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Ramchandra Bhandari

Role of Grids for Electricity and Water Supply with Decreasing Costs for Photovoltaics

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Preface

Conventionally, the utilities are supplying electricity and water to households through electricity grid and water networks. Huge transmission grids for electricity transmission and vast pipeline networks for water supply are prerequisites for the distribution of these resources from the generation site to the consumers. These infrastructures need a lot of investment that leads either to higher unit costs of electricity and water to the ultimate users or to higher governmental subsidies to utilities. At individual level, a newly built house needs to be connected to the electricity grid and the water network. This cost could be very high, if the house is located distant from the existing grid/network. Nonetheless, the household should also pay the monthly electricity and water bills based on their consumption. The unit cost for conventional electricity and water usage has increased annually in the past years and it will continue in coming years as well. In such a situation, if the household prefers to supply its electricity and water demand by using distributed generation systems at house premises, it could not only avoid initial grid connection costs but also the consumption dependent burden. Such a dilemma of using either utility grids or distributed generation systems has been analysed in this study with the help of economic analysis model developed for the purpose.

Limited reserves of fossil fuel resources, their volatile and increasing price in the energy market and emission of several environment hazardous substances while burning are the reasons why sustainable and environment friendly alternatives to fossil fuels have to be sought urgent. Moreover, electricity generating power plants based on fossil fuels are centrally located and there is a need of huge infrastructure for fossil fuel transportation up to the power plants and for electricity transmission from power plants to the consumers. This leads not only to big investment in infrastructure but also to electricity loss in power lines. Distributed generation of electricity at the consumer's site using environment friendly renewable energy technology that theoretically have unlimited resources might be one of the best solutions to overcome these problems of fossil fuel based power plants. Solar photovoltaic technology that is user friendly, globally available and suitable for any range of applications is one of such renewable energy technologies and also the focus of this study.

Once the cost for electricity through distributed generation such as from solar PV could be brought down, it could positively contribute to the economics of water sector, because freshwater supply and wastewater treatment require electricity. An autonomous freshwater supply and wastewater treatment concept (i.e. freshwater supply from rainwater harvesting, process water supply from greywater recycling and on-site wastewater treatment and disposal) could be an important step to assist ensuring sufficient quantity and quality of water. However, such system will still need an initial investment and operating costs, including energy expenses. The economic analysis of autonomous water supply system has been carried out in this study.

Abstract

In the first part of this study, the grid connected solar photovoltaic technology is analysed. With the help of experience curves, different projections for the future PV installations as well as their cost reduction have been carried out for the period of 2007-2060, worldwide and in Germany. It is estimated that cumulative PV installation will reach to 98 GW_p in Germany and 4400 GW_p (~ 3.3-6.6 PWh) worldwide and c-Si module price will decrease to 0.51 €/W_p by 2060. Grid parity for German electricity market has been calculated using an economic analysis model developed for this purpose. It has been found that PV systems will reach grid parity in around 2012 and 2021 in the retail and the wholesale electricity market, respectively. With the use of PV electricity at the time of its generation, the real grid parity year has been calculated and it has been found to be between 2017 and 2013 for the PV systems with life time varying between 25 and 40 years, respectively. Different scenario and sensitivity analyses have been carried out in order to project the different grid parity years.

Stand alone PV systems for urban locations have been analysed in the second part of this study. It has been found that stand alone PV systems will not be competitive to grid electricity in Germany within the next few decades. The breakeven years are found to be between 2026 and 2034, for the systems with life times of 40 and 25 years, respectively. One of the reasons for their late occurrence is the higher variations in average daily global radiation in different seasons. While omitting the seasonal variations, module size would decrease from 22.1 kW_p to 7.8 kW_p and battery size would decrease from 71.8 kWh to 59.9 kWh in order to supply the yearly household electricity demand of 3500 kWh to a reference household in Cologne, Germany. The breakeven values for different parameters have been calculated (e.g. module price: -64 €/kW_p or battery price: -497 €/kWh or grid access distance to house: more than 2.1 km). For the same market and equal average annual global radiation value, but without seasonal variations in climate, the breakeven values would have been around 77 €/kW_p for module price or -143 €/kWh for battery price or 690 m for grid access distance to house.

In the third part, Nepal's energy overview and details on solar PV status have been presented. Economic analysis for solar PV systems for Nepalese urban areas has been made and the breakeven year is supposed to fall in between 2036 and 2026. The rural electrification option from utility's (grid extension) and consumer's (stand alone solar PV) perspective has been analysed. A village with about 100 households having an estimated average annual electricity demand of 100 kWh/hh has been chosen as a reference village and the calculations are made. Based on the assumptions made in the study, it has been found that, neither grid extension nor stand alone solar PV installations are feasible in these rural areas without government support.

In the last part of the study, the previously implied economic analysis model has been used for the calculations of an autonomous water supply household. It has been found that the water usage costs will be around 9.7 €/m^3 for an autonomous household. This is higher than the actual value of utility water use charge of about 4 €/m^3 in Cologne. Breakeven grid access distance would be about 1.6 km if a household should go for electricity and water autonomy.

Zusammenfassung

Herkömmliche Versorger sind für die Lieferung von Strom und Wasser an die Haushalte zuständig. Vorraussetzung für die Verteilung dieser Ressourcen von der Herstellerseite zum Kunden sind riesige Übertragungsnetze für den Strom und ausgedehnte Rohrleitungsnetze für die Wasserversorgung. Diese Infrastrukturen benötigen hohe Investitionen, welche entweder zu höheren Kosten von Strom und Wasser an den Endverbraucher oder zu höheren staatlichen Subventionen der Versorger führen. Im einfachsten Fall muss ein neu gebautes Haus an das Strom- und Wassernetz angeschlossen werden. Die sich daraus ergebenden Kosten können sehr hoch werden, wenn das Haus beispielsweise weit entfernt von einem schon existierenden Stromnetz bzw. Rohrleitungssystem ist. Nichtsdestotrotz sollte ein Haushalt die nach dem eigentlichen Verbrauch monatlich anfallenden Rechnungen für Strom und Wasser tragen können. In den letzten Jahren sind die Kosten für den herkömmlichen Strom- und Wasserverbrauch jährlich angestiegen, welches sich in den kommenden Jahren weiter fortsetzen wird. In dem Fall, in dem ein Haushalt es bevorzugt seinen Strom- und Wasserbedarf über dezentrale Versorgungssysteme zu decken, können nicht nur die Kosten für den Anschluss an das Netz vermieden werden, sondern auch die auf den Verbrauch bezogenen Kosten. Das Dilemma zwischen der Nutzung von Übertragungsnetzen und dezentralen Versorgungssystemen wurde in dieser Studie unter Zuhilfenahme eines für diesen Zweck entwickelten Wirtschaftlichkeitsanalyse Modells analysiert.

Fossile Brennstoffe sind nur in begrenzten Reserven vorrätig. Die unbeständig steigenden Preise im Energiemarkt und die bei der Verbrennung entstehenden Emissionen von umweltschädlichen Substanzen sind Gründe, nach nachhaltigen und umweltfreundlichen Alternativen zu suchen. Weiterhin basieren die zentralisierten Elektrizitätskraftwerke auf fossile Brennstoffe und es bestehen ein hoher Bedarf an Infrastrukturen, um die fossilen Brennstoffe zu den Kraftwerken zu transportieren, und der produzierte Strom von den Kraftwerken zu den Endverbrauchern zu übertragen. Dies führt nicht nur zu großen Investitionen in die Infrastrukturen, sondern auch zu Stromverlusten in den Leitungen. Eine der besten Möglichkeiten, um das Problem der auf fossilen Brennstoffen basierenden Kraftwerke zu lösen, wäre die dezentral Stromerzeugung direkt vor Ort des Kunden, indem umweltfreundliche und nachhaltige Technologien genutzt werden. Die benutzerfreundliche Photovoltaik Technologie, welche weltweit erhältlich und für alle Anwendungen verwendbar ist, ist eine solche erneuerbare Energie Technologien, welche auch den Fokus in dieser Studie darstellt.

Der Markt für Photovoltaik (PV) boomt seit Beginn des Jahrhunderts sowohl weltweit als auch in Deutschland. Die Industrie fokussiert sich weltweit auf die Förderung weiterer PV Systeme. Schwerpunkte werden auch auf die Verbesserung der technischen und wirtschaftlichen Leistung von PV Modulen und Systemen, auf die Entwicklung neuer Technologien und auf das Erlassen von staatlichen Regulierungen und Beschlüsse (z.B. der Einspeisetarif für erneuerbare Energien) gesetzt. Viele Länder haben bereits unterschiedlichen PV Förderprogramme in ihre nationalen Elektrizitätsgewinnungspläne (z.B. Subventionen)

eingeführt. Dennoch hindern die mit den PV Systemen verbundenen hohen Kosten die Wettbewerbsfähigkeit, so dass sie ohne Subventionen und anderen Förderungen nicht marktfähig sind. Nichtsdestotrotz ist eine starke Kostensenkung seit der kommerziellen Einführung in den 1980er Jahren zu beobachten.

Die Literatur zeigt über die Analyse von Erfahrungskurven auf, dass eine „Progress Ratio“ (PR) von 80 % häufig bei vielen Autoren über c-Si PV Modulen genutzt wird. In dieser Studie wurde ein gleichwertiger Wert von 80 % PR für c-Si Modulen und BOS angenommen, obwohl in einigen Schriften erwähnt wird, dass die Lernrate von BOS Komponenten schneller sein könnte als die der Module. Mit Hilfe der in der Literatur genannten Entwicklungsrate, der voraussichtlichen weltweiten Kapazität zukünftiger PV Installationen und der Erfahrungskurven wurde der zukünftige Preisverfall von PV Systemen berechnet. Es wurden unterschiedliche Möglichkeiten des zukünftigen Preisverfalls von PV Modulen mit Zuwachs der kumulierten Installationen extrapoliert. Die Modulpreise für 2060 wurden mit 0,28 €/W_p, 0,51 €/W_p, 0,89 €/W_p und 1,52 €/W_p für die jeweiligen PRs von 75, 80, 85 und 90 % berechnet.

In der Zurzeit erhältlichen Literatur wird nicht detailliert auf Erfahrungskurven von Solarbatterien eingegangen. Seitdem die Batterietechnologie bezüglich der PV Module angestiegen und reif ist, wurde für die Wirtschaftsanalyse dieser Studie eine höhere PR von 90 % angenommen.

Aufgrund der schnellen Preissteigerung der Elektrizität von konventionellen Brennstoffen auf der einen und den Fortschritten und weiterer Erfahrung in der PV Technologie, welche zur Massenproduktion führen auf der anderen Seite, wird in Zukunft der Tag kommen, an dem der Preis für Netzstrom generiert aus konventionellen Brennstoffen genauso hoch oder höher als der Preis für generierten Strom aus solarer Photovoltaik. Es gibt viele Marktfaktoren, die diesen Zeitpunkt ermitteln können. Diese Studie hat als eines seine Ziele gesetzt das Jahr der Netzparität zu ermitteln, welches der zukünftige Zeitpunkt ist, an dem es der Strom einer netzgekoppelten PV möglich ist mit dem Strom von konventionellen Brennstoffen in Wettbewerb zu treten, als auch die Grenzbedingungen der notwendigen Marktparameter für dieses Ereignis festzulegen. Für diesen Zweck wurde ein Wirtschaftlichkeitsanalyse Modell entwickelt, dass er eine Kosten-Nutzen-Analyse und eine Break-Even-Analyse durchführt. Die notwendigen Daten für die solare Einstrahlung, das jährliche Lastprofil eines Haushalts und weitere Marktparameter wurden einem Referenz Ort in Köln, Deutschland entnommen.

Ein Referenz-Haushalt in Köln, Deutschland verbraucht an Strom im Durchschnitt jährlich 3500 kWh. Der Gebrauch eines PV Systems mit einer Kapazität von 3,9 kW_p könnte einen solchen Haushalt in einen Null-Elektrizitäts-Haushalt wandeln. Die mit der Installation eines PV Systems verbundenen Hauptkosten sind die Fixkosten, z.B. die Investitionskosten um das Modul zu kaufen als auch die BOS Komponenten. Die Betriebsunkosten (z.B. Instandhaltungskosten) sind minimal. Die Einkünfte basieren auf die Menge des Stromertrages von dem System. Aus diesem Grund sind netzgekoppelte Systeme eine bessere

Option als Inselanlagen, da 100 % der von der PV Anlage erzeugen Strom an das Netz verkauft werden kann. Weiterhin sind die Investitionskosten dieser Systeme geringer, weil ein Gebrauch von Speicherkapazitäten nicht nötig ist.

Das Ergebnis der Kosten-Nutzen-Analyse gibt wieder, dass ein netzgekoppeltes PV System sich in Deutschland unter den Grenzbedingungen, die in dieser Studie benutzt wurden, immer noch nicht wirtschaftlich lohnt. PV Systeme könnten wirtschaftlich möglich werden, wenn die preiswerteren Solarmodule (z.B. Dünnfilm) den Markt dominieren würden. Die Break-Even Analyse weist auf, dass die Systeme bereits heute an der Rentabilitätsgrenze sein könnten, wenn der Modulpreis 0,88 €/W_p oder der Großhandelsstrompreis des Bezugsjahres 0,24 €/kWh betragen hätte. Das Jahr des Break-Evens wurde für 2019 berechnet, wenn die Lebensdauer des Systems 25 Jahre beträgt. In diesem Jahr wird der Modulpreis bei 1,71 €/W_p liegen und das der Großhandelspreis im Bezugsjahr wird 0,12 €/kWh betragen. Die Lerninvestition für PV Systeme wird zwischen 2009 und dem Break-Even Jahr 2019 in Deutschland etwa 23 Mrd. Euro betragen. Dieser Verlust wird durch Installationen in den Jahren danach gedeckt werden können, während das Jahr, in dem reiner Gewinn durch die Anlage erzielt wird, 2027 ist.

Die Netzparität für den Großhandelspreis für Strom wird 2021 eintreten, wird der Endverbraucherpreis für Strom berücksichtigt, wird die Netzparität bereits 2012 eintreten. Diese berechneten Jahre können sich jedoch durch unterschiedliche Markttendenz (z.B. die Fortschrittsrate, der jährlichen Wachstumsrate der kumulierten Installationen, die Preiszuwachsrate, Bankzinssatz etc.) verschieben.

Mit der durchschnittlichen stündlichen Solareinstrahlung in Köln kann einen Null-Elektrizitätshaushalt ca. 42 % der Strom, die von der PV Anlage gewonnen wird, bereitstellen. Weiterhin müssen 58 % des Haushaltsbedarfs mit Strom vom Netz gedeckt werden. Aus diesem Grund wird der Strompreis für eine kWh, für die Haushalte angepasst, die ein PV System auf dem Dach haben. Dieser angepasste Wert wird für die tatsächliche Bestimmung der Netzparität benutzt. Auf diesem Wege konnte berechnet werden, dass die Netzparität in den Jahren 2017, 2015 und 2013 für PV Systeme mit Lebensdauern von 25, 30 und 40 Jahren in Wirklichkeit eintreten werden.

Kann der Anteil des Stromverbrauchs im Erzeugungszeitraum gesteigert werden, würden sich PV Systeme schon früher wirtschaftlich lohnen. Durch Anwendung der Einstellungen der Laststeuerung auf dem Haushaltsniveau oder durch den Gebrauch von an der Steckdose aufladbaren Hybrid-Elektro-Fahrzeugen, welche den Markt in näherer Zukunft betreten werden, könnte dies erreicht werden. Neueste Debatten über Lebensmittelengpässe auf Grund der Benutzung von Biogas in Fahrzeugen können durch den Gebrauch von Elektrofahrzeugen vermieden werden. Dennoch sollten von nationalen und internationalen Interessenvertretern Programme gestartet werden, die der Öffentlichkeit dies ins Bewusstsein rufen. PV Systeme sollten in Ländern mit einer hohen durchschnittlichen Solareinstrahlung und deren Systeme bereits den Break-Even Punkt erreicht haben, energisch beworben werden. Installationen an diesen Orten können die weltweit kumulierten Installationen mehrfach verdoppeln und sie würden zusätzlich zur weltweiten Reduzierung der Modulpreise beitragen, die bereits jetz schon ein globales Produkt darstellen.

Das nächste Ziel dieser Studie ist die Analyse von PV Inselanlagen. Die Wirtschaftlichkeitsanalyse für eine Inselanlage wurde auch hier für einen Referenzhaushalt in Köln, Deutschland, durchgeführt. In Köln lag der Strompreis für den Haushaltskunden im Januar 2008 bei 21,43 €ct/kWh. Der größere Teil der Rechnung fällt allerdings nicht für die Stromerzeugung oder den Großhandelspreis an, sondern für die Übertragung, die Verteilung und die verschiedenen Steuern. Wenn man sich für ein PV Inselanlage entschieden hat, kann dieser Teil der Ausgaben auf der Rechnung vermieden werden. Diese vermiedenen Ausgaben können dafür verwendet werden, in ein PV Inselanlage zu investieren, um so verlässlichen und umweltfreundlichen Strom sicherstellen zu können.

Eine PV Inselanlage ist dennoch nicht frei von Mängeln. Das erste Problem ist die Erfordernis eines Stromspeichers, da der Strombedarf des Haushalts zeitlich nicht mit der Zeit der Stromerzeugung durch die PV Anlage zusammenfällt. Die durch die Vermeidung der Netze vermiedenen Ausgaben müssen umgelagert werden in eine Stromspeichereinheit, die normalerweise eine größere Batteriespeicherbank ist, um den Bedarf des Haushaltes auch in den Zeiten zu decken, in denen die Sonne nicht scheint. Das nächste Problem ist die Erfordernis eines übergroßen PV Systems, welches notwendig ist um die Stromversorgung über das ganze Jahr sicherzustellen (wegen Saisonelen Schwankungen in Globaleinstrahlungen). Da das PV Modul die teuerste Komponente des PV Systems ist, erhöht es die Gesamtkosten des Systems und die Erzeugungskosten für einen kWh Strom bezeichnenderweise.

Es überrascht nicht, dass die Ergebnisse dieser Studie zeigen, dass die PV Inselanlagen sich für deutsche Haushalte zurzeit wirtschaftlich nicht lohnen. Die Break-Even Jahre befinden sich zwischen 2026 und 2034 für Systeme mit einer Laufzeit zwischen 40 und 25 Jahren. Einer der Gründe für das späte Auftreten der Break-Even Jahre sind die Schwankungen der Globaleinstrahlung in den unterschiedlichen Jahreszeiten. Werden die saisonalen Variationen vernachlässigt, würde sich die Modulgröße von 22,1 kW_p auf 7,8 kW_p, sowie die Batteriegröße von 71,8 kWh auf 59,9 kWh verringern, um den jährlichen Strombedarf eines Referenzhaushaltes in Köln von 3500 kWh zu decken. Die Break-Even Werte wurden für verschiedene Parameter berechnet (z.B. Modulpreis: -64 €/kW_p oder Batteriepreis: -497 €/kWh oder Abstand des Hauses zum nächsten Netzzugang: mehr als 2,1 km). Für denselben Markt und einer ähnlichen jahresdurchschnittlichen Globaleinstrahlung, aber ohne die saisonalen Variationen des Klimas, liegen die Break-Even Werte bei 77 €/kW_p für Module, -143 €/kWh für Batterien oder 690 m Entfernung des Hauses bis zum nächsten Netzzugang.

Das sehr späte Auftreten des Break-Even Jahres (um 2034) könnte bedeuten, dass Haushalte nie zu PV Inselanlagen in Deutschland wechseln werden, um den eigenen Strombedarf zu decken. Dies ist darauf zurückzuführen, dass andere billigere Technologien schon auf dem Markt sein können, bevor die oben genannten Break-Even Jahre erreicht werden.

