11.23
Kentucky	4.94	10.34
Mississippi	4.44	11.16
Tennessee	4.37	10.40
West South Central		
Arkansas	4.69	9.51
Louisiana	4.63	8.70
Oklahoma	4.99	9.00

Texas	4.92	11.33
Mountains		
Arizona	6.36	10.75
Colorado	4.87	11.44
Idaho	4.70	9.64
Montana	3.99	10.42
Nevada	5.98	12.41
New Mexico	6.77	11.36
Utah	5.26	10.56
Wyoming	6.06	10.57
Pacific Contiguous		
California	4.77	17.3
Oregon	3.72	10.39
Washington	3.57	9.19
Pacific NonContiguous		
Alaska	3.55	19.6
Hawaii	6.02	26.86

Using equation 1 and the input data discussed above, the LCOE was calculated for plug and play PV systems in each state. Figure 13 shows the effects of varying the capital cost of plug and play solar PV module, varying solar irradiation received, which consequently affects the capacity factor in the U.S. states on the LCOE of the solar plug and play solar PV system. The LCOE of the system is determined at different discount rates of 1%, and 7% and for a life span of 25 years with 0.5%/year degradation rate. The capital cost of the plug and play solar PV module is varying from $0.25-1.25/W. The states chosen in the graphs were representative of the principal solar flux viewed in the continental U.S.

Figure 13 A is for Michigan, which falls in the region that receives a minimum solar irradiation ranging between 4.00 - 4.50 kWhr/m^2/day with a minimum capacity factor of 16.7%. Figure 13 B shows New Jersey, which has between 4.50 – 5.00 kWhr/m^2/day with a minimum capacity factor of 17.5%. Figure 13 C represents South Carolina which falls in the region which receives 5.00- 5.50 kWhr/m^2/day with a minimum capacity factor of 21.1%. Figure 13 D shows data for Nevada, which falls in the region which receive solar irradiation ranging from 5.50 – 6.00 kWhr/m^2/day with a minimum capacity factor of 24.9%. Figure 13 E represents Wyoming, which falls in the region with 6.00 - 6.50 kWhr/m^2/day with a minimum capacity factor of 25.3%. Figure 13 F represents Arizona with solar irradiation above 6.50 kWhr/m^2/day with a minimum capacity factor of 26.5%.

It can be observed from the Figure 13 A-F that the capital cost of the system is directly proportional to the LCOE and dominates the electricity costs. For example, in Figure 13 A the LCOE of the system with 1% discount rate and capital cost \$0.25/W is \$0.006/kWh whereas for capital cost \$1.25/W is \$0.028/kWh.

The discount rate of the system affects the LCOE of the system to a great extent. It can be observed from Figure 13 A-F that as the discount rate of the system increases the LCOE of the system increases with capital cost and life span maintained constant. For example from Figure 13 D the discount rate of the system increases from 1% to 7% the LCOE of the system also increases from \$0.004/kWh to \$0.008/kWh at \$0.25/W and life span of 25 years.