Dennoch wird die Systemgröße signifikant abnehmen, wenn das System dafür ausgelegt wird, den kompletten Strombedarf von nur elf oder zehn Monaten und den partiellen Bedarf von ein oder zwei Monaten in Jahr zu decken. Folglich könnten die Stromerzeugungskosten einer PV Anlage für ein kWh gering ausfallen. Aufgrund der saisonalen Variationen der erhältlichen Sonneneinstrahlung in Deutschland, können nur etwa 35 % der erzeugten Strom genutzt werden, während etwa 65 % der Erzeugung Verluste darstellen (dieser Verlust ist tatsächlich genauso groß wie 82 %, wenn man eine Q von 75 % und einen Einstrahlungswinkel von 30° genauso wie in dem Fall eines netzgekoppelten PV Anlagen annimmt). Dieser Verlust kann in netzgekoppelten PV Systemen vermieden werden, da 100 % des erzeugten Stroms in die Netze eingespeist werden können und aus diesem Grund der Gewinn aus den netzgekoppelten Systemen wirtschaftlich attraktiver ist.

Um das dritte Ziel dieser Studie zu erreichen, wurde das Modell für die Wirtschaftlichkeitsanalyse, welche für die Untersuchung der PV Systeme am deutschen Markt genutzt wurde, nach Nepal für ähnliche Studien übertragen. Es werden eine Energieübersicht Nepals und Details über den Status von PV Systemen präsentiert. Die Wirtschaftlichkeitsanalyse für PV Systeme in nepalesischen Stadtgebieten ergibt, dass die Break-Even Jahre zwischen 2036 und 2026 liegen. Dieses Break-Even Jahr ist soviel später, weil der Netzstrom ausschließlich aus Wasserkraft erzeugt wird und ein kWh diesen Stroms relativ preiswert ist.

Es wurde die Option für die zur Verfügungsstellung von Strom in ländlichen Gebieten einmal von Versorgerseite (Netzerweiterung) und von Konsumentenseite (PV Inselanlagen) analysiert. Ein Dorf mit rund 100 Haushalten und einem geschätzten jährlichen Strombedarf von 100 kWh/hh wurde als Referenzdorf gewählt und für die Berechnungen genutzt. Basierend auf die gemachten Annahmen in der Studie, konnte festgestellt werden, dass weder eine Netzerweiterung noch eine PV Inselanlage in diesen Gegenden ohne staatliche Unterstützung realisiert werden können.

In vielen abgeschiedenen und isoliert gelegenen Dörfern in Nepal gibt es aber keine überzeugende technisch-wirtschaftliche Alternativen zur Erzeugung von Strom über ein PV System, da das PV System modular aufgebaut werden kann. In solchen Gebieten würden die Kosten für eine Netzerweiterung pro übertragenen kWh Strom sehr hoch werden, da es auf der einen Seite um weit verbreitete Siedlungen und auf der anderen Seite auf geringen Strombedarf basiert. Selbst wenn es eine Preissenkung der Solarmodule in Zukunft geben sollte, wird es keinen großen Einfluss in der Preissenkung für sehr kleine Systeme (für häufig genutzte Systemgröße von 40-75 W_p) haben. Mit Stromversorgung werden die Leute, die Strom aus PV Systemen für Licht benutzen, eine große soziokulturelle Bedeutung haben, da diese Menschen sich nicht marginalisiert und ausgeschlossen fühlen von der Menge an Menschen, die sich an den Vorzügen des Stadtlebens erfreuen.

Wenn die Stromkosten durch verteilte Erzeugung, z.B. in Form von solarer PV, reduziert werden kann, hat dies positive Effekte auf die Wasserwirtschaft, weil die Trinkwasserversorgung und die Abwasseraufbereitung Strom benötigen. Ein selbstständiges Trinkwasserversorgungs- und Abwasseraufbereitungskonzept (z.B. Trinkwassergewinnung durch Sammeln von Regenwasser, Prozesswasserversorgung durch Grauwasseraufbereitung und vor Ort Aufbereitung und Verwertung von Abwasser) könnte ein wichtiger Schritt sein, um eine ausreichende Menge und Qualität von Wasser sicherzustellen. Dennoch benötigt auch solch ein System eine Anfangsinvestition und hat Betriebsinstandhaltungskosten, die Energieausgaben mit einbeziehen. Die Wirtschaftlichkeitsanalyse von Inselwasserversorgungssystemen wurde in dieser Studie als viertes Ziel durchgeführt.

Der Gebrauch eines Inselwasserversorgungskonzeptes macht es möglich, die Verbindungskosten an das Wassernetz und die daran beteiligten Kosten einzusparen. Die Wasserbilanz eines selbstständigen Hauses mit vier Bewohnern in Köln, Deutschland wurde wie folgt berechnet: Aufbereitete Grauwasserversorgung: 48 %, Sammeln von Regenwasser und die Versorgung dadurch: 29 %, Grundwasserextraktion und -versorgung: 23 %, Abwassererzeugung und –Aufbereitung: 47 % (mit zusätzlichen 5 % des wieder aufbereiteten Grauwassers, welches für die Gartenbewässerung benutzt wird).

Die Kosten-Nutzen Analyse zeigt, dass das Inselwasserversorgungssystem sich wirtschaftlich nicht lohnt. Die Umladekosten des Wassers würden 9,7 €/m^3 kosten, im Vergleich dazu kosten derselbe Service vom Versorger nur um die 4 €/m^3. Jedoch wären solche Systeme wirtschaftlich realisierbar, wenn das Haus sich weiter als 287 m von dem nächsten Wassernetzwerk befinden würde.

Der Strombedarf für die Nutzung der Wasserversorgung und des Aufbereitungssystems wurde auf 443 kWh/Jahr geschätzt. Wenn ein PV Inselanlage installiert wird, um den Strombedarf zu decken, wird die berechnete Systemgröße für ein Modul 2,3 kW_p und die Batterie 7,4 kWh betragen.

Es wurde auch eine Analyse des Stroms (von einer PV Anlage) und des Wassers im selbstständigen Fall untersucht. Da keine dieser Systeme die Rentabilitätsgrenze bisher erreicht hat, wird die Kombination von beiden erhöhte Verluste hervorrufen. Jedoch könnte ein Haus, welches in einer Entfernung von etwa 1,6 km von der nächsten existierenden Stroms- und Wasserinfrastruktur befindet, ein selbstständiges Strom- und Wasserversorgungssystem benutzen. Das Paritätsjahr bei der Nutzung der kombinierten Strom- und Wasserversorgung wurde für 2038 berechnet.

Resultat dieser Dissertation ist, dass die Haushalte nicht vom Gebrauch des Netzes zu netzunabhängigen Systemen wechseln sollten, um deren Strom- und Wasserbedarf in dicht besiedelten Gebieten, die eine gute Infrastruktur aufweisen, zu decken. Dies wendet sich an den deutschen und den nepalischen Fall. Dennoch gibt es in ländlichen Gebieten, in denen die

Infrastruktur noch nicht gut genug ausgebaut ist, keine bessere Alternativen als PV Inselanlagen. Mit sinkenden Kosten für Photovoltaikanlagen in den kommenden Jahren wird die Entwicklung der Netzinfrastruktur in ländlichen Gegenden weniger interessant bleiben, da die Gewinnschwelle für Lieferungen von Inselanlagen höher wird als bei Netzerweiterung.

Weiterhin wird es einen höheren Bedarf an Netzen geben, um den von anderen erneuerbaren Energien generierten Strom mit einfließen zu lassen. Daher sind weitere Investitionen in die Entwicklung und in den Betrieb von stabilen Netzen notwendig. Die Rolle der Netzinfrastruktur wird in der Zukunft nicht abnehmen, sondern zunehmen.

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Ramchandra Bhandari
17.03.2010

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List of Symbols

Symbol	Unit	Description
A_c	m^2	Catchment area
b	-	Rate of innovation or learning parameter
B	€	Benefit
C_0	€	Unit cost at $t = 0$
C_b	€/kWh	Battery price
C_{bos}	€	Present value of cost associated with initial investment for BOS
C_{bosrpl}	€	Present value of BOS replacement cost
C_{brpl}	€	Present value battery replacement cost
C_{bt}	€	Present value of initial battery expenditure
C_{ga}	€	Present value of grid access cost
C_{gt}	€/m	Cost of grid extension per unit distance
C_{iga}	€	Initial grid access cost
C_m	€/kW_p	Module price
C_{mbos}	€	Present value of initial BOS expenditure (excluding battery)
$C_{mbosrpl}$	€	Present value of BOS replacement cost (excluding battery)
C_{mt}	€	Present value of module expenditure
C_t	€	Unit cost of production at time t /present value of total system cost
C_v	€	Present value total variable cost
d	%	Real discount rate
D	days	Effective energy consumption days in a year
D_a	days	Number of autonomy days
DOD	%	Maximum depth of discharge
E_d	kWh/yr	Annual electricity demand
E_n	kWh	Annual energy yield
f	%	Grid fee (in % of electricity price)
G	$kWh/m^2.yr$	Global radiation
G_h	$kWh/m^2.yr$	Global radiation on horizontal surface
G_i	$kWh/m^2.yr$	Global radiation on inclined surface
H	-	Number of households
i	%	Real interest rate
I_{stc}	kW/m^2	Standard solar radiation
k	-	Module price reduction factor
k_{bos}	%	BOS cost factor
k_{bosrpl}	%	BOS replacement cost factor
k_{brpl}	%	Battery replacement cost factor
k_v	%	Variable cost factor
L	m	Average distance
M	mm	Average rainfall
N	yr	System life time

n_b	yr	Battery replacement year
N_g	yr	Grid infrastructure life time
N_r	yr	BOS component life time (replacement year)
P_{el}	€/kWh	Base year electricity price
$P_{el,e}$	€/kWh	Base year end use electricity price
$P_{el,w}$	€/kWh	Base year wholesale market electricity price
P_{peak}	kW_p	Peak power
P_w	€/m^3	Base year freshwater price
P_{ww}	€/m^3	Base year wastewater disposal charge
Q	%	Quality factor (performance ratio)
Q_0	no.	Cumulative production by firm at $t = 0$
Q_t	no.	Cumulative production by firm at time t
r	%	Growth rate
R	€	Revenue
$r_{1\text{-}4}$	-	Battery replacement frequency, from 1 to 4
r_e	%	Annual growth rate for end use electricity price
r_g	%	Grid extension price growth rate
$R_{P/L}$	-	Production to load ratio
r_w	%	Annual growth rate for wholesale electricity price
r_{fw}	%	Annual growth rate for freshwater price
r_{ww}	%	Annual growth rate for wastewater charge
s	%	Annual degradation of energy yield
T_s	m^3	Rainwater storage tank size
V_r	m^3/month	Harvested rainwater quantity
V_w	m^3/yr	Volume of recycled greywater
y_d	-	Day of the year
α	^{o}	Elevation angle
β	^{o}	Angle of inclination for module
δ	^{o}	Declination angle
η_b	%	Battery energy conversion factor (ageing factor)
η_c	%	Rainwater collection efficiency
η_r	%	Efficiency of rainwater treatment systems
φ	^{o}	Latitude of the location

List of Abbreviation

€	Euro
$€_{ct}$	Euro Cent
AC	Alternating Current
BCG	Boston Consulting Group
BEP	Breakeven Price
BOD	Biological Oxygen Demand
BOS	Balance of Systems
Brek	Breakeven
Cap	Capacity
CBA	Cost Benefit Analysis
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
c-Si	Crystalline Silicon
CSPS	Community Solar Photovoltaic Systems
Cum	Cumulative
DC	Direct Current
Deg	Degree
DOD	Depth of Discharge
E. coli	*Escherichia coli*
EEX	European Electricity Exchange
Elect	Electricity
EU	European Union
FIT	Feed in Tariff
FV	Future Value
Gen	Generation
GHGs	Greenhouse Gases
GR	Growth Rate
GW_p	Giga Watt Peak
hh	Household
HH 1	Household Type 1
HH 2	Household Type 2
IEA	International Energy Agency
ISPS	Institutional Solar Photovoltaic Systems
kfW	Kredite für Wiederaufbau (German Development Bank)
kg	Kilogramm
km	Kilometer
kW	Kilowatt
kWh	Kilowatt Hour
l	Liter
LLP	Loss of Load Probability
LR	Learning Rate

m	Meter
M10/11/12	PV Electricity Generation to Cover the Full Demand of 10/11/12 Months
MBR	Membrane Bioreactor
mg	Milligram
ml	Milliliter
MW	Megawatt
N	Nitrogen
NASA	National Aero Space Agency
NEA	Nepal Electricity Authority
NPV	Net Present Value
NRs	Nepali Rupees
NSV	No Seasonal Variation
NTU	Nephelometric Turbidity Unit
O_2	Oxygen
^oC	Degree Celsius
p	Peak
P	Phosphorous
pH	Hydrogen-ion Concentration (in water)
PR	Progress Ratio
PV	Photovoltaic
PWh	Petawatt Hour
R & D	Research and Development
RBC	Rotating Biological Contactor
RE	Renewable Energy
RETs	Renewable Energy Technologies
s	Second
SA PV	Stand Alone Photovoltaic
SAG	Stand Alone Systems in Germany
SAU-NSV	Stand Alone Systems in Urban Areas – No Seasonal Variation
SBR	Sequencing Batch Reactor
SHS	Solar Home Systems
SSHS	Small Solar Home Systems
TN	Total Nitrogen
TP	Total Phosphorous
TSS	Total Suspended Solid
TWh	Terawatt Hour
US$	United State Dollar
UV	Ultraviolet
V	Volt
VDC	Village Development Committee
W	Watt
WLED	White Light Emitting Diodes
yr	Year

1 INTRODUCTION

1.1 Overview

About 80 % of present worldwide energy consumption is derived from fossil fuels and nuclear energy [WEC, 2007]. Several risks are associated with the use of centralized fossil fuel power plants. Energy infrastructures i.e. power plants, transmission lines and substations, and gas and oil pipelines, are all potentially vulnerable to natural and/or human disasters. Adverse weather conditions also have negative effect to those power plants. For example, during the summer of 2003, one of the hottest and driest European summers in recent years, the operations of several thermal power plants in Europe were put at risk owing to a lack of water to cool the condensers [WEC, 2007]. In other parts of the world, hurricanes and typhoons put the central fossil and nuclear power plants at grave peril. World demand for fossil fuels (especially oil and natural gas) is expected to exceed its annual production, probably within the next two decades. Shortages of oil and/or gas can procreate international economic and political crises and conflicts. Moreover, burning of fossil fuels releases emissions such as carbon dioxide, nitrogen oxides, aerosols, etc. which affect the local, regional and global environment [Nguyen, 2007]. Figure 1.1 illustrates the high dependency of world population on fossil fuel resources to fulfil their electricity demand.

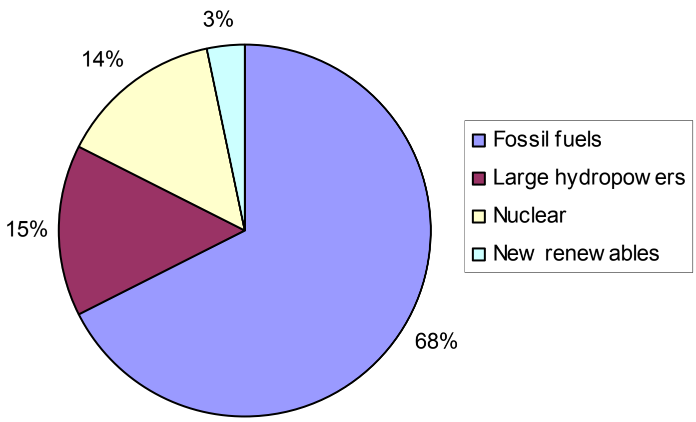


Figure 1.1: World electricity generation by fuel types in 2006 [REN21, 2008]

Combating climate change is one of the most decisive challenges mankind has ever faced [Borenstein, 2008]. Fourth Assessment Report of Intergovernmental Panel in Climate Change found that human actions are ‘very likely’ cause of global warming, meaning a 90 % or greater probability, indicating CO_2 emission from fossil fuel burning as one of the major causes [IPCC, 2007]. As fossil fuel prices have risen and concerns over greenhouse gases (GHGs) and global climate change have increased, alternative technologies e.g. renewable energy technologies for producing electricity have received greater attention in recent years. Solar radiation and other renewable energy resources are more equally distributed than oil, coal, gas or uranium. This suggests that by transitioning to renewable energy, developing nations are less exposed to imported energy costs. Renewable energies also reduce the pressure on fossil fuels and are therefore less exposed to armed conflicts over scarce resources [ISES, 2005]. Because of these several disadvantages of acute dependence on fossil fuels, many countries have already started developing and using renewable energy technologies.

Countries like Germany have already a significant share of renewable energies in their electricity mix. This trend has to grow worldwide to avoid the problems related with continuous use of fossil fuels. Figure 1.2 shows the share of renewable energies in German electricity market in 2007.

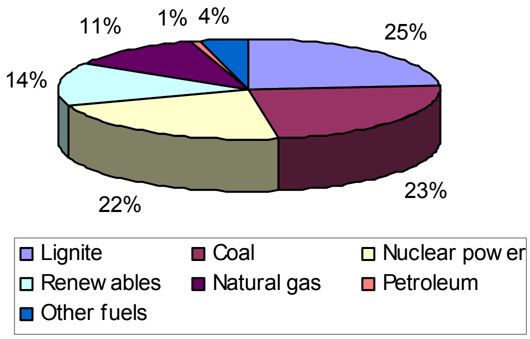


Figure 1.2: German electricity generation by fuel types in 2007 [BMU, 2008a]

In spite of the recent success of renewable energies in some areas, the growing global energy consumption still causes an increase in the consumption of fossil fuels and associated CO_2 emissions. This highlights the urgency to develop and implement renewable energy technologies that can be made available to all people in urban as well as in rural areas and that can make a substantial contribution to meet increasing energy demand. There is general consensus that solar photovoltaic (PV) (conversion of solar radiation into electricity) is one of such technologies. PV has the unique property that arrays can be built ranging from milliwatts up to megawatts installation. PV modules can be part of a consumer product, mounted on roofs of houses, integrated in a building or assembled into large power stations. Because of its modularity, it is accepted as a means to serve energy needs in dispersed and isolated communities. It can be designed to be very robust and reliable, at the same time it is quiet and safe [EC, 2005]. PV offers possibilities to match between electricity supply and demand by generating electricity during day time, when demand of electricity and its price is also high. Although PV offers so many advantages, its exploitation is very limited so far. Even in countries like Germany, which is worldwide PV market leader at present, share of solar PV in renewable electricity mix is quite less, only about 4 %, as shown in figure 1.3.

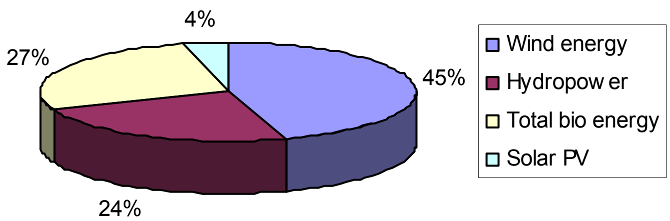


Figure 1.3: Electricity generation by RE source in Germany in 2007 [BMU, 2008a]

Although reliable PV systems are commercially available and widely installed, further development of PV technology is crucial to enable PV to become a major source of electricity in global market. EC-PVTP [2007] mentioned that the current price of PV systems is already low enough in some parts of world for PV electricity to compete with the price of peak power in grid connected applications and with alternatives like diesel generators in stand alone applications, but cannot yet compete with the consumer or the wholesale electricity prices in the most of other parts. A drastic further reduction of turn key system prices is therefore needed and it is fortunately possible. Photovoltaic conversion of solar energy is a vital part of future sustainable energy supply and, slowly but sure, is becoming a mature source of energy. EPIA [2008a] and Wyers [2007] estimated that PV may contribute to the reduction of CO_2 emissions by an equivalent of 75 coal fired power plants or 45 million cars in 2020. According to EPIA [2008a] estimation, solar PV already provides more than a million households with electricity in developing countries and emerging economies. Solar PV has the following variety of unique characteristics, which give this option a leading role in a sustainable energy supply of future [Wyers, 2007]:

- It is the only sustainable energy source with virtually unlimited potential
- It is available worldwide, also at high latitudes
- The product, electricity, is suitable for all applications
- Due to its wide geographical availability, it is the preferred solution for rural areas
- Because of the absence of moving parts, emissions, and noise generation, it is suitable for use in heavily populated areas
- Since it can be integrated into buildings and infrastructure, it occupies little space
- Solar electricity enjoys widespread public support

Even though the shift from fossil fuel to a sustainable global energy system is urgent, its implementation is a huge challenge worldwide at present and this transition will take long time (e.g. 30 years or more [EC, 2005]). This process involves huge financial investment and a strong and continued political commitment in the wide use of these technologies. In such a transitional phase, solar PV has already proven it as a key renewable energy technology. The current but relatively early stage of development of solar PV indicates a large potential for steady and high growth rate up to and beyond 2030 [EC, 2005]. It is envisaged that PV will be established as a viable electricity supplier by 2030, and the PV market will continue to grow thereafter at full speed.