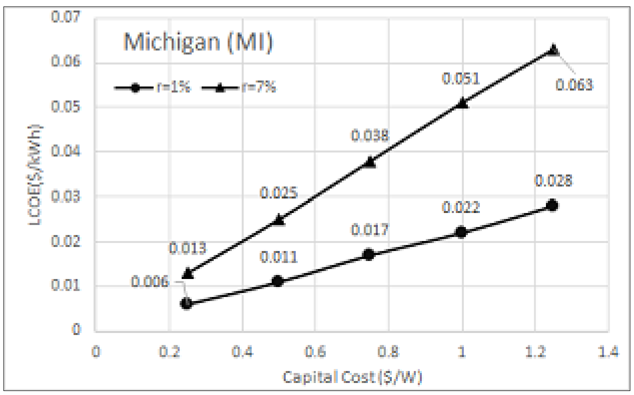

Figure 13 A-Michigan

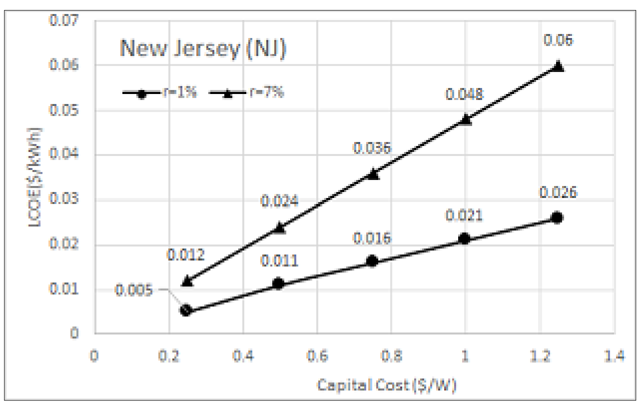

Figure 13 B- New Jersey

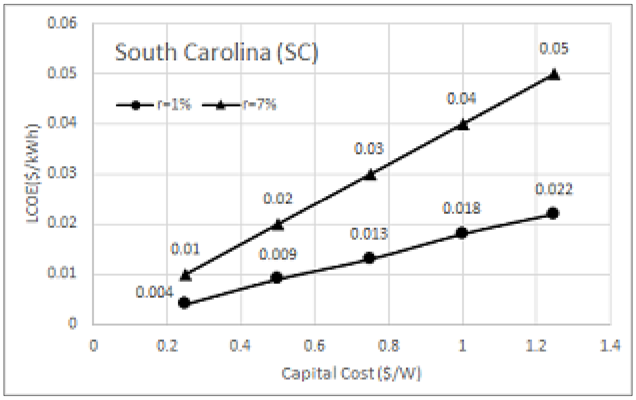

Figure 13 C-South Carolina

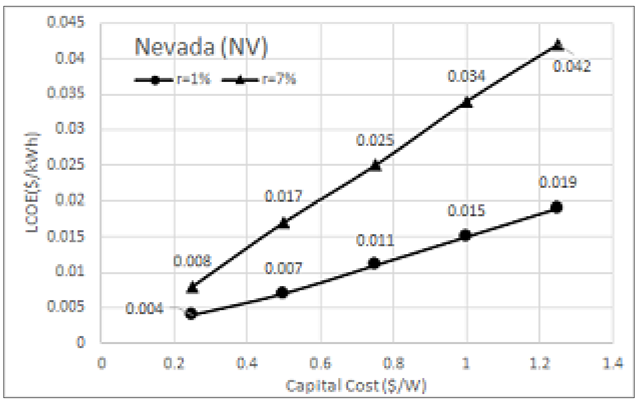

Figure 13 D- Nevada

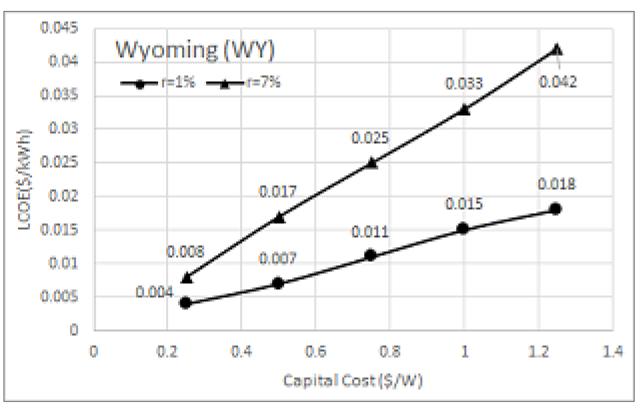

Figure 13 E-Wyoming

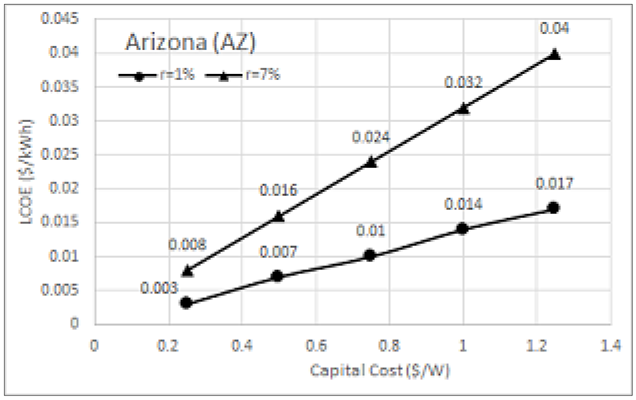

Figure 13 F- Arizona

Figure 13 A-F: LCOE of the plug and play solar PV systems at discount rates 1% and 7% for varying capital cost of the system ($0.25/W to $1.25/W) and varying capacity factor depending on geographical locations (16.7% to 25.3%). The life span of the system is 25 years with 0.5%/year degradation rate.