In this study, different market scenarios (worldwide in general, and especially in Germany and in Nepal) for the solar PV development have been analysed. Different market parameters that play an instrumental role in the economics of solar PV have been thoroughly studied. Similarly, different criteria for grid connection and off grid rural electrification approach have been proposed. The methodology for market and economic analysis for solar PV systems have been developed and it has been applied for analogical analyses of water use at household level because both electricity and water utilities share the similar approach i.e. both are distributed to the users from their source of generations using the infrastructure network, which is one of the most costly components. Hence, together with the study of electricity autonomous household, the economics analysis of the water autonomous household has been carried out.

1.2 Motivation

More than two billions people worldwide have their dinner under kerosene light, candles and wood flames or even in dark. The reasons are obvious that they do not have electricity because of technical, economical, political, social, geographical, etc. reasons. Due to lack of electricity, they are deprived of manifold benefits- ranging from health and education up to economic development. Sustainable and cost free renewable energy resources are one of the best options for electricity supply to the people living in those areas. Renewable energy resources are for free, unfortunately the users have to pay for technologies. This is the main cause why many people have to live in dark as of today.

Power generation in central station requires significant investment in transmission and distribution infrastructure, an investment that could potentially be reduced if the power was generated on site [Borenstein, 2008]. Distributed generation has many advantages over conventional grid systems. Distributed generation is often supported for its security value [Borenstein, 2005]. The argument is that small scale on site generation makes the electricity system less vulnerable to human acts (e.g. terrorist attack) because it reduces the number of high value targets where a single strike could cut power to many users, it cuts down the grid instability that could result from loss of a large power generator or transmission line, and in the case of solar PV, it reduces the use of dangerous fuels (e.g. nuclear fuels) that create additional potential hazards to mankind.

Decentralized renewable energy technologies can be located closer to the users so that distribution and transmission cost and consequently energy and capital losses are reduced. They also avoid the need for high cost utility generation (e.g. gas turbines) that would have to be brought on operation because the households consume more electricity at peak times when the demand on the grid is also at the highest (around mid day). Solar PV does not require fuel i.e. its operation is independent from fuel supply availability and fuel cost. From a social point of view, solar PV creates more employment opportunities, in particular for the local workforce, because its installation, operation and maintenance are done almost exclusively in user's sites. In environmental terms, solar technologies are clean. Thus, the use of renewable energy (e.g. solar PV) for rural electrification will provide the benefits by reducing emissions of air pollutants and greenhouse gases, increasing employment opportunities and strengthening the economy through effective and sustainable utilization of local resources.

Solar PV technology for electricity generation has already proven its manifold applications and it is accepted worldwide. However, high investment costs associated with PV are the major causes hindering its widespread dissemination. Literatures show that production cost for a technology decreases with its mass production and with its maturity and it also applies to solar PV technology. This phenomenon is described by many authors using experience curves (details in chapter 3). In market economy, production is only increased if there is sufficient demand. Theoretically, there exists an enormous worldwide market for solar PV and, at the same time; there are many industries capable of producing this technology. Manufacturers have mainly concentrated in industrialized countries e.g. Germany, Japan, USA, etc., whereas electricity demand (population without electricity) is high in developing countries. If this demand and supply could be brought to a common meeting point in the market, supply cost of PV (i.e. market price of PV) could be reduced drastically. This would result in millions of households worldwide provided with electricity from solar PV. This market push should be started from the wealthy communities and authorities, who can afford the current high price of technology i.e. grid connected systems in developed countries. If production is increased in the first phase targeting people who can afford this, it will significantly reduce the production costs in a long run. Afterwards, this cheap product could be provided to people, who can afford only at a smaller amount. Even if there would have been long lasting and enough fossil fuel reserves worldwide to generate grid electricity, it is almost impossible to connect electricity grids to some regions in the world because of their unfavourable geographical locations. In such cases, there is no alternative for distributed generations. Fortunately, solar radiation is available in many such remote areas worldwide.

This study aims to analyse the diverse market conditions that are needed for full-swing and self sustained growth of solar PV in grid connected systems (especially developed countries like Germany, where grid infrastructure already exists). The lesson learnt from the outcome of this section is used to analyse the role of solar PV systems for the electrification in developing countries (i.e. in Nepal as a reference country, both in urban and in remote and isolated areas).

People even without electricity should have access to drinking water for their living. Water quality, water availability, access and cost are different issues for discussion. The similarity between electricity and water is that both the systems, for distribution, use some kinds of network systems, i.e. transmission lines for electricity and piping for water. More or less, both resources are available on site i.e. different renewable energy sources for electricity and rain or freshwater sources for water.

Unlike electricity, water has to be treated to bring it back to a certain quality level after its use. Its disposal also needs piping systems leading to double cost for its transport. From environmental as well as economic point of views, it might be interesting to reuse the water at its point of consumption. For sure, the economics of autonomous water supply plant at household depends on utility costs for water use and its disposal as well as cost for the investment in autonomous water supply plant and its operation. Socio-cultural issues might also play an important role for accepting or rejecting the technology. In this study, the economic feasibility of autonomous systems at household level in Germany has also been studied. The developing countries like Nepal could also apply such technology, especially in tourism sector (hotels and others tourist spots), the second biggest economy of the country.

1.3 Objectives

Solar photovoltaic sector is booming worldwide and in Germany as well since the beginning of this century. Germany has been the market leader worldwide in recent years. The industries are focusing their efforts in promotion of more PV systems worldwide. Focuses are also concentrated in increasing technical and economic performances of PV modules and systems, developing new technologies, enacting effective government regulations and policies (e.g. feed in tariff). Many countries have already included different PV promotion programmes (e.g. subsidies) in their national electrification plans. However, high cost associated with solar PV systems is still hindering its market competitiveness and it can not survive yet in the market without these subsidies and supports. Nonetheless, costs are decreasing rapidly since its commercial application started in 1980s. Because of rapid increase in prices of electricity from conventional fuels on one hand and improvements and further experiences in PV technology leading to mass production on the other hand, a day will come in the future when the price for grid electricity generated from conventional fuels will be same or even higher than the price of the electricity generated from solar PV. There are many market factors that may determine sooner or later commence of such time. **Hence, the first objective of this dissertation is to find out the 'grid parity year' that is the time point in future when the electricity from grid connected PV will be able to compete with the electricity from conventional fuels, and to assess the conditions of market parameters necessary for its happening.**

When the household electricity bill is analysed, major part of the bill does not fall under electricity production or wholesale price, but it comes under transmission, distribution and different taxes on electricity. In Germany, electricity price for a household customer in January 2008 was 21.43 €ct/kWh, out of which wholesale price accounted only 6.49 €ct/kWh [RWE, 2008; BDEW, 2008]. Prices of conventional energy resources (e.g. oil and natural gas) are increasing rapidly in recent years. However, the price of renewable energy technologies has been decreasing annually because of their mass production, innovation, better efficiency, experiences of the industries, etc. The price of solar photovoltaic system has been decreasing with a factor of about 20 % for each cumulative doubling in its production. One day in the future, installation of a distributed generation system, e.g. solar PV, at own home premises might be cheaper than paying the regular electricity bills to utilities for using the electricity from grids plus paying the initial cost associated with grid access to newly built house. This has been analysed in framework of this study with the help of experience curve analysis and cost benefit analysis. For reference purposes, climatic data and economic parameters from Germany and Nepal are used in the calculations. **Hence, the second objective is to find out the time point in future and the necessary market conditions, when installing a stand alone solar PV system at home premises might be cheaper than buying the grid electricity from the utilities.**

As mentioned earlier, more than one third people worldwide have no access to grid electricity. It is obvious that in many human settlements in developing countries (e.g. Nepal), it is almost impossible to extend the central grid because of their isolated and adverse geographical location. In other cases, it might be very expensive to extend the central grid to the geographically accessible but small communities. Grid extension cost (cost per kWh or cost per household) depends on many factors e.g. number of people living in the site, energy consumption pattern or demand, distance between central grid node and site, type of terrain (cliff, flat land, mountain, river, road side, etc.), etc. Electricity supply by using stand alone solar PV system might be one of the best options in those areas, where the grid extension is either costlier or illogical. **Hence, the third objective is to find out the market conditions under which rural electrification should be carried out by grid extension and under which stand alone solar PV or other distributed systems have to be chosen.**

Finally, using the similar concept used for the analysis of grid and off grid PV electricity use, **the fourth objective is to develop a concept for an autonomous water supply system in household level in Germany, to carry out its cost benefit analysis and to determine the PV system size required in order to supply the energy demand for the operation of such water supply system.**

Beside these major objectives discussed above, the other points that will be considered in this study are:

- To develop a model for the calculation of aforementioned economic analyses (grid connected, off grid urban, and off grid rural)
- To assess solar PV development in Nepal
- To carry out a rural electrification case study in a Nepalese village by implementing the results from the economic analysis

In summary, one will get the answers for the following questions after reading this study thoroughly:

- Under which market conditions will the solar PV system be a free market good?
- When will someone start to generate electricity using PV at his/her own home premises and cancel the contract with his/her then electricity supplier?
- If someone builds a new house today, will he/she buy a PV system for electricity supply in his/her new house?
- As a rural electrification project manager, will someone go for grid extension from the nearest available point or will he/she go for stand alone PV generation at individual houses?
- What are the consequences in home energy balance and home economy if someone installs an autonomous water supply system in his/her house premises?

1.4 Outline

This dissertation consists of nine main chapters and varying sections under each chapter.

Chapter 1 dealt with general overview on the topic of the dissertation, motivation behind the study, and its objectives.

Chapter 2 deals with basics of solar PV technology. Working principle of solar PV, its components, its applications and recent developments worldwide have been discussed.

Chapter 3 deals with experience curve analysis of solar PV systems. Basics of learning and experience curve theory, their advantages, limitations and applications in solar PV systems have been discussed.

Chapter 4 deals about solar PV prospects in Germany and worldwide. PV module and system price as well as their cumulative installation in Germany and worldwide have been projected for the period of 2009-2060.

Chapter 5 deals with the economic analysis of grid connected solar PV systems. A model has been developed for cost benefit analysis. Grid parity year for solar PV systems has also been discussed. Results from the cost benefit analysis and breakeven analysis for the reference country Germany have been presented. Partial results of this chapter have been published in [Bhandari and Stadler, 2009a].

Chapter 6 deals with the economic analysis of stand alone solar PV system for urban areas. Similar to chapter 5, results from cost benefit analysis and breakeven analysis have been presented. German market and climate data have been taken for reference scenario. The comparison has been made for a hypothetical case if there was no seasonal variation in the climate in Germany. Partial results of this chapter have been published in [Bhandari and Stadler, 2009b].

Chapter 7 gives an overview of energy consumption and status of solar PV systems in Nepal. Analysis for the stand alone systems for Nepalese cities has been carried out. Discussion about grid extension and stand alone solar PV system has also been made. A case study site in Nepal has been selected and a rural electrification plan has been presented. Grid extension in new location and costs associated with it has also been discussed in order to show where to extend central grid and where to go for stand alone PV systems. Partial results of this chapter have been published in [Bhandari and Stadler, 2010].

Chapter 8 deals with the technology and economics of the autonomous water supply system in a German household. Stand alone water supply system that consists of greywater recycling, rainwater harvesting, groundwater extraction and wastewater treatment and disposal has been studied. The boundary conditions (price) for when to use utility's water supply and disposal systems and when to use own autonomous water supply system have been discussed. A PV system size needed for operating the autonomous water supply plant has been also calculated.

Chapter 9 reviews the conclusions of the dissertation. Some recommendations for future works have also been proposed.

References are given at the end of this dissertation, i.e. after chapter 9.

2 SOLAR PHOTOVOLTAIC SYSTEMS

2.1 Solar Energy

Solar energy is the most abundant permanent energy resource on earth and it is available for use in both direct (solar radiation) and indirect (wind, biomass, hydro, etc.) forms. The current study is limited only to the direct use of solar radiation, the earth's prime energy resource. WEC [2007] mentioned that even only 0.1 % of this energy could be converted at an efficiency of only 10 %, it would be four times world's total generating capacity of about 3000 GW (however, EIA [2008] mentioned the installed capacity in 2005 about 3900 GW).

2.2 Solar Photovoltaic

Although the basic principles of PV were discovered in the 19th century, it was not before the 1950s and 1960s that solar cells found practical use as electricity generators, a development that came about through early silicon semiconductor technology for electronic applications [EC-PVTP, 2007]. Today, a range of PV technologies are available in markets and under development in laboratories. They constitute mono-crystalline and poly-crystalline silicon cells, thin film solar cells (cadmium telluride, copper indium gallium selenide, amorphous silicon), concentrating PV cells, etc. Among them, crystalline silicon has the biggest share in market till today; however, thin film solar cells are likely to rule the future market. Complete PV systems consist of two elements; the first one is module, which contains solar cells, and the next is balance of systems (BOS).

BOS includes ancillary equipments necessary to install and deliver electricity from a PV module. BOS requirements vary between applications due to site specific power and reliability requirements, environmental conditions and power storage needs. BOS components comprise mounting equipment such as frames and ballasts to support and elevate the PV module. A small portion of installed PV systems also use tracking systems to follow the sun, thereby increasing the exposure to incident sunlight. Power conditioning equipment limits current and voltage, maximizes power output and converts direct current (DC) electricity generated by the PV array into alternating current (AC) electricity through a DC/AC inverter. Power storage is a desirable or in many instances a compulsory power system requirement, and thus a battery and a charge controller device must be added to BOS. PV systems necessitate protective electrical hardware such as diodes, fuses, circuit breakers, safety switches and grounds, as well as wiring to connect the PV module and BOS components [Notton, 1998 and NREL, 2008]. In applications where a PV system will be supplementing a base load or where power must always be available (i.e. night time or cloudy day), a PV system is usually integrated with an auxiliary electric generator. This hybrid system does not necessarily fall under the definition of BOS. An additional electric generator will reduce the overall size of PV module, battery and BOS components.

2.3 Types of Solar PV Systems

IEA-PVPS [2007] has categorized the solar PV systems into four types based on their primary applications. They include:

i. Grid Connected Centralized Systems

They perform the functions of centralized power stations. The power supplied by such a system is not associated with a particular electricity customer, and the system is not located to specifically perform functions on the electricity network other than the supply of bulk power. These systems are typically ground mounted and functioning independently.

ii. Grid Connected Distributed Systems

Those systems are installed to provide power to a grid connected customer or directly to the electricity network, specifically where the part of the electricity network is configured to supply power to a number of customers. Such systems may be often on the demand side or integrated into the customer's premises, on public and commercial buildings, in the built environment, on motorway sound barriers, etc.

iii. Off Grid Non Domestic Systems

Those installations were the first commercial application for terrestrial PV systems. They provide power for a wide range of applications, such as telecommunication, water pumping, vaccine refrigeration and navigational aids. These are applications where small amounts of electricity have a high value, thus making PV commercially cost competitive with other small generating sources.

iv. Off Grid Domestic Systems

These systems provide electricity to households of the dwellings that are not connected to the electricity grid. They provide electricity for lighting, electronic appliances and in some cases for refrigeration and other low power loads. Such household systems, normally referred as solar home systems, have been installed worldwide and are often the most appropriate technology to meet energy demands of rural communities. Off grid domestic system sizes typically range from few watts to few kilowatts and they generally offer an economic alternative to extending the electricity distribution network from existing distant power grids.

IEA-PVPS [2007] had published data for PV installations in IEA countries stating that about 90 % of the installations by 2006 were only grid connected systems (figure 2.1).

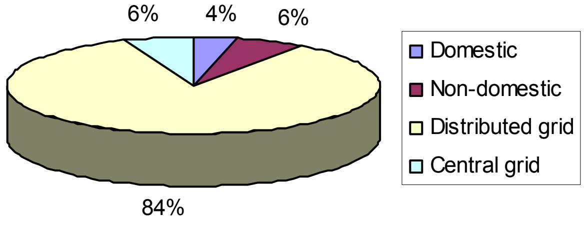


Figure 2.1: PV installation in IEA countries by system types by 2006

As an extreme example, figure 2.2 shows that almost all the systems installed in Germany by 2006 were grid connected. This trend has not been changed much until today. This is, however, opposite in the developing countries, where most of the installed systems are off grid stand alone systems. For example, almost all the PV installations in Nepal are stand alone systems, either used by individual households or used by communities.

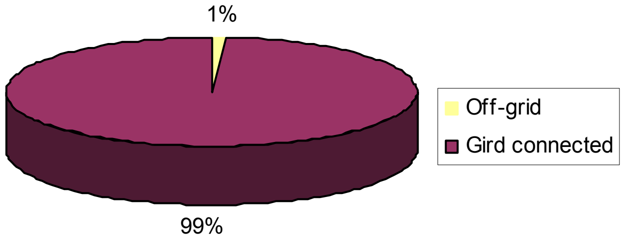


Figure 2.2: PV installation in Germany by system types by 2006 [IEA-PVPS, 2007]

2.4 End Use Applications of PV

PV systems are utilised in several forms, ranging from consumer appliances to big power plants in multi megawatt range. Individual applications are described below:

Consumer applications: Watches, calculators, garden lights, alarm devices, etc.

Distributed rural electrification (DRE): DRE aims at meeting basic electricity needs (e.g. potable water, water for livestock, refrigeration, lighting for dispensary, etc.), improving quality of life (e.g. residential lighting, telephone service, radio and television, community lighting such as street lighting, schools, meeting halls, etc.) and powering small scale commercial applications (e.g. pumping for farming irrigation, vegetable gardening, storage, motorisation for mills, presses, small craft industries, etc.).

Remote dwellings in industrialised countries: Many dwellings that are far from the central grid can benefit from PV generated electricity for lighting, television, refrigeration, etc. also in the industrialized countries.

Other applications: The applications such as parking meters, emergency phones along highways, small scale commercial use by enterprises, telecommunication, etc.

2.5 Advantages of PV

Electricity from solar PV is generally produced during peaks in daily demand, when the marginal cost of electricity production is the highest. In south European climates, the season in which electricity demand peaks (i.e. summer) is the time when the output of photovoltaic systems is at the highest. PV can be relied upon in the cases of extreme heat and water shortage when thermoelectric power plants have to reduce their output due to a lack of cooling water [EC-PVTP, 2007].

Very large scale deployment of PV is only feasible if PV electricity generation costs are drastically reduced. However, because of the modular nature of PV, the possibility to generate at the point of use and the specific generation profile i.e. overlap with peak electricity demand; PV electricity could eventually emerge as cheap as wholesale electricity. During the heat wave that affected Europe in July 2006, peak prices paid at the European Electricity Exchange (EEX) spot market exceeded the PV feed in tariff paid in Germany [EC-PVTP, 2007]. This will happen more frequently in future as the feed in tariff decreases- the occasions when PV electricity is a cost effective form of generation even without the support mechanisms will become more common.

Although PV currently appears an expensive option for producing electricity compared to other energy sources, many countries uphold the innovation because of its promising potentiality and for additional benefits besides generating electricity. These benefits are already effective at present and have been identified and quantified. IEA-PVPS [2008] has listed a wide range of important added values from PV systems, which increase the social welfare towards sustainability.