It can be seen from Figure 13 that the capital cost of the plug and play solar PV system affect the LCOE of the system by a significant amount. Even a small change in the value of capital cost was having a considerable amount of impact of the LCOE of the system. It can be observed that for all the states that as the capital cost of the system was reducing the LCOE of the system was decreasing. It can also be observed from the Figure 13 that discount rate also has a considerable amount of impact on the LCOE of the system. It can be observed that the LCOE of the system increases with increase in discount rate (1%-7%) for the system with same capital cost.

Figure 14 shows a geographic representation of the savings gained by installing such a plug and play PV system in all the states of the U.S., which depends on the LCOE of the solar plug and play solar PV system and current electricity rates for the residential sector for each state (equation 2). The LCOE of the system is determined at different discount rates of 1% and 7% and for a life span of 25 years with 0.5%/year degradation rate and where the capital cost of the system is considered to be $1.25/W.

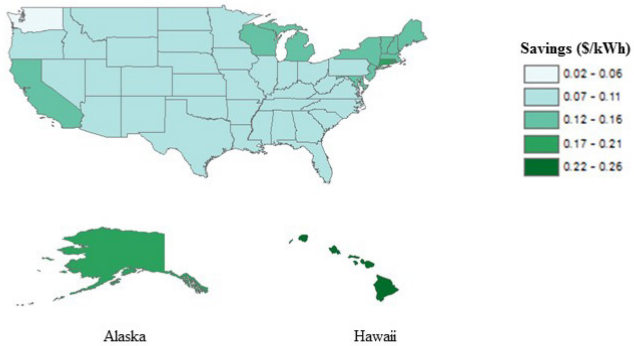

Figure 14A. The geographical representation of saving with 1% discount rate

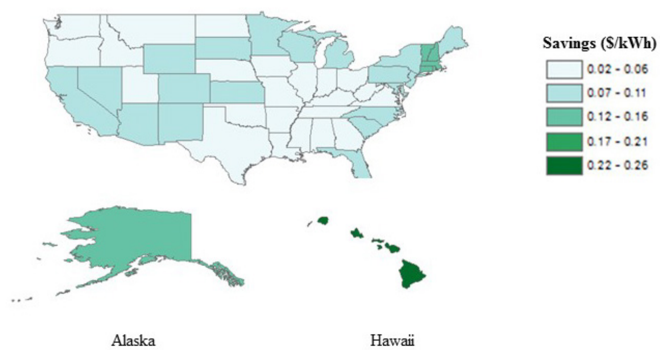

Figure 14B. The geographical representation of saving with 7% discount rate

Figure 14 Prosumer savings obtained by installing the solar plug and play system at A) 1% and B) 7% discount rate respectively. Assumptions- the capital cost of the system is considered as $1.25/W and life span of the system is 25years with 0.5%/year degradation rate and current electricity rates for residential sector.

In Figure 14 the United States is divided into 5 regions depending upon the ranges of savings in which the state falls. From the Figure 14A it can be observed that the prosumer has a considerable amount of savings after installing such a system of 1kW even though the escalation rate of the electricity cost is considered to be 0% and capital cost of the system is considered to be at its maximum $1.25/W. The largest potential savings can be found in states such as Alaska, Hawaii, and variable states in the northeast region, with a range between $0.17-$0.26/kWh. The lowest potential savings, with a range of $0.02-$0.06/kWh can be found in states such as Washington. Total savings range from $0.02-$0.26/kWh.

Also from the Figure 14B it can be observed that the prosumer has a considerable amount of savings after installing such a system of 1kW even though the escalation rate of the electricity cost is considered to be 0% and capital cost of the system is considered to be at its maximum \$1.25/W. Comparing Figure 14 A with B it can be observed that the prosumer savings for maximum number of states reduces with increase in the discount rate. For example the savings obtained by installing such a system in Utah (UT) with discount rate 1% lies in that range \$0.07/W to \$0.11/W and with discount rate 7% lies in the range \$0.02/W to \$0.06/W. Also the savings obtained by installing such a system in Alaska (AK) with discount rate 1% lies in that range \$0.17/W to \$0.21/W and with discount rate 7% lies in the range \$0.22/W to \$0.26/W. Again, the largest potential savings can be found in states such as Alaska, Hawaii, and variable states in the northeast region and across the U.S., with a range between \$0.12-\$0.26/kWh. The lowest potential savings, with a range of \$0.02-\$0.05/kWh can be found in states such as Washington, Oregon, Louisiana, Arkansas, Missouri, Ohio, West Virginia. Total savings range from \$0.02-\$0.26/kWh.

It is striking that the BOS savings made possible by plug and play PV systems enable economic savings for essentially the entire U.S. Thus Z in equation 4 and 5 becomes 1. Applying the conservative estimates to the market for households of renters and owners amounts to about 13GW and 44GW, respectively. Following equation 3 this results in a total potential U.S. market for plug and play PV systems of over 57 GW. Moreover, the total U.S. market for plug and play solar systems ranges from \$14.3 billion – \$71.7 billion depending on the capital cost of plug and play solar systems (\$0.25-\$1.25/W).

Following equation 6, these plug and play PV systems would generate approximately 108,417 thousand MWh per year, which is roughly 4 times the electricity generated from solar in the U.S. in 2015 (EIA, 2015). With the average cost of electricity in the U.S being about \$0.12/kWh this represents roughly \$13 billion/year in electricity cost savings for prosumers.

4.4 Discussion

A straightforward methodology for calculation of LCOE of plug and play solar PV systems and the savings prosumers would accrue from installation has been presented to determine the economic viability of such a system. The results from applying this methodology indicate that plug and play solar PV systems are profitable for prosumers if installed in any state in the U.S. The results from Figure 13 provide a quantitative view of the effects on the LCOE with changes in various input factors like capital cost, discount rate and capacity factor. The results from Figure 14 provide an overview understanding of prosumer savings that can be obtained after installing such a system.

The installation of such a system for residential sector irrespective of the geographical location in United States gives considerable amount of prosumer savings. From Figure 14 it can been seen that there is considerable amount of savings obtained by prosumer for both the discount rates (1% and 7%) with maximum capital cost and 0% escalation rate of the electricity cost for all the states in United States. It can also be observed that the savings are high with less discount rate (1%) as compared to the one with higher discount rates (7%).

The results of both the LCOE of the system (Figure 13) and the prosumer savings obtained by installing the system (Figure 14) provide decision makers with clear guides for the economic benefits of installation of plug and play solar photovoltaic systems. The lower LCOE costs and a considerable amount of prosumer savings obtained by installing the plug and play solar PV systems offers support to preliminary analysis that indicate a bright future for installation of plug and play solar PV system at residential or small commercial business levels.

4.4.1 U.S. Market and Employment

According to SEIA, residential solar installation has increased by 66% between 2014 and 2015 and reached 2GW of total residential solar PV installations (SEIA-Q4, 2015). The U.S. market analysis conducted in this paper shows homeowners or renters can install plug and play solar systems, ultimately expanding the potential market. Installation of such a system of just 1kW per residence can raise the residential solar installation on the U.S. market to over 57GW. Thus, the total residential solar installation in U.S. could be expanded by a factor of more than 28 if plug and play solar PV is legalized.