- PV uses a worldwide abundant and locally available energy source i.e. the sun
- PV contributes to supply security by avoiding the use of fossil fuels and reducing fuel price risks together
- PV reduces greenhouse gas emissions and air pollutants, and accordingly avoids external costs which ultimately have to be borne by the society
- PV offers a chance to develop new industries by creating export possibilities and jobs
- PV contributes to peak shaving which means PV electricity is available especially in the mid day when demand is high
- It reduces the environmental cost burden like CO_2 certificate costs
- It creates a green image and offers new business opportunities
- PV system is noiseless, relatively maintenance free, reliable and easy to install on sites

PV technologies have some other technical advantages compared to other electricity generating technologies i.e. they require low maintenance and can operate for long periods unattended. Moreover, if necessary, additional generating capacity can be readily added, which would offer them a good choice for electricity generation in remote applications. Luther [2007] mentioned that PV electricity could provide least cost options for basic rural energy needs in many developing countries. Solar PV, together with other renewable energy sources, will become a standard and well accepted supplier of energy in the future, supporting the grid or in stand alone mode [EC, 2005].

2.6 Critics of PV

The major barrier preventing PV's uptake in today's market is its high cost, making the electricity produced too expensive for many applications. The present market perception of the technology is that it is for niche applications, and not for general use. Another problem is the seasonal variation in energy production. Staffhorst [2007] had calculated the energy yield from PV systems installed in Germany (with data collected from meteocontrol GmbH for about 10 MW capacities) and he found that the generation in months from March to October was nearly 90 % of whole year's production. In life cycle analysis, PV systems release some emissions to the environment as fossil fuels are still used in the manufacturing process. The health and environmental impacts of such emissions may be expressed in monetary terms as external costs. For current PV installations in southern Europe, Fthenakis [2007] has estimated the external costs to be about 0.15 €ct/kWh, which is; however, remarkably lower than the external costs of the fossil fuel technologies that PV displaces.

2.7 Scope of Stand Alone PV Systems

Figure 2.3 shows the household electricity bill (21.43 €ct/kWh) breakdown in Germany as of January 2008. It is illustrated that the major part of electricity bill does not fall under generation cost, but transmission costs and taxes. If the stand alone generation is opted, major part of this bill could be slashed. The savings could be used to invest in stand alone PV generation at house with securing reliable and environment friendly electricity.

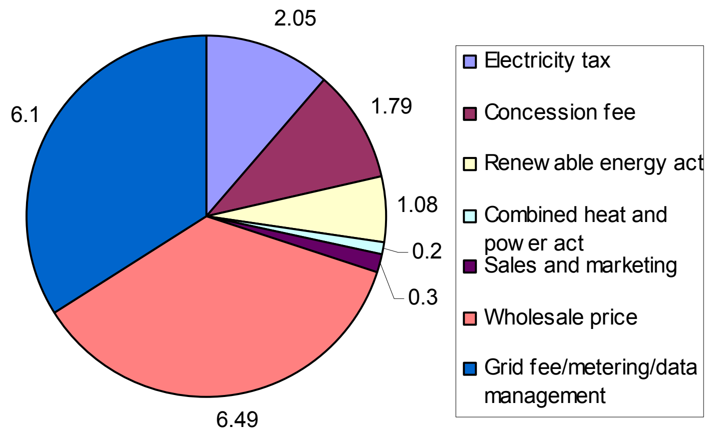


Figure 2.3: Composition of household electricity bill (in €ct) in Germany [RWE, 2008]

Schmid [2007] wrote in favour of solar PV systems stating they are often the most suitable solution for stand alone applications. Moreover, solar energy can provide viable solutions where power is required at remote locations. For larger electrical loads, PV can be combined with other renewable energy technologies or a small diesel generator to form a PV hybrid system. According to WEC [2007], annually about 8-10 million new buildings are constructed worldwide and most of them are in developing countries. Large areas of these countries do not have access to grid electricity, thus making solar PV an attractive alternative. Moner-Girona [2008] agreed that grid extension is not a feasible option due to low potential electricity demand and economic development in these areas and sometimes also due to political reasons. Even if only a tiny fraction of these buildings were served by solar PV, the implications for the solar industry and the society as a whole could be enormous, not only from a technological viewpoint but also from a cultural viewpoint. It would be a contributory factor to change people's mindset about conventional energy sources and solar PV.

The high cost of energy transport and transmission infrastructure, such as high voltage power lines, oil and gas pipelines, is one of the factors responsible for the low progress in expanding national distribution electricity grids in many countries [Matrinot and Reiche, 2000]. It is now widely accepted that in many rural locations an alternative to grid extension is required. Stand alone solar PV systems have been confirmed as an appropriate option for bringing electricity to scattered households. Reaching the rural population without electricity is often only possible through distributed energy systems. By 2007, more than 2.5 million households in developing countries received electricity from solar home systems [REN21, 2008]. A remarkable growth was witnessed in a few specific Asian countries (Bangladesh, China, India, Nepal, Sri Lanka and Thailand), where the affordability problem was overcome either with micro credit or with the government and the international donor support programs. Rural electrification programs in several other countries are explicitly incorporating large scale investment in solar home systems. Governments are recognizing rural areas that are not geographically viable for grid extension and are enacting explicit policies and subsidies for renewable energies in these areas to supplement grid extension electrification programs.

2.8 Concluding Remarks

Solar energy is abundant on the earth's surface and the exploitation of even only a small portion could easily supply the electricity demand of the world population. Solar PV systems are used to convert sunlight into electricity. PV system consists of solar module and BOS components (e.g. storage systems i.e. battery, inverter, mounting structures, electronics, etc.). Most of the PV modules installed so far are made of crystalline silicon, but the thin film modules are supposed to rule the future market because of their lower market price. PV systems could be of grid connected types or of off grid types. So far, most of the systems installed in developed countries are grid connected types and those installed in developing countries are off grid types. Grid connection needs the available grid infrastructure as well as the regulations so that the grid operator is obliged to accept the PV generated electricity from independent power producers using solar PV.

PV systems can be used from small appliances e.g. watches to industrial applications as well. Household lighting is the most common use of off grid PV systems in developing countries. PV offers many advantages - modular in nature, no operating costs, no high skills needed for its operation, not noisy, emission free during operation, etc. It can also generate the electricity in day time when there is a peak demand in electricity grids and the electricity price in spot market is also high. Disadvantages of PV are its high market price, fluctuations in electricity generation due to weather/seasonal variations and a storage system needed to secure the electricity supply in no sun hours. A hybrid system combined with an auxiliary power generator could make the PV systems reliable electricity supplier. Although the manufacturing of solar cells and BOS components releases some pollutants and greenhouse gases, the emission as compared to per unit electricity generation from PV is far less than the same from conventional fuels. So far, solar PV systems can not sustain without government subsidies or donor supports in most of the countries worldwide. PV system price is expected to decrease significantly along with the introduction of thin film cells in the future.

Stand alone solar PV has a bright prospect in the market because many dwellings in developing countries lack access to electricity supply; and due to the remoteness of such locations, grid extension is not expected in foreseeable future. Solar PV could be one of the best options for the electrification of these rural communities.

3 EXPERIENCE CURVE ANALYSIS

3.1 Learning Curve Theory

Learning curves depict the relationship between cumulative production and marginal labor cost of a given product manufactured by a specific firm. In 1936, T. P. Wright introduced formal learning curve analysis in a study of airplane manufacturing [Argote and Epple, 1990]. The conceptual foundation for learning curve theory is that production experience facilitates worker skill improvements and that benefits increase in proportion to cumulative production [Duke and Kammen, 1999]. The conventional equation for learning curve is given by:

$$C_t = C_0 \left(\frac{Q_t}{Q_0} \right)^b \qquad [3.1]$$

where,

C_t is unit cost of given cumulative production at time t

C_0 is unit cost at $t = 0$

Q_t is cumulative production at time t

Q_0 is cumulative production at $t = 0$

b is rate of innovation or learning parameter (the value of b is negative because the cost decreases with increase in the production)

The logarithm transformation of equation 3.1 is given by:

$$\ln C_t = \ln C_0 + b \ln \left(\frac{Q_t}{Q_0} \right) \qquad [3.2]$$

The conventional measure of learning is the progress ratio (PR) [Argote and Epple, 1990; Dutton and Thomas, 1984]. The cost per unit product decreases by learning rate (*1-PR*) for each doubling of cumulative production. The progress ratio is given by:

$$PR = 2^b = 2^{\frac{\ln \frac{C_t}{C_0}}{\ln \frac{Q_t}{Q_0}}} \qquad [3.3]$$

3.2 Experience Curve Theory

During the 1970s, Boston Consulting Group (BCG) introduced the experience curve concept which generalizes the labour productivity learning curve to include all costs necessary to research, develop, produce and market a given product [BCG, 1972]. Experience curves illustrate how cost apparently declines with cumulative production, where cumulative production is used as an approximation for the accumulated experience in producing and employing a technology. An explicit characteristic of experience curves is that cost declines by a constant percentage with each doubling of the total number of units produced (figure 3.1). The observed cost reduction for different technologies cover a learning rate range from approximately 35 % to 0 % [Argote and Epple, 1990] for each doubling of the total number of units produced.

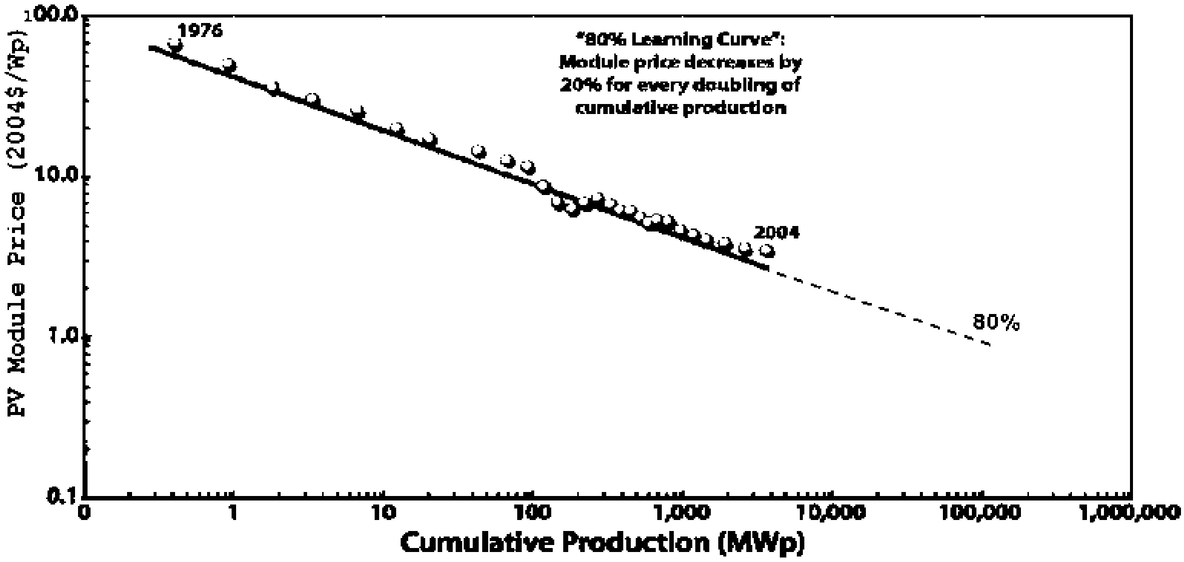


Figure 3.1: Example of an experience curve for solar PV modules [Sunnyguy, 2008]

The cost reductions in the experience curve refer to total costs and changes in production (process innovations, learning effects and scaling effects), products (product innovations, product redesign and product standardization) and input prices. Overall, gaining experience is a lasting process which represents the combined effect of a large number of parameters, which may undergo fluctuations over short periods. The underlying pattern or trend can be distinguished only after many doublings of experiences. BCG argued that learning by doing occurs not only in the labour productivity improvements, but also in associated research and development, overhead, advertising and sales expenses. These efficiency gains, in conjunction with the benefits from economies of scale, often yield cost reductions that can be characterized by an experience curve with the same functional form as equation 3.1, except that C_t incorporates all production costs. Dutton and Thomas [1984] compiled over 100 firm level studies from a variety of manufacturing sectors and a consistently strong relationship was confirmed. However, there is substantial progress ratio variability both within and across industries, products and processes and other variables also drive cost reductions.

A fundamental assumption in the experience curve functional form is that cumulative production levels steer marginal cost. This is problematic to the extent that there are also economies of scale, defined as decline in marginal cost driven by increase in the level of current production. In reality, however, economy of scale only explains some fraction of the observed unit cost reductions over time for any given technology. Lieberman [1987] cited an empirical literature suggesting that learning effects typically dominate economy of scale in driving cost reductions. Hall and Howell [1985] argued that, in addition to economies of scale, cost reductions are driven by four factors: (i) technological progress (ii) input price changes (iii) internal efficiency improvements, and (iv) learning by doing. Schaeffer et al [2004] added two more factors: learning by learning and learning by expanding.

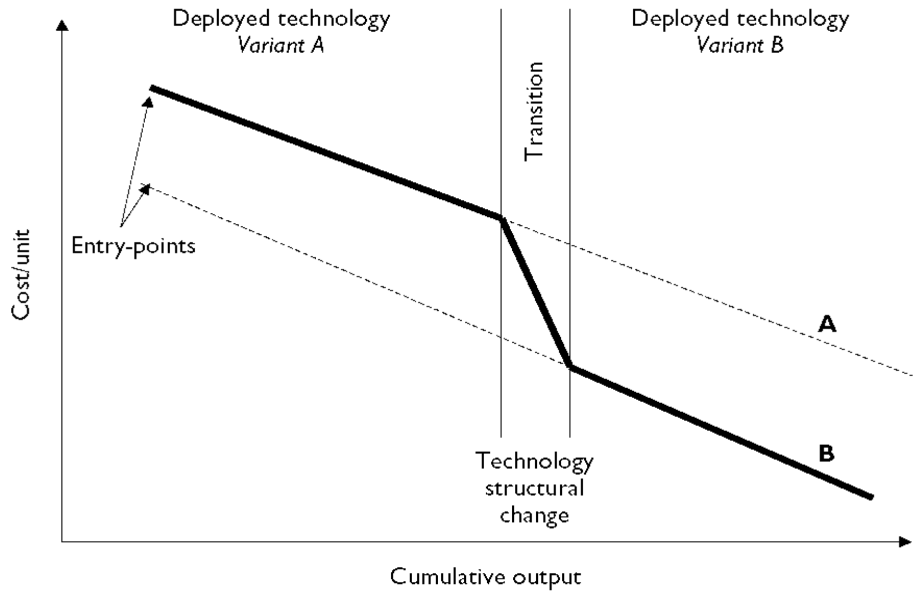
One of the possible uses of experience curve approach is to forecast costs of a technology over time. This means an additional assumption will have to be made concerning the expected market development. For technologies in an early stage of market penetration (e.g. solar PV) this could be done by assuming a growth rate over the years (detail in section 4.2).

3.3 Trend Changes in Experience Curves

Basically while dealing with the experience curves, two kinds of changes in the curve i.e. technology and market structural changes are discussed in literatures, e.g. IEA [2000]. These changes will help understand the price reduction pattern in a better way when product faces competition from many producers in the market (e.g. change of solar PV from space applications to commercial application) or drastic change in the technological innovation (e.g. change from c-Si solar cells to thin film ones). These changes are briefly described below.

3.3.1 Technology Structural Change

An important question is how any R & D breakthrough, a major technical change or shift in production process may appear in the experience curve, e.g. a breakthrough in the production of thin film photovoltaic cells. These sorts of changes are referred as technology structural changes. The name specifies that there has been a radical change in the content of the development process, e.g. a shift in the technology paradigm leading to a new variant of the technology or a major change in the way the technology is produced. The change represents a stepwise shift of the technological frontier, and is expected to signal an increased learning rate in the experience curve for technology costs. The technology structural changes show up as discontinuities in the experience curve, as specified in figure 3.2. The discontinuity is a step down in the experience curve, indicating a change in the entry point and possibly also in the progress ratio before and after the change. Before the transition period, technology variant A is deployed, but during the transition period investors realise the advantages of variant B. The two variants are assumed to be similar, so that during the transition period, variant B can accumulate the experience learned from deploying variant A [IEA, 2000].



The heavy line is the expected behaviour of the experience curve during a shift of technology from variant A to variant B.

Figure 3.2: Technology structural change [IEA, 2000]

3.3.2 Market Structural Change

BCG [1968] analysed the relationship between price and cost experience curves. Figure 3.3 shows a complete price cost cycle for the market introduction of a new product. The cycle for a viable technology has four phases. In the development phase, the initial producer sets prices below cost to establish the market. Generally, the initial producer maintains some degree of market power as his cost becomes lower than price. As a market leader, he may maintain prices and hold a price umbrella over the higher cost producers that are entering the market. The typical progress ratio for this phase is 90 % or more [IEA, 2000].

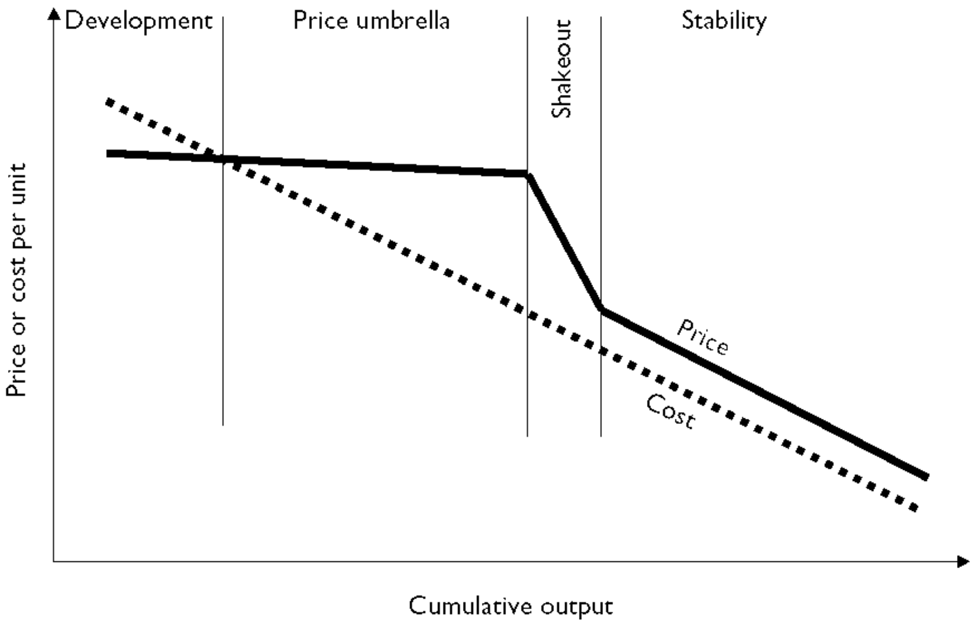


Figure 3.3: Market structural change [BCG, 1968; IEA, 2000]

Under the price umbrella, the new producers will learn and thereby reduce their cost. This leads to an unstable situation, where more producers become low cost producers and the difference between price and cost for these producers becomes higher. The market enters the shakeout phase when prices fall faster than cost. BCG [1968] found progress ratios typically around 60 % for this phase, but there are considerable variations around this value. The shakeout progress ratio is not sustainable because it would bring prices below cost if it is maintained for a longer period. In the last phase, prices stabilise around an experience curve with the same progress ratio as the cost curve. Stability entails a fixed cost/price ratio. The price progress ratio in a stable market is thus equivalent to the cost progress ratio. It may be difficult to obtain measurement series long enough to ensure that stable conditions have been reached. The price cost cycle provides guidance for determining cost progress ratio from shorter series. The average price progress ratio over one cycle also provides information on cost progress ratio. The analysis indicates that two discontinuities at start and end of the shakeout phase signal changes in market structure. Parallel to technology structural change, which can be observed from the cost experience curve, market structural change can be observed from the price experience curve. The two are quite distinct phenomena, because a market structural change will have no effect on the cost curve. However, cost curves are difficult to measure, which may tempt the analyst to use the price curve as an indicator for technology structural change [IEA, 2000].