According to NSJC, solar industry employment has grown by 123% between 2009 and 2015, resulting in nearly 115,000 domestic living-wage jobs from solar (2015). Moreover, the total solar industry employment was around 208,859 in Nov 2015 showing an increase of 20.2% from Nov 2014-2015 (NSJC, 2015). Solar employment is sub divided into various components out, of which manufacturing, sales and distribution, installation, and project development constitutes 80% of the total employment. Overall solar installation was around 1GW in year 2010 which, raised to 7.43GW installation in year 2015 (740% increase), whereas solar employment has increased approximately from manufacturing

(20,000 from 30,000 or 50%), sales and distribution (10,000 to 25,000 or 150%), installation (40,000 to 120,000 or 300%), and project development (15,000 to 25,000 or <50%) (NSJC, 2015). The relatively small employment percentage increases for manufacturing and project development are due to importing of PV components and standardization of installs, respectively. Only for plug and play solar PV only the jobs associated with manufacturing and sales and distribution are expected to increase with plug and play installations. The largest increase would be expected in sales and distribution as, companies previously unassociated with the PV market (e.g. both brick and mortar retail stores like Wal-Mart and online retailers like Amazon) have the potential to acquire significant profits from the shares of a new market that is estimated to be between $14.3 billion – $71.7 billion.

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Chapter 5

Conclusions and Future Work

5.1 Conclusion

5.1.1 Overview

The research work was directed towards technical as well as economical analysis of new technologies for residential solar PV systems. The new technologies which are analyzed in the work can not only increase PV penetration level in the U.S but also increase environmentally responsible electric generation which, can eventually result in electricity cost savings. The following are the conclusions that can be drawn from the respective studies:

5.1.1.1 LCOE of hybrid system:

A new method to calculate the LCOE of a complex PV+battery+CHP system was presented. A case study for residential electricity and thermal demand in an extreme worst case environment (Houghton, Michigan) showed that with reasonable economic assumptions and current costs such off-grid hybrid systems already provide a potential source of profit for grid defectors.

A sensitivity analysis for LCOE of such a hybrid systems on the capital cost of the three energy sub-systems, capacity factor of PV and CHP, efficiency of the CHP, natural gas rates, and fuel consumption of the CHP provide decision makers with clear guides to the LCOE of distributed generation with off-grid PV+battery+CHP systems.

The most important factors for determining LCOE of hybrid system are system cost, financing, operation and maintenance cost, fuel cost, loan-term and lifetime. With favorable financing terms, declining of the initial system cost due to advancement in the technology, and grid electricity rate escalation, such a hybrid system can become an economically advantageous source for fulfilling the electricity demand along with contributing for the thermal demand of the residential units throughout a wide collections of geographic locations.

The results offer support to the preliminary analysis that indicated a potential increase in grid defection in the U.S. in the near future as it is clear that PV+battery+CHP is already economically feasible in some locations and as markets for the distributed generation technologies continue to mature economics without subsidies will provide incentives for grid defection and assist in increasing PV penetration levels in the U.S.

5.1.1.2 Technical Review of plug and play solar in U.S.:

This study investigated the potential technical hurdles for prohibiting the installation of plug-and-play solar PV for residential and small commercial use.

Relevant codes and standards from the National Electric Code, local jurisdictions and utilities for PV with a specific focus on plug-and-play solar were reviewed and discussed along with the current net metering and interconnection application procedure and the time required. Commercially available microinverters and AC modules on the market were found to be technically and safety compliant for use in plug-and-play PV systems.

The analysis also exposed the redundancy of the utility accessed AC disconnect switch for residential and small commercial grid connected solar PV. It is clear that the AC disconnect switch is not technically necessary and thus imposing it is an economic barrier to grid entry for solar PV systems with UL listed microinverters.

A streamlined application with only technical requirements was generated to reduce the time required for interconnection process. In addition, a free and open source streamlined application webpage is provided to ease utility implementation.

Finally, the advantages of supporting plug-and-play solar PV with UL certified microinverters is made clear because of greater uptake and PV penetration levels, improved prosumer economics, reduced installation costs and more environmentally responsible electric generation.

5.1.1.3 U.S. Market Analysis for plug and play solar:

A new method to calculate the LCOE and potential savings for prosumers of a plug and play solar photovolatic system was presented.

A sensitivity analysis of such a system on the capital cost of the system, the discount rates and the capacity factor depending on the geographical location for each state in U.S. was carried out. The results show that for available costs, plug and play PV systems are economic throughout the U.S. already.