3.4 Cost or Price Data

Experience curves based on cost would be ideal, but it is not easy to get, so price data is used in the calculations of this study. Cost and price experience curves can vary sometimes, but in the long run they always come back to the same average progress ratio due to competition among market participants. In free market, it might work as accurate as cost data. Duke and Kammen [1999] stated that price provides a legitimate proxy if any of the following conditions is met:

- Price to cost ratio margins remain constant over time
- Price to cost ratio margins change, but in a controlled manner
- Changes in margins are small relative to changes in production costs

3.5 Advantages of Experience Curve Model

A PV experience curve provides an appealing model for several reasons. First, the experience curve analysis provides the possibility to estimate future price developments of PV depending on cumulative capacities. Comparing this estimate with the price of other electricity sources, breakeven price (BEP) and breakeven capacity can be calculated together with learning investment, which is cumulative difference between BEP and experience curve. Learning investment is expected to become the dominant resource for technology development in later stages or in market transformation program, the objectives of which are to overcome cost barriers and make technology affordable and more commercial [Wene, 2003]. Second, availability of the two empirical time series required to build an experience curve, cost and production data, facilitates testing of the model. Third, earlier studies of the origin of technical improvements, such as in the aircraft industry [Alchian, 1963] and ship building [Rapping, 1965], provide narratives consistent with the theory that firms learn from past experience. Fourth, studies cite the generally high goodness of fit of power functions to empirical data over several years, or even decades, as validation of the model. Fifth, the dynamic aspect of the model, the rate of improvement adjusts to changes in the growth of production, makes the model superior to forecasts which treat change purely as a function of time. Sixth, the reduction of the complex process of innovation to a single parameter, the learning rate, provides a way to include technological change in models, such as energy supply and external costs of greenhouse gas emissions [Nemet, 2005].

3.6 Limitations of Experience Curve Model

The combination of empirical literature and more recent applications of learning curves in predictive models have revealed following weaknesses.

First, the timing of future cost reductions is highly sensitive to small changes in the learning rate. Nemet [2005] mentioned that while plotting the experience curves based on the two most comprehensive world surveys of PV prices [Maycock, 2002; Strategies-Unlimited, 2003] a learning rate of 26 % was found for Maycock data and that of 17 % for Strategies Unlimited data. He calculated how long it will take for PV costs to reach a threshold of 0.30 $\$/W_p$, a mid range estimate for competitiveness with conventional alternatives, and found the time point of 2039 for the 26 % learning rate and 2067 for the 17 % learning rate, a difference of 28 years. Second, the experience curve model gives no way to predict discontinuities in the learning rate [Schaeffer, 2004]. Discontinuities present special difficulties at early stages in the life of a technology. Early on, only a few data points define the experience curve, while at such times decisions about public support may be most critical. Third, studies that address uncertainty typically calculate it in the learning rate using data for cost and cumulative capacity. This approach ignores uncertainties and limitations in the progress of the specific technical factors, e.g. constraints on individual factors such as theoretical efficiency limits, which are important in reducing the cost. Fourth, the hypothesis that experience, as represented by cumulative capacity, is the only determinant of cost reductions ignores the effect of knowledge acquired from other sources, such as from R & D or from other industries. Sheshinski [1967] separated the impact of two competing factors, investment and output. Others have addressed this limitation by incorporating additional factors such as workforce training [Adler and Clark, 1991], R & D [Miketa and Schrattenholzer, 2004] and the interactions between R & D and diffusion [Watanabe et al, 2003]. Fifth, experience curves ignore changes in quality beyond the single dimension being analyzed. The dependent variable is limited to cost normalized by a single measure of performance i.e. €/W_p. Measures of performance like these ignore changes in quality, such as reliability of power generation.

3.7 Experience Curve for Solar PV Module in Literature

Aghion and Howitt [1998] stated that research and development plus learning by doing are the essential endogenous mechanisms for reducing uncertainty and improving performance and costs of an infant technology. Watanabe [1995] had empirically demonstrated that there is 36 % reduction in PV cost per each doubling of cumulative production in 80s and 90s. A learning curve for the progress in silicon wafer based technology can be drawn that spans three decades. It shows that the price of the technology has decreased by 20 % for each doubling of cumulative installed capacity [EC-PVTP, 2007]. Two driving forces are behind this process, market size and technology improvement. Such progress was not made by chance but the combined result of market stimulation measures and research, development and demonstration activities with both private and public support.

Since most of the module manufacturing is done by internationally operating companies and there is extensive exchange of scientific and technological information on module technology, learning at PV module level makes no distinction between global and local learning. It is expected that there will be knowledge spill-over in R & D, despite the fact that spill-over may be incomplete as knowledge may be sticky. According to IEA survey in PV system price in 2004, very few countries maintained a balance between local production and capacity installed (six - seven countries were said to have significant production available for export, eight countries produced between 0 % and 40 % of their demand). This suggests that PV module production learning will also spill-over among countries. Statistics also feature that there are a number of examples of imported modules selling for considerably less cost than the local production. This means while production learning may be local and that companies may have different costs, there will be one worldwide or global price for module and which is outside the control of local (country) PV program [Wiser et al, 2007].

Beneking [2007] estimated PV experience curve learning rate for the period before 1980 to beyond 2015 will follow 20 % with module price well below than 1 €/W_p. According to Harmon [2000], worldwide cumulative installed capacity of PV modules doubled more than thirteen times, from 95 kW_p to over 950 MW_p between 1968 and 1998, while costs were reduced by an average of 20.2 % for each doubling. If the progress ratios for PV modules are calculated for a single country, the results vary significantly. Countries that have installed more PV capacity than average will see less favourable PR (e.g. case of Germany shown in section 4.4), because the price will decline with same pace in other countries, but the number of doublings will be higher than in average. Schaeffer, et al [2004] found PR for PV modules around 90 % for Germany whereas the global PR found was in the range of 75-80 %. They found PR for grid connected residential PV systems in Germany 80 %. They claimed the improvement of progress ratio from 80 % to 77 %, calculated value for 1976-2001 being 80 % and calculated value only for 1987-2001 being 77 %. A list of PR from different literatures is given in the table 3.1.

Table 3.1: Progress ratio in the literature

Author	PR (%)	Time period	Region	Component
IEA [2000]	79	1976-1996	EU	Modules
Harmon [2000]	79.8	1968-1998	World	Modules
	77.2	1981-2000	World	Modules
Parente et al [2002]	79.8	1981-1990	World	Modules
	77.4	1991-2000	World	Modules
Poponi [2003]	75	1976-2002	World	Modules
	80.5	1989-2002	World	Modules
	80	1976-2001	World	Modules
	77	1987-2001	World	Modules
Schäffer et al [2004]	74	1988-2001	EU	Modules
	78	1992-2001	Germany	BOS
	81	1992-2001	Netherlands	BOS
Beneking [2007]	80	1980-2015	World	Modules

3.8 Experience Curve for BOS in Literature

As discussed earlier, BOS of a PV system consists of all the system components apart from the PV modules. The cost for learning of BOS has not been studied as widely as the cost learning of PV modules. For grid connected residential systems, Schaeffer et al [2004] found that the BOS experience curve in Germany was sustaining a progress ratio of 78 % during 1992–2001. However, unlike PV module learning, which is both R & D driven and production or manufacturing driven; BOS learning has not been attributed to cost reductions of individual hardware components. In fact, most of these hardware components are the mass produced electrical components with mature markets outside the solar industry. Therefore, BOS learning can mostly be attributed to cumulative experience of system design, integration and installation attained through greater system integration and a reduction in the number of BOS parts. According to Harmon [2000], this system oriented learning was equal to or even greater than that of modules. This was reinforced by a study from Wiser et al [2007].

One of the key questions in the characterization of BOS learning is whether it is local or global in character. Inverter part is partially an international market as several manufacturers deliver inverters to several leading user countries. There are differences in building norms, practices and regulations in countries. All these result in non ideal and less than perfect system engineering knowledge spill-over effects among countries, complicated by individual users' requirements [Beise, 2004]. As a result, the locus of cost learning of BOS is local or even application driven.

The way to understand the differences in learning cost between the module subsystem and BOS subsystem is in terms of differences in the extent of users' participation [Shum and Watanabe, 2008]. The production of module is essentially dominated by module manufacturers with minimal participation of the users. In this regime, production scale, learning by doing, R & D, production yield become the primary concerns in cost learning [Shum and Watanabe, 2007]. As discussed earlier, BOS subsystem learning is driven by experiences in system design and integration, project management or an outright reduction of BOS component counts.

Remarks over Similar Studies

Staffhorst [2007] differentiated the experience curves between €/kWh vs. kW_p cumulative installations and €/kW_p vs. kW_p cumulative installations. He analysed the both aspects and came to a conclusion that the contribution of soft factors'(e.g. the effects of life time extension and decrease in energy yield degradation) learning rate to the overall PV module learning rate was about 6 % (total PR of 81.2 %) in Germany and 10 % (total PR of 65.3 %) worldwide.

In the current study, the progress ratio based on €/kW_p vs. kW_p cumulative PV system installation have been considered for both- module and BOS components. It is thought that, industrial development can influence only until the system installation phase, and it does not have much influence in the so called soft factors improvement (e.g. operating/maintenance, degradation in energy yield, etc.). Such things are very much site and user's awareness to the PV systems dependent, e.g. manual tracking of module inclination angle, shading, dust/snow deposition on it, etc. Therefore, it is very difficult to get the exact information on individual installation sites and to calculate the progress ratio based on €/kWh including these soft factors. Moreover, in a broad sense, the PR for PV system price is supposed to include the learning effect on such soft factors.

However, in cost benefit, grid parity and breakeven analyses of this study, the effects of these parameters e.g. system life time, interest rates, etc. have been taken into consideration while calculating the kWh PV electricity generation prices. Details are given in chapter 5.

3.9 Concluding Remarks

Learning curves depict the relationship between cumulative production and marginal labor cost of a given product manufactured by a specific firm. The conventional measure of learning is the progress ratio. The cost per unit product decreases by learning rate (*1-PR*) for each doubling of cumulative production. The experience curve generalizes the labour productivity learning curve to include all costs necessary to research, develop, produce and market a given product. The cost reductions in the experience curve refer to total costs and changes in production (process innovations, learning effects and scaling effects), products (product innovations, product redesign and product standardization) and input prices. An explicit characteristic of experience curves is that cost declines by a constant percentage with each doubling of the total number of units produced.

While dealing with the experience curves, two kinds of changes in the curve i.e. technology and market structural changes are discussed in literatures. These changes will help understand the price reduction pattern in a better way when product faces competition from many producers in the market (e.g. change of solar PV from space applications to commercial application in electricity generation) or drastic change in the technological innovation (e.g. change from c-Si solar cells to thin film solar cells).

A PV experience curve provides the possibility to estimate future price developments of PV depending on cumulative capacities. However, the timing of future cost reductions is highly sensitive to small changes in the learning rate. Comparing this estimate with the price of other electricity sources, breakeven price and breakeven capacity can be calculated together with learning investment.

Analysis of experience curves based on cost data would be ideal, but it is not always easy to get the production cost details from the manufacturers because of competition reasons. Therefore, many literatures use price data in their calculations. Cost and price experience curves can vary sometimes, but in the long run they always come back to the same average progress ratio due to competition among market participants. In a perfect market, it works as accurate as cost data.

The learning level at PV module makes no distinction between global and local learning because the most of the module manufacturing is carried out by internationally operating companies and there is extensive exchange of scientific and technological information on module technology. The cost for learning of BOS has not been studied as widely as the cost learning of PV modules. BOS learning rate is site specific.

Different literatures agree that solar PV has been following a PR of 80 % since its commercial use. An equal value of 80 % PR for modules and BOS has been considered in this study, though some literatures state that BOS component learning rate might be faster than that of module. There are no detail literatures available on experience curves of solar batteries. Since battery technology is already advanced relative to solar PV systems, a PR of 90 % will be used in the economic analysis of this study in the next chapters.

Since the autonomous water supply systems are not extensively commercialized, no study has been found with the reliable data on PR of autonomous water supply plants. Since there are no authentic data on the number of these systems installed over the past years, it is difficult to estimate for the future, too. This is why, the future installation of autonomous water supply plants and its experience curve has not been estimated, but the economic analysis has been carried out with the actual and/or estimated price data on such systems as of today.

4 SOLAR PV IN FUTURE ELECTRICITY MARKET

4.1 PV in Future Market in the Literatures

Many authors have projected different values of PV installation growth rates for the future. EC-PVPT [2007] estimated the total PV market increase in the last decade enormous, annual growth of about 50 % during 2002-2007, with crystalline silicon accounting for more than 90 % of the total volume. Different photovoltaic industry associations as well as European Renewable Energy Council (EREC) have developed scenarios for the future growth of PV. Table 4.1 shows the projection roadmaps of Japanese, US and European Photovoltaic Industry Association (EPIA). The EREC Advanced International Policy Scenario (AIP) and Dynamic Current Policy Scenario (DCP) have also been shown in the same table.

Table 4.1: Evolution of cumulative solar PV capacities in GW_p until 2030 [EREC, 2004]

Year	2000	2010	2020	2030
USA	0.14	2.1	36	200
Europe	0.15	3	41	200
Japan	0.25	4.8	30	205
World DCP	1	8.6	125	920
World AIP	1	14	200	1830

IEA-PVPS [2007] anticipated that there will be very high PV market growth rates of 30-40 % per year continuing worldwide, provided PV retains the political favour it currently enjoys in a number of key markets for the next decade. Cameron [2007] projected worldwide annual PV installation for years 2010, 2020 and 2030 to be 5.6, 48, and 193 GW_p, respectively under the policy driven scenario referring to the data of EPIA workshop conclusions of December 2006. His pessimistic projections were also above 10 and 60 GW_p for years 2020 and 2030, respectively. EPIA [2007] expected 7 GW_p of annual installations by year 2010 and 10.9 GW_p by 2012 under policy driven scenario (annual growth rates well above 25 % expected), which its author claimed to be the most representative projection. With this scenario, a global cumulative capacity of 44 GW_p could be achieved by the end of 2012. Germany is expected to remain the market leader and even increase its market size considerably over the next years.

EC [2005] described, saying ambitious though realistic growth figures, the installed capacity may increase to around 200 GW_p (200 TWh) in EU and 1000 GW_p (1000 TWh) worldwide by 2030, representing 4 % of world electricity production. By 2030, PV will have developed into a large economic sector, both worldwide and in Europe. There will be a strong European PV industry with significant exports. The number of jobs created in the EU will be between 200 and 400 thousands (based on a European yearly production of 20-40 GW_p), many of them linked to the installation and building sectors. These estimates were consistent with the Japanese Government's objective where Japan aimed at 5 GW_p by 2010, and has developed roadmaps for 50-200 GW_p of PV capacity by 2030 [NEDO, 2004]. Those estimates are still far below the estimated technical potential of many countries; and therefore, it is expected that

PV could grow much larger in the decades beyond 2030. The large scale dissemination of PV for rural use in developing countries will have provided access to electricity to millions of families by 2030, thus positively affecting the lives of half a billion people [EC, 2005].

Stierstorfer [2005] assumed the worldwide annual growth rate of 26-32 % for the year up to 2020 and 15 % for the years between 2020 and 2040. He forecasted global installed capacity by 2020 to be about 205 GW_p. His estimations for Europe were 25 % market growth rate until 2010 and 22.5 % beyond 2010. Straffhorst [2007] estimated the PV growth rate worldwide 25 % until 2010. After 2010, he further mentioned that growth rate will be different for Germany and for the world, with 10 % in Germany and 25 % worldwide during years 2010-2020. EPIA [2008b] has published its new projection for cumulative worldwide solar PV installations of 1864 GW_p by 2030. About 60 % of these systems are supposed to be grid connected systems. While talking the market share of PV modules types, according to EC-EPTP [2007], the market share of thin film PV is below 10 % of total PV production, but it might grow to 20 % by 2010 and beyond 30 % in the long term. The global production capacity of thin films is expected to reach 1 GW_p/yr in 2010 and 2 GW_p/yr in 2012.

As discussed earlier, there is no consistency in the solar PV installation growth rate figures for the future. The growth rate depends on many factors, e.g. price of PV systems, government policies, innovations leading to the success of thin film solar modules, awareness of the technology in new locations, and economy of any country as a whole, among many others. This complicates in estimating future market of solar PV in accurate manner. Considering the assumptions made by other researchers, author's own estimation is given in section 4.2.

4.2 PV Installation in Germany and the World

The initial parameter needed for the extrapolation of experience curves is the estimation of future PV systems installation. In this section, the different projections for solar PV installation are made. Figure 4.1 shows the cumulative installation of solar PV in Germany and the world during 1994-2006. The year 1994 is taken as starting year because data for the worldwide installations are available only after this year in the publication from IEA-PVPS [2007].

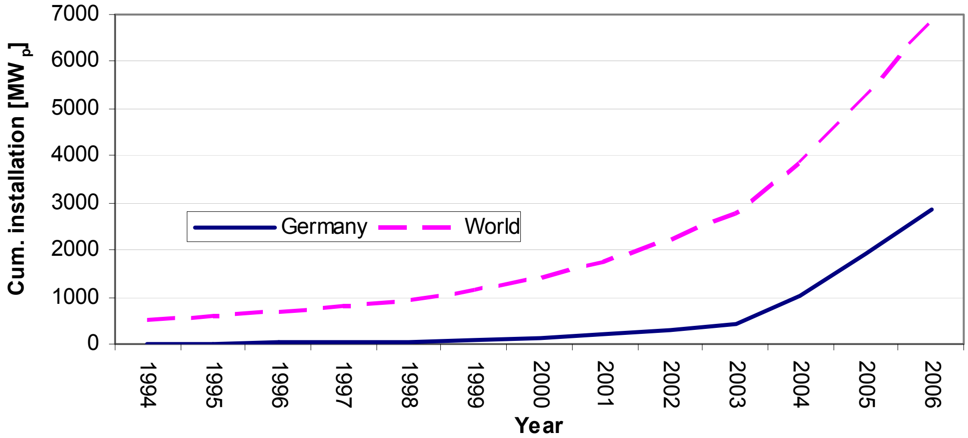


Figure 4.1: Cumulative PV installation in Germany and the world, 1994-2006

There are some propositions about the PV growth potential in future, e.g. if 0.71 % of the European land mass was covered with PV modules, this would meet Europe's entire electricity consumption, or if only 4 % of the world's very dry desert areas were used for PV installations, this would meet the whole world's total primary energy demand [EPIA, 2008b]. There is a common consensus that PV installations will grow in the coming years. However, some people argue that periodical economic crises might impede rapid increase in fossil fuel prices and conventional electricity price, making PV systems not competitive in the coming decades. Nevertheless, fossil fuel reserves are limited and they have severe environmental concerns. EPIA [2008a] had estimated that an average of 0.6 kg of CO_2 would be saved per kWh of PV electricity generation and external costs for fossil fuels were considered within a range of 4.3-160 US$ per tonne of CO_2. Fortunately, this has been realized by scientific and political communities and many governments have already focused in PV expansion.

Different authors project different optimism over worldwide PV growth rate. In many publications [IEA-PVPS, 2007; EPIA, 2007; Stierstorfer, 2005), worldwide annual growth rate for coming years was estimated over 20 %. EPIA [2008a] has published pessimistic to optimistic data range on annual growth rate of 30-40 % during 2007-2010, 21-28 % during 2011-2020, and 12-18 % during 2021-2030 leading to a cumulative installation of 912-1864 GW by 2030. In another EPIA [2008b] report, annual installations of 12-22 GW in 2013 and 281 GW in 2030 are projected. WBGU [2004] had estimated lower values i.e. an annual installation of 10 GW in year 2020. Again, very optimistically, it illustrated that about 20 % of world primary energy demand will be met by PV in 2050 and this will increase to above 50 % by 2100. In general, there is no common growth rate projection agreed upon by all stakeholders.