If plug and PV is legalized in the U.S. the results show the total potential U.S. market is over 57 GW, which represents an opportunity for sales for retailers of a new product from $14.3 billion – $71.7 billion.

Such a mass deployment of distributed PV systems would generate over 100,000 thousand MWh per year, which is roughly four times the electricity generated from solar in the U.S. in 2015. This distributed solar energy would provide prosumers approximately $13 billion/year in electricity cost savings, which would be expected to increase by about 3% per year for the 20 year lifetime of the plug and play solar PV systems.

5.2 Future Work

5.2.1 Overview

The research work is directed towards technical as well as economic analysis of new technologies for residential solar PV systems. In this research work just preliminary analysis is carried out for such systems. Hence, there are certain limitations that can be addressed and the work can be carried out further. The followings are the limitations and future work that can be performed for the respective studies:

5.2.1.1 LCOE of hybrid system:

It should be pointed out here that Houghton should not be considered representative of the U.S. in any way. It has more severe winters (and thus higher heating costs and less solar flux) than most of the rest of the U.S. In addition, Houghton electric rates are particularly high for the U.S. because of the geographic (and thus grid) isolation in the upper peninsula of Michigan and the mining-centric nature of the electric loads. However, some of the same circumstances that drive higher utility rates also increase the installed cost of PV as compared to the U.S. national average. Thus this case study should only be considered as an example of the methodology and future work is needed to evaluate representative locations in each region of the country as demarcated by solar flux, natural gas prices and electricity prices.

This study focused on the LCOE and thus the cost of electricity from a hybrid system. The analysis is inherently conservative as it does not include the additional value of the heat from the CHP unit. However, the thermal demand that will be satisfied by the CHP module in the hybrid system is 18 MMBTU/year (i.e. 20% of the total annual demand in the case study region). The remaining 80% is to be satisfied with a conventional heater or furnace unit. The natural gas utilized by the heater and its corresponding cost can be taken into account and can be considered for future work for a complete economic analysis of such hybrid systems. In addition, future work could investigate modeling larger CHP systems to satisfy not only the electrical demand, but also the thermal demand of a residential building.

The CHP project, while not free of greenhouse gas emissions, is a least cost option to back up the PV system that also offers a reduction of approximately 60% in source energy and carbon versus a coal plant and creates approximately as many jobs as a wind or solar project of similar capacity (Quinn, James, Whitaker, 2013). CHP offers reductions in total primary fuel consumption on the order of 30% to 35%, which means equivalent CO_2 emissions reduction if the same fuel is consumed (Quinn, James, Whitaker, 2013). Thus, to further improve the work done the GHG emission rates can be considered.

An absorption chiller can be added to the CHP output to utilize the maximum amount heat energy available, thus raising the efficiency further. Such systems are known as trigeneration systems or CCHP (combined cooling heating and power) and have been investigated technically and appear promising (Pearce, 2009; Nosrat, & Pearce; 2011; Li, & Ogden, Pearce, 2011; Nosrat, Swan, & Pearce, 2013; Nosrat, Swan, & Pearce, 2014). Tri-generation, being one of the most promising technologies, allows the efficient simultaneous production of heat, cooling and power with all the three potential benefits technical, economic and environmental (Jradi, Riffat, 2014). Future works is needed to couple the cost of cooling into a complete life cycle cost analysis of such complex systems over a range of geographical locations and local climates.

In addition, optimizing such hybrid systems for GHG emission reductions can be considered in the future using dynamic life cycle analysis that reduced life-cycle carbon emissions (Kenny , Law , & Pearce ; 2010). One way to do this is with biomass-fueled CHP systems, which can produce heat and power with reduced net GHG emissions, and thus can be much more climate-friendly than systems fueled with fossil natural gas, coal, or oil. Biomass can be considered as renewable with low carbon emission and increasingly cost competitive alternative to traditional fossil fuels for heat and/or electric power generation (Salomón et.al; 2011). By substituting biomass for fossil fuel, carbon emissions from non-renewable, fossil fuels can be avoided (Fact Sheet: Combined Heat and Power, 2013). Finally, in some areas it may be possible to use a solar-only trigeneration systems for even more aggressive GHG emission cuts (Magalhães et. al., 2012). Again, further work is needed to provide a complete economic analysis of these types of systems.