However, if very high growth rate continues for the next some decades, this will top either national electricity demand in some countries or feasible solar PV exploitation potential in the other countries. Krewitt et al [2005] said that worldwide feasible surface limit for PV production is around 16500 GW_p and for Germany it is around 165 GW_p. World will not only focus in solar PV for electricity generation, but in other renewable energy technologies (e.g. wind, hydropower, solar thermal, other new technological innovations, etc). Another argument is that the production capacity of the industries might attain high levels, but demand might not be enough to meet the supply capabilities. Too high growth rate (i.e. demand), if happened, will create scarcity cost and PV system prices will become higher than those expected; and hence, growth rate might ultimately decrease.

In this study, the estimation for different growth rate scenarios has been adjusted with the values found in the literatures and the own data are presented in table 4.2. Many countries have just started installing solar PV systems and worldwide annual growth rate is expected to be high in near future (i.e. 20 %). This will persist until 2020 when many pioneer countries might be near to their target PV portfolio in electricity mix or in some cases near to their technically or economically feasible potential. Subsequently, the growth rate will slow down (i.e. 15 %). This is supposed to continue for a decade and cumulative PV installation worldwide could reach around 599 GW_p in 2030 (EIA [2008] estimated worldwide installed power generation capacity of about 7000 GW for 2030). Annual growth rate will slow down to 5 % after the year 2031 and this rate will continue up to 2040. Beyond 2040, a constant annual installation, same to that of year 2040 (i.e. 135.2 GW_p), is supposed to continue up to 2060 leading to a cumulative installations of 4400 GW_p by 2060. Considering annual average global radiation for many countries between 1000 and 2000 kWh/m^2 and performance ratio of 75 %, electricity share in global market from PV in 2030 will be still low i.e. around 450–900 TWh (3.3-6.6 PWh in 2060). For comparison, according to EIA [2008], the worldwide net electricity generation from central power plants in 2005 was about 17.35 PWh and the projected value for 2030 is about 33.3 PWh.

Table 4.2: Estimation of PV installation in the future

	Period	**Annual growth rate (%)[a]**	**New installations [b] (GW_p)**	**Cumulative installations [b] (GW_p)**
World	2007-2020	20	20.5	120
	2021-2030	15	83.0	599
	2031-2040	5	135.2	1696
	2040-2060[c]	0	135.2	4400
Germany	2007-2020	10	3.6	32
	2021-2030	0	3.6	68
	2031-2060	-	1	98

[a] annual growth rate applies for the new installations, e.g. new installation in year (*n+1*) is equal to (1+*growth rate*) times new installations in year *n*.

[b] values apply to the last year of the given period. Numbers are rounded.

[c] the estimation has been made until the year 2060. This is because if a stand alone system is considered, breakeven year will occur around the year 2040 under pessimistic scenarios. In this case, if a system is installed in 2040, BOS replacement will happen in year 2060 (assuming system life time of 40 years and BOS life time of 20 years). Since the BOS cost factor is derived from module cost, the module cost of year 2060 is needed to calculate the BOS cost in order to calculate the overall system cost. However, in grid connected systems, estimation until year 2050 would have been sufficient.

In Germany, keeping in mind that annual installation is already a high value; a lower growth rate of 10 % is considered for the period from 2007 to 2020. While the new installation of year 2020 is already a high number (i.e. 3.6 GW_p), annual growth rate might not increase further. However, the following years are expected to maintain the constant installations of 3.6 GW_p for a decade leading to a cumulative installation of about 68 GW_p by 2030. Beyond 2030, new installations every year are supposed to be as of today, i.e. around 1 GW_p. This will lead to around 88.5 TWh of PV electricity generation in Germany by 2060 (for comparison, German electricity consumption in 2007 was about 547 TWh [CIA, 2009]).

4.3 Module and System Price

The second parameter required for the extrapolation of experience curves is current module price. Solar PV module price for different countries worldwide are documented by IEA-PVPS [2007] for the year 1994-2006. The values differ from country to country, showing the

PV module is not a fully developed global market product yet. But with the increasing trade on solar products worldwide, it can be expected that it will become a more global product soon. The values of module prices listed by IEA for the German market are presented in figure 4.2. The presented module and system prices are for the constant currency as of €$_{2007}$ corrected from the nominal prices using GDP deflator given by Bundesbank [2008]. In the system price given in figure 4.2, the data for the period 1994-2003 are adopted from the calculations made by Straffhorst [2007], where he used the average of the system price data published by IEA [2005], Schaeffer [2004] and KfW [2004]. Based on the data published by IEA [2005] for the previous years, further estimations are made for the year 2004 and 2005. Data for 2006 is taken from IEA-PVPS [2007].

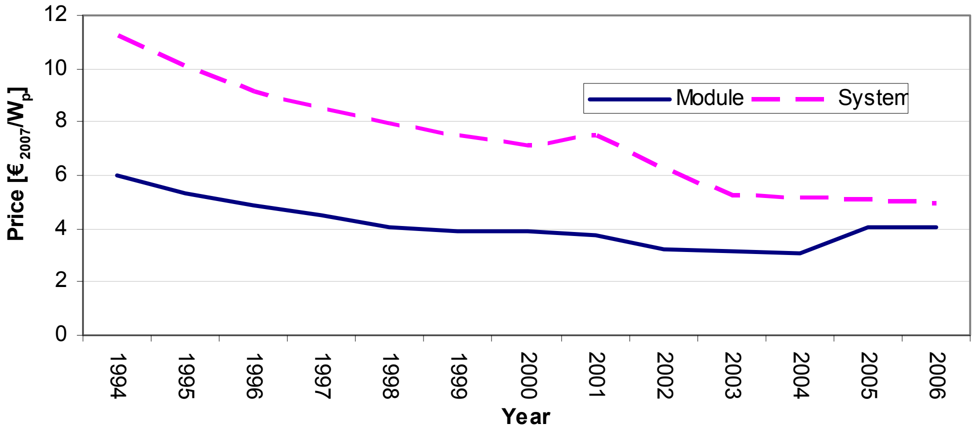


Figure 4.2: PV module and system price in Germany, 1994-2006

Module price in 2005 in Germany was higher than in 2004 (figure 4.2) due to high cost of silicon [IEA-PVPS, 2007]. If the massive automation in production can be introduced, system prices can be lowered despite increasing cost of silicon. There are other publications available for the module and system prices for the same period that vary from the data given above. Method of data collection, included installation volume, region, etc might be the reasons for different values. For comparison purpose, some values are given in table 4.3.

Table 4.3: Comparison of module and system prices (€$_{2007}$/W$_p$) from literature

Year	Module, Germany [Schaeffer, 2004]	Module, Germany [Staffhorst, 2007]	System, Germany [Schaeffer, 2004]
1994	5.88	6.02	12.04
1995	5.83	5.65	10.95
1996	6.11	5.54	9.77
1997	5.00	4.76	9.35
1998	4.84	4.44	8.89
1999	4.59	4.75	7.91
2000	4.81	4.60	8.01
2001	5.68	5.01	9.02
2002	4.94	4.34	6.93

Data on module prices are easier to find than those on system price, as kW_p system price is dependent on many local factors e.g. system size, local market conditions for auxiliary components and manpower, etc. BOS components are normally not purchased from a single supplier unlike modules, and it is difficult to come up with a standard value of sum.

Different literatures give diverse projection on the price reduction pattern for PV modules and systems for the coming years. The module has traditionally been the most costly component, typically accounting for 50-70 % of the costs at system level [EC-PVTP, 2007]. This varies considerably with application and system size, since BOS components and installation costs do not scale proportionally with system size. In the projections of system costs for future, it is assumed that the module will still remain the highest cost item. EC-PVTP [2004] estimated future prices for PV systems are given in table 4.4.

Table 4.4: System prices in selected countries (€/W_p)

Country	Year					
	2004	2010	2015	2020	2025	2030
Australia	7.34	5.02	3.66	2.67	2.33	2.03
Europe	6.09	3.45	2.54	1.87	1.60	1.37
Japan	4.94	3.03	2.48	2.01	1.64	1.34
USA	4.99	3.38	2.76	1.96	1.70	1.63

Modified from [EC-PVTP, 2004], using1 US$ = 0.818 € as of June 2004 [Xe, 20008]

EC [2005] had published different target for module and system prices in its report. Targeted module prices (in €/W_p) were given 2, <1 and <0.5 for the years 2010, 2020 and 2030, respectively. Similarly the targeted system prices (in €/W_p) were given as 3, 2 and 1 for the same years, respectively. Turn key prices (excluding value added tax) for Germany in 2007 published in Photon magazine were given as 5259 €/kW_p for system size 1-2 kW_p, 4853 €/kW_p for system size of 2-5 kW_p, 4624 €/kW_p for system size of 5-10 kW_p and 4403 €/kW_p for system size greater than 10 kW_p [BMU, 2006].

Acknowledging the boost in production facility sizes, improvements in module efficiency and differences in the calculation methods used by the PV industry, EC-PVTP [2007] published the total manufacturing costs will be in the range of 1-1.5 €/W_p in 2010. It further estimates that additional cost reduction to below 0.75 €/W_p in 2020 and 0.5 €/W_p by 2030 can be made. Little difference in cost between the different thin film technologies is expected in the long term. In the same publication, the studies performed in Germany, the Netherlands and the UK have estimated BOS prices to be in between 1.6-2.5 €/W_p for building mounted systems on domestic properties, with some optimistic projections that prices could be as low as 1.2-2 €/W_p. Even the lower prices can be expected for large ground based systems. Cell and module efficiency has direct impact on the overall cost of PV module and have historically been a focus for technological development. Increasing the efficiency of the solar cells and the power density of the modules, together with the reduction of the specific consumption of silicon, are the main paths to cost reduction (an increase of 1 % in efficiency alone is able to reduce the costs per W_p by 5-7 % [EC-PVTP, 2007]).

4.4 Experience Curve and Future PV Prices

Progress ratios (PR) for different combination of cumulative installations and module and system prices are calculated using equations 3.1-3.4. Using the solar PV installation data from figure 4.1 and module price data from figure 4.2, PR for PV modules in German market has been calculated as 95 % for the period 1994-2006. However, for the system price data from figure 4.2, PR for PV systems in German market has been calculated as 90 % for the same period. Considering German system price to be the same with world system price (figure 4.2), PR has been calculated using world cumulative PV installation data and it has been found to be 80 % for the period 1994-2006. This PR value of 80 % is more or less equal to the value agreed by many other authors (e.g. table 3.1). IEA [2000] agreed a PR of 80 % represents a best fit to the available information on the experience curve analysis of solar PV.

Experience curves have been plotted in for different scenarios of PR (75, 80, 85 and 90 %). It is assumed that module price of 4.06 $€_{2007}/W_p$ and system price of 4.97 $€_{2007}/W_p$ in 2006 for Germany would be the same for world module and system price in the same year. This is indeed not true for each country, but it is difficult to get a common value that represent all countries, this is why prices for the year 2006 are assumed to be equal in order to make calculations easier. Projected world module prices for the period 2006-2060 (using equation 3.1 and cumulative installation data from table 4.2) are given in figure 4.3.

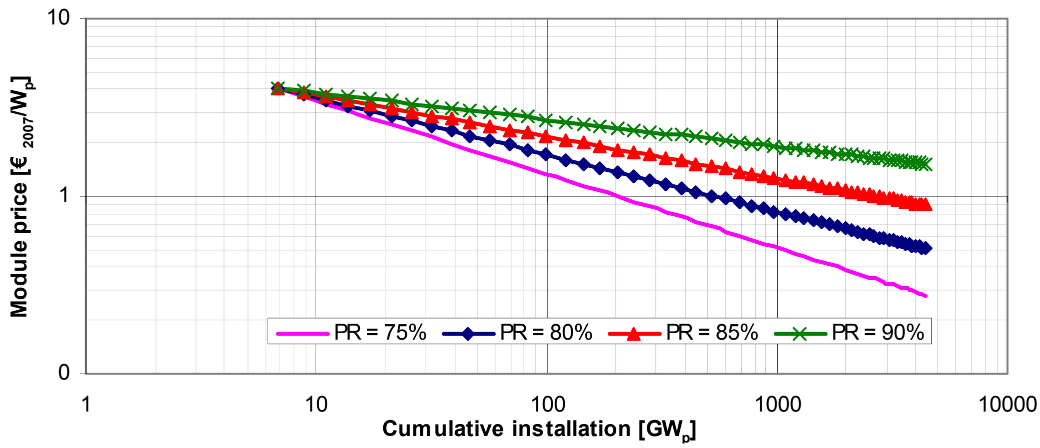


Figure 4.3: PV experience curve for world module price, 2006-2060

Different possibilities of future PV module price decrease with increase in cumulative installations can be evidently seen in figure 4.3 (e.g. in year 2060, module price will be 0.28, 0.51, 0.89 and 1.52 $€/W_p$ for PRs of 75, 80, 85 and 90 %, respectively). For the calculations of economic analysis, a module price decrease for 80 % PR has been used in this study. Projected world system prices for the period 2006-2060 (using equation 3.1 and cumulative installation data from table 4.2) are given in figure 4.4.

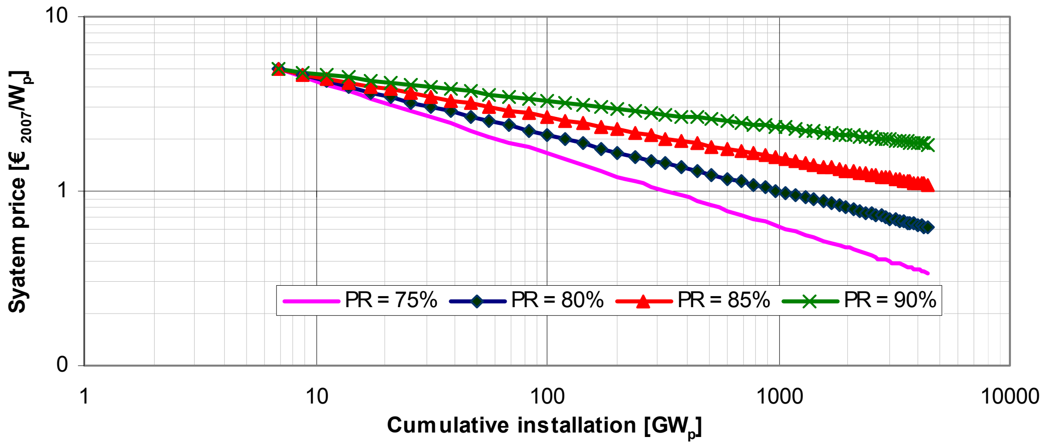


Figure 4.4: PV experience curve for world system price, 2006-2060

Scenarios for annual decrease in world module prices for different performance ratios are presented in the linear curves of figure 4.5. The future module and system prices presented here (for PR 80 %) are quite higher than those projected by some authors (section 4.3). Too low module price (e.g. 0.5 €/W_p after 2030) is questionable because of the increasing prices of silicon in the past years. Price of the thin file modules could be lower, but their progress ratio and price reduction pattern can not be assessed so far due to their recent entrance in the market. Other economic factors in the market will also hinder dropping down the production costs sharply. However, even if those prices fall according to the estimation in figure 4.5, solar PV will reach the grid parity in some years even in the countries like Germany, which has low annual average global radiation (details in chapter 5).

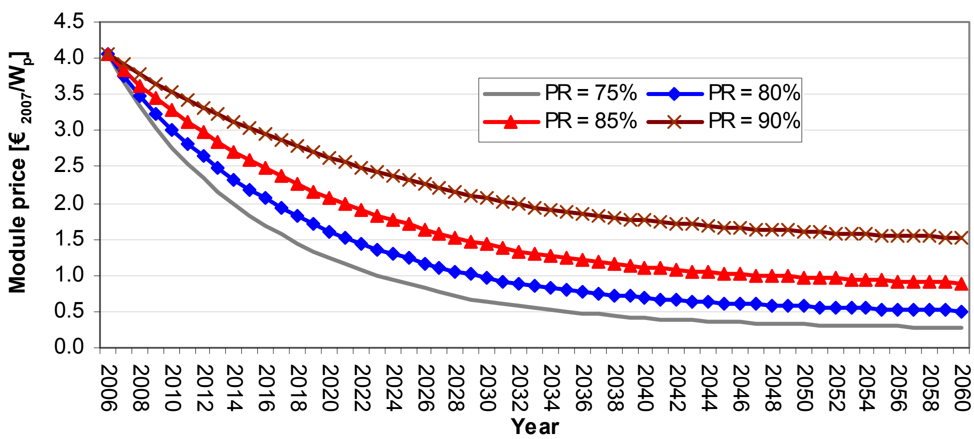


Figure 4.5: Projected world module price for different progress ratio

4.5 Electricity Storage

As mentioned in chapter 2, stand alone PV systems necessitate electricity storage devices in order to supply electricity demand during no sun period. There are many electrical energy storage systems available in the market in order to support the electricity supply systems. They could be of non-electrochemical types (e.g. pumped hydroelectric, compressed air energy storage, etc.) or of electrochemical types (batteries). The core function of these storage systems is to convert the electrical energy at the time of its generation into a form that can be stored for converting back into electrical energy when needed. Such a process enables electricity to be produced at times of either low demand, low generation cost or from intermittent energy sources and to be used at times of high demand, high generation cost or when no other means of generation is available. Due to intermittent nature of sun, such storage systems are very important in solar PV sector, especially in those which are of off grid types. Batteries are the most commonly used storage devices in this sector. According to Divya and Ostergaard [2009], some of the important features of a solar battery are efficiency, life span (stated in terms of number of cycles), operating temperature, depth of discharge (batteries are generally not discharged completely and depth of discharge refers to the extent to which they are discharged), self discharge (some batteries cannot retain their electrical capacity when stored and self-discharge represents the rate of discharge) and energy density.

Currently, significant development is going on in the battery technology. Different types of batteries are being developed of which some are available commercially, while some are still in the experimental phase. Some of the common types of batteries are:

i. Lead Acid Batteries

Lead acid is one of the oldest and most developed battery technologies. It is a low cost and popular storage preference. Its application for energy management; however, has been very limited due to its short life-cycle. The amount of energy (kWh) that a lead acid battery can deliver is not fixed and depends on its rate of discharge [ESA, 2009]. Each cell of a lead acid battery comprises a positive electrode of lead dioxide and a negative electrode of sponge lead, separated by a micro-porous material and immersed in an aqueous sulphuric acid electrolyte (contained in a plastic case) [Divya and Ostergaard, 2009]. This is the most widely used battery in off grid solar PV sector.

ii. Lithium Ion (Li-ion) Batteries

The cathode in these batteries is a lithiated metal oxide and the anode is made of graphitic carbon with single layer structure. The electrolyte is made up of lithium salts dissolved in organic carbonates. When the battery is being charged, the Lithium atoms in the cathode become ions and migrate through the electrolyte toward the carbon anode where the combine with external electrons and are deposited between carbon layers as lithium atoms. This process is reversed during discharge. While Li-ion batteries took over 50 % of small portable market in a few years, there are some challenges for making large scale Li-ion batteries. The main hurdle is the high cost due to special packaging and internal overcharge protection circuits [ESA, 2009].

iii. Flow Batteries

This type of battery consists of two electrolyte reservoirs from which the electrolytes are circulated (by pumps) through an electrochemical cell comprising a cathode, an anode and a membrane separator. The chemical energy is converted to electricity in the electrochemical cell, when the two electrolytes flow through. Both the electrolytes are stored separately in large storage tanks outside the electrochemical cell. The size of the tanks and the amount of electrolytes determines the energy density of these batteries. However, the power density in flow batteries depends on the rates of the electrode reactions occurring at the anode and cathode. Flow batteries are often called redox flow batteries, based on the redox (reduction–oxidation) reaction between the two electrolytes in the system [Divya and Ostergaard, 2009].

iv. Zinc Bromine (Zn-Br) Batteries

In each cell of a Zn-Br battery, two different electrolytes flow past carbon plastic composite electrodes in two compartments separated by a micro porous polyolefin membrane. During discharge, Zinc and Bromine combine into zinc bromide. This will increase the Zn^{2+} and Br^{-} ion density in both electrolyte tanks. While charging metallic zinc will be deposited (plated) as a thin film on one side of the carbon plastic composite electrode. Meanwhile, bromine evolves as a dilute solution on the other side of the membrane, reacting with other agents (organic amines) to make thick bromine oil that sinks down to the bottom of the electrolytic tank. It is allowed to mix with the rest of the electrolyte during discharge.

v. Sodium Sulphide (Na-S) Batteries

Na-S batteries consist of liquid (molten) sulphur at the positive electrode and liquid (molten) sodium at the negative electrode as active materials separated by a electrolyte. The electrolyte allows only the positive sodium ions to penetrate it and combine with the sulphur to form sodium polysulphides. During discharge, positive Na^{+} ions flow through the electrolyte and electrons flow in the external circuit of the battery. The battery is kept at about 300 ^{o}C to allow this process. The demand for NaS batteries as an effective means of stabilizing renewable energy output and providing ancillary services is expanding [ESA, 2009].

vi. Metal Air Batteries

Metal-air batteries are the most compact and, potentially, the least expensive batteries available. They are also environmentally benign. The main disadvantage, however, is that electrical recharging of these batteries is very difficult and inefficient. Although many manufacturers offer refuelable units where the consumed metal is mechanically replaced and processed separately, not many developers offer an electrically rechargeable battery. The anodes in these batteries are commonly available metals with high energy density like aluminium or zinc that release electrons when oxidized. The cathodes or air electrodes are often made of a porous carbon structure or a metal mesh covered with proper catalysts. The electrolytes are often a good OH^{-} ion conductor such as KOH. The electrolyte may be in liquid form or a solid polymer membrane saturated with KOH. While the high energy density and low cost of metal-air batteries may make them ideal for many primary battery applications, the electrical rechargeability feature of these batteries needs to be developed further before they can compete with other rechargeable battery technologies [ESA, 2009].

vii. Nickel Cadmium (Ni-Cd) Batteries

Ni-Cd batteries usually have a metal case with a sealing plate equipped with a self sealing safety valve. The positive and negative electrode plates, isolated from each other by the separator, are rolled in a spiral shape inside the case. This is known as the jelly roll design and allows a Ni-Cd cell to deliver a much higher maximum current than an equivalent size alkaline cell. Ni-Cd batteries are used in low to moderate discharge devices such as scanners, portable radios, cordless phones and power tools. Since these batteries contain cadmium, a toxic heavy metal, they require special disposal.

Many authors [Kowal and Sauer, 2007; Divya and Ostergaard, 2009; DOE/NETL, 2008; Sauer, 2007] have discussed advantages and disadvantages of different battery types and some of these features are summarized in table 4.5.

Table 4.5: Features of different battery types

Battery Types	Advantages	Disadvantages
Lead acid	• Mature technology - over a century old • Familiar - the most widely used storage system • Inexpensive (100-250 €/kWh) • Readily available (45-50 % of battery sales)	• Low specific energy (kWh/kg) • Short life time in cycles/DOD (1200-3000 / 80 %)[a] • High maintenance requirements • Environmental hazards (lead and sulphuric acid) • Lower efficiency (80-85 %)
Li-ion (Cobalt Oxide-based)	• High energy density • Higher efficiency (90-95 %) • Long life time in cycles/DOD (4000-10000 / 80 %)	• Relatively early-stage technology • High cost (300–1000 €/kWh) • Safety issues require special handling
Redox flow (Vanadium)	• Scalable for large applications • High energy and power density • Long life time in cycles/DOD (13000 / 100 %)	• Relatively early-stage technology • Relatively expensive (150-400 €/kWh) • Lower efficiency (60-75 %)
ZnBr	• Scalable for large applications • High energy density • Long life time in cycles/DOD (4000-5000 / 100 %) • Inexpensive (100–300 €/kWh)	• Relatively early stage technology • Potentially high maintenance costs • Safety hazard: corrosive and toxic materials require special handling • Lower efficiency (70-80 %)
NaS	• High energy density • Long life time in cycles/DOD (10000-15000 / 100 %) • Relatively well established	• Relatively higher cost (150–500 €/kWh) • High temperature safety issues • Lower efficiency (70-80%)
Metal-air	• Inexpensive (50–200 €/kWh)	• Lower efficiency (50 %) • Recharging is difficult
Ni-Cd	• Mature technology • Higher energy density • Long life time in cycles/DOD (5000-10000 / 800 %)	• Higher cost (400–700 €/kWh) • Limited long-term potential for cost reductions due to material costs • Toxic components (cadmium)

[a] This value varies among authors between 100 and 3000

The Li-ion, NaS and Ni-Cd batteries appear to represent the leading technologies in high-power density battery applications. Li-ion possesses the greatest potential for future development and optimization. Another type seen potential for the future is flow battery. The flow batteries are also promising for applications which require long duration storages due to its non-self-discharge capability.

Amongst all the batteries mentioned in table 4.5, the lead acid battery is the oldest and most mature technology, which has been used for majority power system applications. It is widely available worldwide and mostly used in off grid solar PV systems. Therefore, this sort of battery is chosen in the PV systems discussed in chapter 6-7 of this study.

Scenario for the battery price decrease has been calculated and given in figure 4.6 (price for 2009 is taken as 100 €/kWh, the similar values are mentioned by Sauer [2007]). It is hard to get a common approach on price reduction trend that fits to all regions worldwide; however, it is assumed that it will follow the progress ratio of 90 % and production doubling will follow to the same factor of PV modules production doubling. This will be only true if the share of off grid and grid connected PV system remains the same in the future PV market.

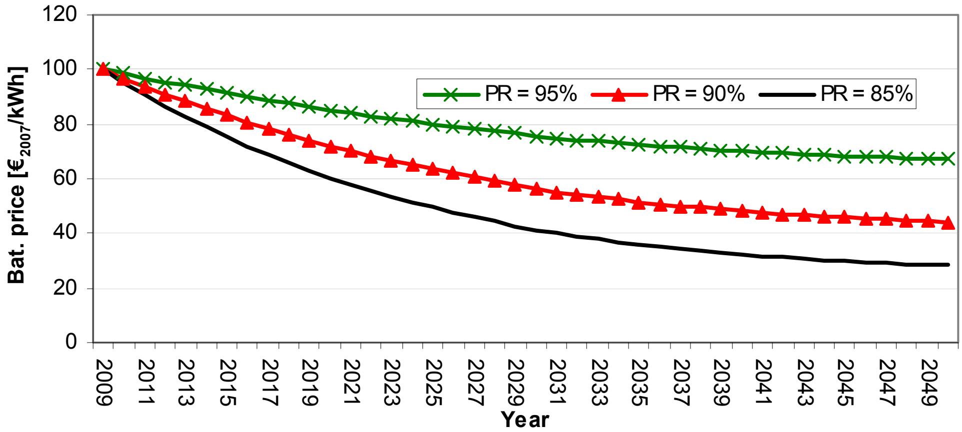


Figure 4.6: Projected battery price

However, it can be expected that the future market share of stand alone system will increase and therefore cumulative doubling for batteries might get faster leading to further battery price reductions.

4.6 Economic Analysis Model

Although there are already several models developed for the economic analysis of different renewable energy technologies (e.g. HOMER, RETScreen, PVSOL, PVSYST, etc.), those are not used in this study and own model has been developed. It is because those models are suitable for general purposes and do not well focus in the costs of grid access and grid extensions criteria. More importantly, these models can not give the outputs in time series when the calculations are made. Also, there is no provision for changing the progress ratio for solar modules and battery prices in these models. Similarly, these models have no provision to transfer it into water networks in order to make similar calculations. These aspects; however, are included in the model that is developed in this study.

4.6.1 Model Developed in This Study

The study aims at carrying out economic analysis of solar PV systems for three different applications (grid connected systems, off grid systems for urban areas and off grid systems for rural areas) as a major part. For this purpose, a model has been developed so as to carry out the cost benefit analysis. Choosing the right values of a parameter for future is very difficult. Economics of solar PV systems is dependent on many factors. At times, even a small change in one parameter affects the whole economic analysis much. This is why the model developed here will help to carry out the sensitivity and scenario analyses by varying the data range of input parameters. Three different models, each for one application type (grid, off grid for urban and rural areas), have been developed. The basic principle behind all three models and their conceptual analysis is analogous. The individual models and their application in economic analysis of PV systems are discussed in chapters 5-7. The model is also used to analyse the grid extension vs. stand alone PV system installation for rural electrification. The whole concept of economic analysis of electricity generation and distribution has been applied to analyse the economics of autonomous water supply systems, as discussed in chapter 8.

Remarks over Similar Studies

Staffhorst [2007] agreed that construction of experience curves on a kWh basis and then simply extrapolate it into the future can not be done, unlike module and system price (€/kW$_p$ vs. kW$_p$) experience curves. Doing this would imply that future improvements of the soft factors will have the same impact on the kWh price as improvements in the past, which is not true. Some soft factors, e.g. yearly variable costs, annual energy yield degradation, etc. have theoretical limits.

The current study assumes that, extrapolation of experience curve for the couple of decades in future includes much uncertainty because the current energy (in overall) and PV market is very dynamic. In fact it is hard to impossible to estimate the future scenarios accurately. Therefore, in this study, a progress ratio of 80 %, agreed by a number of other authors, has been chosen to estimate the future PV system prices. In other words, the learning rate of all soft factors is assumed to be included in the overall progress ratio of PV systems. Not surprisingly, Staffhorst [2007] also agreed that a progress ratio of 80 % is justified for the extrapolation of experience curves based on €/kW$_p$ vs. kW$_p$ cumulative installations.

4.7 Concluding Remarks

The first parameter needed for the extrapolation of experience curves for solar PV systems is the progress ratio. As discussed earlier in the chapter 3, different literatures agree that solar PV module has been following a PR of 80 % since its commercial use. An equal value of 80 % PR for modules and BOS is supposed to be continued in the coming years, though some literatures state that BOS component learning rate might be faster than that of module. The next parameters needed for the experience curves extrapolation are the estimation of future PV systems installation and the current PV system price.

Solar PV installation has soared exponentially in the recent years in Germany and worldwide. Many authors have projected diverse values of PV installation growth rates for the future. There is no consensus to a single growth rate figure for future. The growth rate depends on many factors, e.g. price of PV systems, government policies, innovations leading to the success of thin film solar modules, awareness of the technology in new locations and economy of any country as a whole, among others. Due to high uncertainties of its market parameters, it is pretty hard to forecast the growth rates in an accurate manner, especially in a long run. Different literatures were studied and own growth rates for the future have been proposed for the period until 2060. It has been estimated that, by 2060, Germany will see the cumulative installation of about 98 GW_p and worldwide cumulative installations will reach to about 4400 GW_p.

Different possibilities to decrease the price of PV module in the future with the increment in cumulative installations have been extrapolated in the experience curves. The calculated results for module price in 2060 are found to be about 0.28, 0.51, 0.89 and 1.52 €/W_p for PRs of 75, 80, 85 and 90 %, respectively. For the economic analysis of PV systems in the following sections of this study, a module price decrease for 80 % PR has been adopted.

There are many battery technologies available in the market in order to store the electricity. The relatively cheaper and most widely used type, i.e. lead acid batteries, has been chosen as storage devices in the calculations for the stand alone PV systems in chapters 6-7. There are no detail literatures available on experience curves of solar batteries. Since battery technology is already advanced relative to solar PV systems, a higher PR of 90 % is used in the further calculations of this study.

5 GRID CONNECTED PV SYSTEMS

The functional model of grid connected solar PV system considered in this study is explained as follows. The model begins with the selection of a system size that basically depending on decision of owners. Owners might decide the system size as per surface area available at their roof top or other free space suited for PV installation. However, it might be interesting to install a system with a size that makes electricity balance household (or zero electricity house) if electricity consumption and generation period of one year is considered. It might be argued that the PV electricity generation in the following years will shrink with degradation of the system and the household will no longer be a zero electricity household. Still, utilizing energy efficient appliances will help to reduce consumption and it will maintain electricity balance over a longer period. Once the system size is decided, planning for system installation and economic analysis of the system are required in the next step. Climate condition of the proposed installation site plays a central role in economic analysis and it should be considered taking reliable climate data. Costs for planning and installation and energy management work are put under the BOS components cost of PV system. The next step involves arrangement of bank loan to pay the initial investment needed for modules and BOS components. It is assumed that it will be possible to get a bank loan at lower interest rates to invest in renewable energy power plants like solar PV. For Germany, it is supposed that banks (e.g. KfW) will provide loan at the interest rate of 6 % for the period equal to that of PV system life time considered in the calculations.

After the money is available, system components could be bought and proper installation of the whole system can be carried out. Installation includes making all the arrangements needed ready to supply the electricity from PV system to the nearby grid by finalizing necessary contracts with grid operators and/or with electricity suppliers. When the PV system starts to generate electricity, revenue can be generated by selling the electricity. Such revenue will be used to pay back the interest of the bank loan, the annual instalment of bank loan, variable costs of PV system operation, and BOS replacement costs whenever needed.

Following its installation, PV system is supposed to run throughout its life time without any troubles. If the system is still in good condition to generate electricity after its standard life time (e.g. 25 years in current market), it could be let to go on generating electricity and extra benefits as revenue can be collected. Otherwise the system can be dismantled and disposed.

The calculations made in this study are based on climate and market data for Germany. By changing those data in input fields of the model, analysis for any other sites can also be made.

5.1 Principle

It would be worthy to invest in a solar PV system and to connect it into the grid when the total cost associated with its installation and operation is at the most equal to the revenue that would be collected from selling the electricity generated from it throughout its lifespan.

This principle has been tested with cost benefit analysis model developed for this purpose. The model calculates all the costs associated with PV system and all the revenue to be generated from PV electricity. Both values are used to calculate the benefit (or loss) from the operation of such systems. This equation for benefit calculation is very important in economic analysis because the equation for breakeven analysis can be derived by making the value of this benefit equation zero. This equation for breakeven analysis can be iterated by varying the data range of input parameters and the breakeven conditions for different scenarios can be obtained. Those scenarios will help to understand the system parameters and their affecting scale in economic performance of the whole system more easily. Diverse scenarios analysis and their results are presented in the later sections of this chapter.

5.2 Model in the Block Diagram

The economic analysis model for grid connected solar PV system is described in a block diagram in figure 5.1.

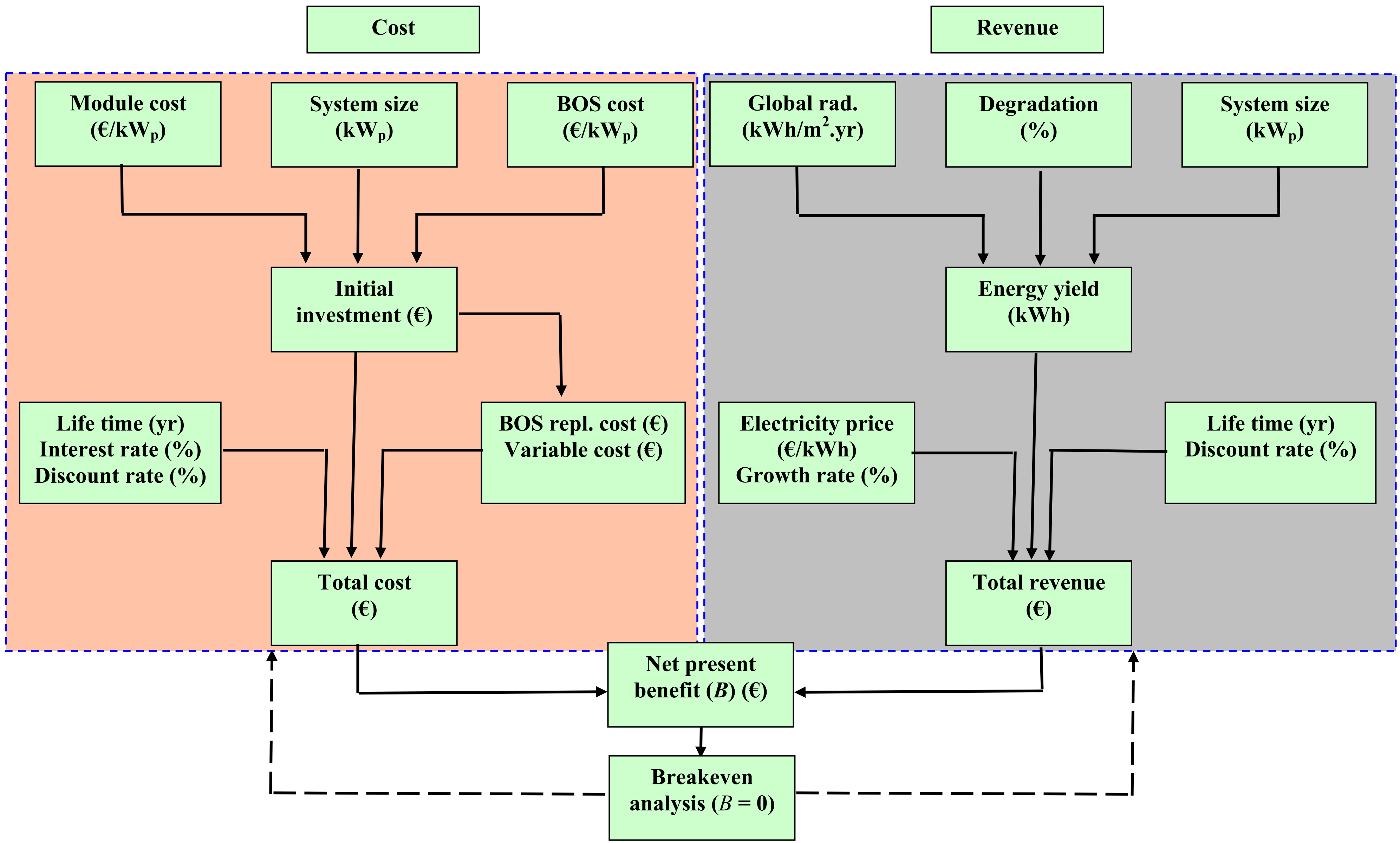


Figure 5.1: Economic analysis model for grid connected solar PV systems

5.3 Assumptions

The following assumptions are considered in the economic analysis:

- Unlimited access for the electricity from PV system into grids
- Revenue based on electricity generation, not based on its consumption
- Electricity trading in free markets (no subsidies, no market distortions)
- Bank loan payment period equal to the PV module life time
- Design and installation cost included into BOS cost
- No disposal cost and salvage value considered
- Calculations on the net present value (NPV) are made for the beginning of year 2009 as a base year unless otherwise mentioned
- Currency is considered in a real value of base year 2007 (€$_{2007}$) unless otherwise mentioned

5.4 Default Values

Most of the default values set in table 5.1 are either based on the calculated data discussed in previous chapters or based on the literatures. Other values are author's own estimations.

Table 5.1: Default values – grid connected PV system

Description	Symbol	Unit	Value
Module price	C_m	€$_{2007}$/kW$_p$	3238
BOS cost factor	k_{bos}	%	30
BOS replacement cost factor	k_{bosrpl}	%	70
BOS component life time	N_r	yr	12
Interest rate	i	%	6
Discounting rate [a]	d	%	4
Variable cost factor [b]	k_v	%	1
Peak power	P_{peak}	kW$_p$	3.874
Global radiation on inclined surface	G_i	kWh/m^2.yr	1205[c]
Standard radiation	I_{stc}	kW/m^2	1
Annual degradation of energy yield	s	%	1
Quality factor (performance ratio)	Q	%	75
Base year wholesale electricity price	$P_{el,w}$	€$_{2007}$/kWh	0.065
Base year end use electricity price	$P_{el,e}$	€$_{2007}$/kWh	0.2143
Annual growth rate for wholesale price	r_w	%	6
Annual growth rate for end use price	r_e	%	4
PV system life time	N	yr	25

[a] discounting rate has been used to consider the opportunity cost of an alternative low risk investment (e.g. bank deposit). In other words, the money at hand today has given a higher value than the same amount in future.

[b] variable cost factor is a portion of initial investment and this expense will be needed annually for module cleaning, maintenance of structure and cables, insurance, etc.