It should be noted that although this case study was for the U.S., the details of the hybrid system economics reviewed in this study are valid elsewhere. The primary differences between the systems would be ensuring they meet the standards of the local regulators. For example, in Europe the guidelines set forth by EURELECTRIC, may influence dispatch strategies (Pierre et.al., 2011).

Historically, the quantity of output power from the distributed generation sources was restricted by the local demand load; however now bi-directional power flow between distribution system and transmission systems can be used due to new system structures allowing distributed grid to export power when local generation exceeds the consumption (L'Abbate et.al, 2007; European Smartgrid Technology Platform-Vision and Strategy for Europe’s Electricity Networks of the Future, 2006; SWECO, 2015). This has resulted in higher complexity in the management of distribution systems and thus the skills of the electrical engineers responsible for the grid. At the same time, it has offered new possibilities to optimize the overall system by allowing distribution networks and distributed renewable energy to participate actively in the system operation (Electric Power Research Institute, 2014). It should be noted that in some parts of Europe, particularly in the southern region of Germany the, output from distributed generation technologies on distribution networks is already exceeding the local load demand (SWECO, 2015; Electric Power Research Institute, 2014; The German Energiewende, 2015). As distributed renewable energy matures throughout the world, this could be the new normal rather than the exception.

5.2.1.2 Technical Review of plug and play solar in U.S.:

Using the approach described in the study and the review of plug-and-play PV regulations in other countries only 1kW can be put in a given circuit. Larger plug-and-play PV systems, may cause power stability issues and safety concerns depending upon the amp rating of the circuit.

A more detailed investigation is needed for larger plug-and-play PV systems to determine the maximum power able to reach for a given circuit and a streamlined method to make this maximum easily determined by the prosumer.

Future work is also needed to determine the ability of Americans to purchase plug-and-play PV systems and that sensitivity to income distribution. This would need to be compared to utility rates and solar flux availability at a granular scale across the country to gauge how plug-and-play PV could be put on the grid and the likely impacts as it scales.

To encourage greater plug-and-play PV system adoption a full scale LCOE could be run for individuals with granularity at the utility/State level and this could be coupled to financing plans and sales from PV vendors.

5.2.1.3 U.S. Market Analysis for plug and play solar:

For the LCOE calculations performed for each state in this paper the minimum solar flux data for that state was taken into consideration, which results in the conservative maximum estimated LCOE for the state.

Thus the savings for particular prosumers in a given state from this analysis may be greatly underestimated as the solar flux in some states varies considerably. For example, Arcata, CA average solar flux yearly is 3.93 kWhr/m^2/day whereas for Santa Maria, CA average solar flux yearly is 5.2 kWhr/m^2/day.

Similarly the representative costs of the electricity for each state may also create a source of error as these values range widely for different utilities within a state.

Future work is needed to do a more granular investigation of both the solar flux and the utility rates, although results presented here and the conclusion drawn from them are overall representative. A more granular approach could assist vendors target the most lucrative areas of the country with plug and play PV first.

Moreover, the shading varies for each house and this affects the energy being generated by the system. The assumptions used here again were conservative, but the error associated with the unshaded residences could be quantified using established techniques for the entire U.S. (Nguyen and Pearce, 2012; Nguyen et al., 2012; Liang, et al., 2014). Thus, a far better estimation could be made if such a system is to be installed for a particular house at a particular place.

As introduced in the discount rate section, low and middle income U.S. households do not have a rate of time preference over 100%, yet it appears that they do in energy efficiency studies because they simply make ununiformed purchasing decisions. Maybe we need better research to understand how purchasing decisions are made and what does influence costumers, but we know education isn't it (Willis, 2008; Lusardi, 2008; Pearce, et al., 2009; Hasting, Madrian & Skimmyhorn; 2013). In regards to this issue for plug-and-play solar PV, it is apparent that the large market estimated in this study is only possible with an education campaign targeted at consumers to understand the rates of return for such systems so they could compare them to their other investment options.

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