[c] other authors e.g. [Staffhorst, 2007] have used comparable values (e.g. 1150 kWh/m^2.yr) for Germany.

A reference household in Cologne, Germany, consumes an average annual electricity of 3500 kWh. While the system is considered to be installed by households, a capacity of 3.874 kW_p is chosen to make zero electricity household. PV system of size 3.874 kW_p will generate 3500 kWh electricity in a year for available solar radiation in Cologne. Literatures point out the typical value for PV system at household level in Germany is 1-5 kW_p [BMU, 2006]. This small system will have an advantage that it could be installed on the roof top. Also, there is capacity constraint for grid connection that PV systems up to 5 kW_p can be connected to the grids in single phase systems that already exist in each household. The systems more than 5 kW_p should be connected to the grid using three phase systems [Lauterbach, 2002]. Dunlop et al [2005] mentioned a typical value of quality factor Q (called performance ratio by some authors) is around 75 % for smaller PV systems (<5 kW_p and typically owned by individual persons). For large systems with more efficient inverters this may be somewhat higher. According to Mayer [2005], PV system performance ratio in Germany was around 64 % for the systems installed before 1995 and around 74 % for the systems installed after 1995. Real interest rate is considered to be of 6 %, which is similar to the value taken by BMU [2007] in the calculations for German renewable energy market. PV system life time is considered to be 25 years in default, similar to used by other authors e.g. Zwaan and Rabl [2003]. However, EC [2005] expected that the PV systems will have a standard technical life time up to 40 years by 2030. Therefore, the calculations for extended life time of 30 and 40 years have also been presented in this study. Annual operation and maintenance cost will be about 0.5-1 % of the investment costs [EC, 2005]. The variable cost factor of 1 % of initial investment is assumed in this study. IEA-PVPS [2007] estimated that BOS components account for between 20 % (standard grid connected system) and 70 % (off grid installation) of the total PV system costs. The BOS cost used in this study for grid connected systems is 30 % of total module costs. BOS replacement cost factor is presumed to be 70 % of the BOS costs assuming that not all BOS components need to be replaced (e.g. system planning and installation costs, PV module support structures, etc.). Cost for land is neglected with the assumption that the PV power plant will be installed at home premises, mainly on roof top. In case of bigger power plants, it is wise to include the land expenditures if these costs are considered in the competitive power plant (e.g. coal, oil, gas fired power plants) to avoid cost distortions in calculations. The spreadsheet model developed in this study is intended to be a general one that can be used for the calculations in different countries. This is why any other factors at national level (such as value added taxes or any existing subsidy schemes) that influence the investment in PV systems are excluded.

5.5 Calculations

Calculations of cost, revenue, and cost benefit analysis are given in details in the following sections.

5.5.1 Cost

Total cost of solar electricity production will be the sum of initial investment costs, BOS replacement costs and variable costs. Current value of the total cost associated with installation and operation of solar PV power plant throughout its life time is given by:

$$C_t = C_{mt} + C_{bos} + C_{bosrpl} + C_v \qquad [5.1]$$

where,

C_t is present value of total system cost [€$_{2007}$]

C_{mt} is present value of cost associated with module [€$_{2007}$]

C_{bos} is present value of cost associated with initial investment for BOS [€$_{2007}$]

C_{bosrpl} is present value of BOS replacement cost [€$_{2007}$]

C_v is present value total variable cost [€$_{2007}$]

Present value of cost and revenue from their annual future value (*FV*) is calculated by using the present value equation and is specified by:

$$\Pr esent\ value = FV\left(\frac{1}{1+d}\right)^n \qquad [5.2]$$

The individual cost components given in equation 5.1 are described below.

i. Module Expenditure

Module cost has been categorized into two parts. The first part is investment cost, the price that is paid in order to buy modules at the time of system installation. It is assumed that module will be bought upon a bank loan. The next part is associated with loan cost, the interest payment to the aforementioned bank loan. Bank loan will be paid in annual instalment basis, an equal value every year throughout the loan period. Annual interest in future years will apply only to the remaining debt of the bank (after annual instalment payment). All annual values of module expenditure are discounted to the base year, i.e. beginning of year 2009, using discount rate *d*. These costs are summed up to calculate present value of total module related costs and it is given by:

$$C_{mt,NPV} = C_m P_{peak}\left\{\sum_{n=1}^{n=N}\frac{1+i(N-n+1)}{N(1+d)^n}\right\} \qquad [5.3]$$

where,

C_m is module price [€$_{2007}$/kW$_p$]

P_{peak} is capacity of the PV power plant [kW$_p$]

N is PV power plant life time [yr]

i is real interest rate [%]

d is real discount rate [%]

ii. BOS Expenditure

It is assumed that BOS will also be bought through bank loan in the beginning. Like in the case of module, all annual values of BOS expenditure are discounted to the base year (i.e. beginning of year 2009) using discount rate *d*. These costs are summed up to get total present value of BOS related costs. This total present value of BOS expenditure is given by:

$$C_{bos} = C_m P_{peak} k_{bos}\left\{\sum_{n=1}^{n=N_r}\frac{1+i(N_r-n+1)}{N_r(1+d)^n}\right\} \qquad [5.4]$$

where,

k_{bos} is BOS cost factor (% of initial investment) [%]

N_r is BOS component life time (i.e. replacement year) [yr]

iii. BOS Replacement Cost

Certain BOS components will have to be replaced once BOS life time is over (some BOS component life time has been considered to be less than module life time). In the calculations for grid connected systems of this study, BOS component replacement time has been considered to be on the half way of system life time. During their replacement, BOS components will be bought by the money collected as revenue by selling electricity and hence bank interest rate has not been considered in the replacement costs. It is assumed that all BOS components do not need to be replaced (e.g. cables, support structure, etc.) and hence the cost for replacement will be a certain factor of BOS cost considered at the time of system installation (i.e. k_{bosrpl}). Present value of BOS replacement cost (after discounting to the base year) is given by:

$$C_{bosrpl} = C_m P_{peak} k \left\{ \frac{k_{bos} k_{bosrpl}}{(1+d)^{N_r}} \right\} \quad [5.5]$$

where,

k_{bosrpl} is BOS replacement cost factor (% of BOS cost) [%]

$k = \frac{C_{m(n+N_r)}}{C_{m(n)}}$ is module price reduction factor

The parameter *k* in equation 5.5 is important because the BOS component cost is determined as a function of module price. Module price of the replacement year should be considered in calculations (not the price of PV system installation year) in order to include the learning effects in BOS components. The learning rate for BOS components is assumed to be 20 %.

iv. Variable Cost

Unlike conventional energy sources, once a PV system has been commissioned, the variable cost of electricity production is only determined by the maintenance works of system, since fuelling is not required. Annual variable cost is calculated by multiplying initial investment and variable cost factor. The present value of variable costs (all the costs of individual year discounted to the base year 2009) is given by:

$$C_v = C_m P_{peak} \left\{ k_v (1 + k_{bos}) \sum_{n=1}^{n=N} \frac{1}{(1+d)^n} \right\} \quad [5.6]$$

where,

k_v is annual variable cost factor (% of initial investment) [%]

v. Total Cost

Substituting the values of cost components from equations 5.3 to 5.6 into the equation 5.1, the present value of total cost is given by:

$$C_t = C_m P_{peak}\left[\begin{array}{l}\left\{\sum_{n=1}^{n=N}\frac{1+i(N-n+1)}{N(1+d)^n}\right\}+k_{bos}\left\{\sum_{n=1}^{n=N_r}\frac{1+i(N_r-n+1)}{N_r(1+d)^n}\right\}\\ +k\left\{\frac{k_{bos}k_{bosrpl}}{(1+d)^{N_r}}\right\}+\left\{k_v(1+k_{bos})\sum_{n=1}^{n=N}\frac{1}{(1+d)^n}\right\}\end{array}\right] \quad [5.7]$$

The net present value of individual cost components (module expenditures, BOS expenditures, BOS replacement costs and variable costs) calculated by using the default values given in table 5.1 for PV systems with life times (*N*) of 25, 30, and 40 years is given in figure 5.2.

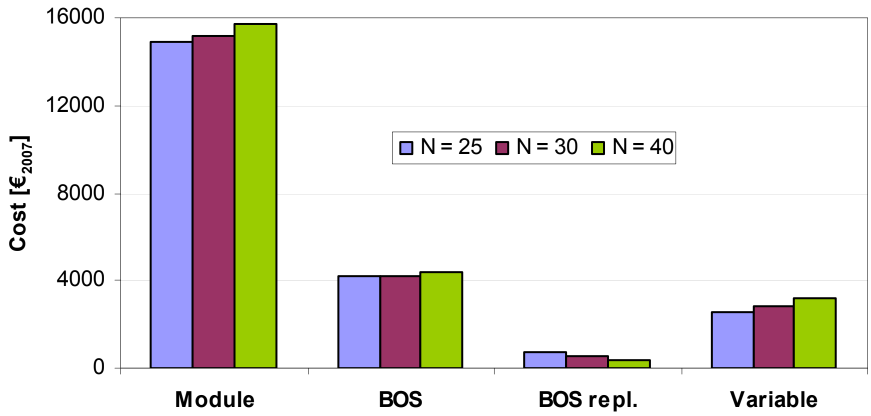


Figure 5.2: Present value of PV system component costs

Although the initial investment for same system size is equal regardless of the system life time, the present values of module and BOS costs are slightly higher for the systems with longer life time as shown in figure 5.2. This is because of higher amount of interest payment to the bank due to the longer loan payback duration. Total variable cost is also higher if the system life time is longer. This is because the variable cost occurs every year i.e. when the life time is longer, it will occur for longer period. Unlike other components, the cost for BOS replacement has been decreased with increase in system life time. This is because of decrease in BOS cost at the future time point driven by learning rates. For the system with longer life time, BOS life is also considered longer and replacement will occur at later time.

5.5.2 Energy Yield

The nominal power production capability of PV systems is normally expressed in watt peak (W_p). This is defined as the power output at the terminals of the PV modules with an in plane irradiance of 1000 W/m^2, a module temperature of 25 ^{o}C and standard air mass (AM) spectrum of 1.5 [Dunlop et al, 2005]. This condition is called standard test condition. In reality the delivered power output will decline due to lower efficiency at higher temperatures, lower irradiances and due to losses in cables and inverters. The ratio between actual performance and nominal performance is termed as quality factor (named performance ratio by some authors) and it is denoted by *Q* [Schmid, 2003]. The annual energy yield of a PV system is given by:

$$E_n = P_{peak} Q \frac{G}{I_{stc}} (1-s)^{n-1} \quad [5.8]$$

where,

E_n is annual energy yield [kWh/yr]
Q is quality factor of PV system [%]
G is average global radiation [kWh/m^2.yr]
I_{stc} is solar radiation for standard test condition [kW/m^2]
s is degradation rate for annual energy yield [%]

The energy yield of the first year of installation is considered to be 100 % and from the next year it will decrease by the degradation rate s. In equation 5.8, the value of G has high influence on the annual electricity yield. Global radiation on module plane depends not only on the site of location, but also on the angle of inclination of module. Therefore, before the PV system is installed, an optimum angle of inclination for modules should be designed.

5.5.2.1 Solar Radiation on Tilted Surface

The power incident on a PV module depends not only on the power contained in the sunlight, but also on the angle between the module and the sun. When the absorbing surface and the sunlight are perpendicular to each other, the power density on the surface is equal to that of the sunlight (in other words, the power density will always be at its maximum when the PV module is perpendicular to the sun). However, as the angle between sun and fixed surface is continually changing, the power density on a fixed PV module is less than that of incident sunlight. The tilt angle has a major impact on the solar radiation incident on a surface. For a fixed tilt angle, the maximum power over the course of a year is obtained when the tilt angle is equal to the latitude of the location [PVCDROM, 2009]. However, steeper tilt angles are optimized for large winter loads, while lower tilt angles use a greater fraction of light in the summer.

The solar radiation data on horizontal surface can be converted into inclined surface by using the following equations [PVCDROM, 2009]:

$$G_i = G_h \frac{\sin(\alpha + \beta)}{\sin \alpha} \quad [5.9]$$

where,

G_i is solar radiation on inclined surface [kWh/m^2.yr]
G_h is solar radiation on horizontal surface [kWh/m^2.yr]
β is angle of inclination for module [degree]
α is elevation angle [degree]

The value of α can be calculated by:

$$\alpha = 90 - \varphi + \delta \quad [5.10]$$

where,

φ is latitude of the location [degree]

δ is declination angle [degree]

The value of δ can be calculated as:

$$\delta = 23.45 \sin\left[\frac{360}{365}\left(284 + y_d\right)\right] \qquad [5.11]$$

where,

y_d is day of the year

In case of grid connected systems, where 100 % of the electricity generated can be sold to the grid, the angle of inclination should be chosen in such a way that annual value of global radiation is at its maximum. Generally the optimal angle of inclination for grid connected solar PV systems in Germany is considered to be about 30 ^{o} [Schmid, 2003[1]].

Figure 5.3 shows the average annual global radiation on horizontal surface for Germany[2].

Figure 5.3: Average annual global radiation in Germany (kWh/m^2.year)

[1] An optimal angle of 30 degrees mentioned for Kassel, Germany

[2] http://www.meteonorm.com/pages/en/downloads/maps.php

5.5.2.2 Cumulative Energy Yield

Cumulative energy yield during the project period, E_t, derived from equation 5.8 is given by:

$$E_t = P_{peak} Q \frac{G}{I_{stc}} \sum_{n=1}^{n=N} (1-s)^{n-1} \qquad [5.12]$$

Figure 5.4 illustrates the annual and cumulative energy yield throughout the system operation period up to 40 years. The calculation is based on the default values given in table 5.1.

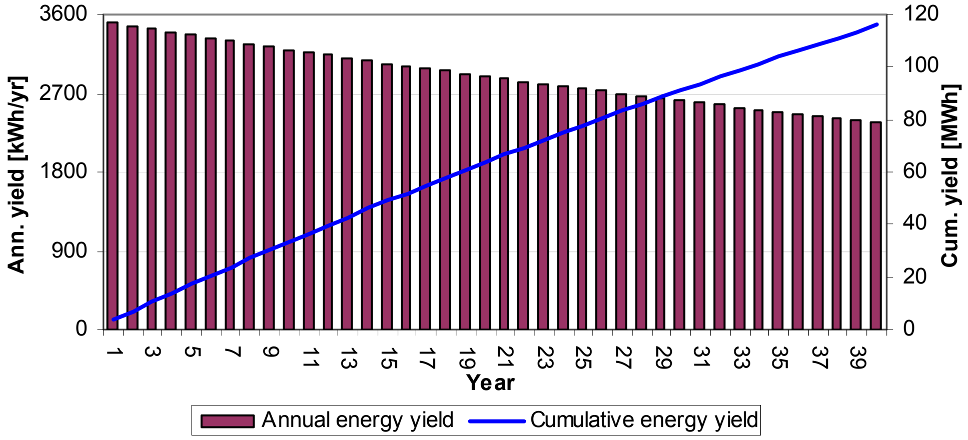


Figure 5.4: Annual and cumulative energy yield

Values for the shorter life time of 25 or 30 years can also be seen in the same figure 5.4. Cumulative electricity yield from the systems with 40, 30 and 25 years lifespan is calculated to be around 116, 91 and 78 MWh, respectively.

5.5.3 Electricity Price

A historical trend of German electricity price development processed from data of EnergieAgentur NRW [2008] is given in figure 5.5. Two different electricity prices are shown, one for household customers and the other for special customers (i.e. the ones with annual electricity consumption of more than 30 MWh). There is a rapid increase of electricity price in two world oil crisis periods of 1973 and 1989. After the year 2000, price increase has again become steep. One of the reasons might be the increase in oil and gas price in the same period. Other causes might be introduction of electricity market liberalisation law in 1999 and ecological taxes in the framework of German Renewable Energy Source Act in 2000.

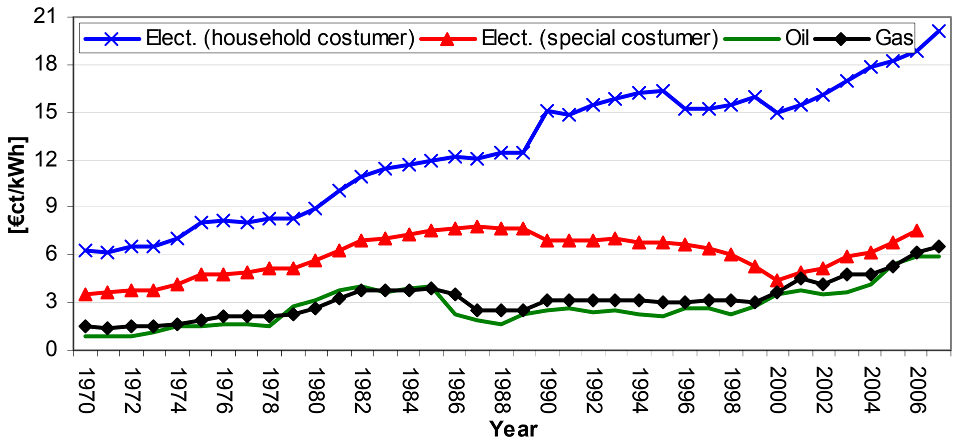


Figure 5.5: Electricity, oil and gas price development in Germany

In the figure 5.5 it can be seen that the gap between oil (and gas) price and household customer electricity price is increasing annually. This might imply that increase in fuel price by one factor might cause increase in electricity prices by many factors. However, there might be other reasons too. One thing for sure is that there will be further increase in electricity price in Germany and in the world as a whole in coming years. While assessing the historical trend, estimating the right value of growth rate for longer period of time is a difficult task, but it is a highly sensitive factor in order to determine the electricity price in coming years. This is why a scenario of different growth rates has been considered in this study.

It is assumed that wholesale electricity price will increase every year with a growth rate of 6 %. However, scenarios with growth rate of 3 % are also analysed. Similarly, the growth rate for end use electricity price is assumed to be 4 %, but the pessimistic scenario with 2 % growth rate has also been analysed. The reason for different growth rates between wholesale price and end use price is that, the price growth will be influenced mostly by generation price (i.e. wholesale price) and other components of end use prices like taxes and transmission and distribution fees will not increase proportionally. Calculations for annual value of electricity price, $P_{el,n}$, is given by:

$$P_{el,n} = P_{el}(1+r)^{n-1} \qquad [5.13]$$

where,

P_{el} is electricity price for base year [€$_{2007}$/kWh]

r is annual growth rate for electricity price [%]

As shown in equation 5.13, the first year price will be actual market price and the price from the second year will increase with annual growth rate. The wholesale electricity price scenario for next 25 years considering different growth rate is given in figure 5.6.

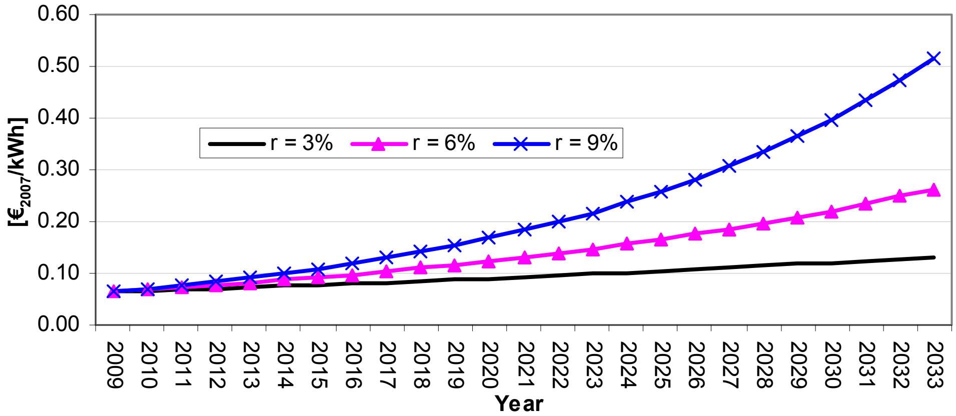


Figure 5.6: Wholesale electricity price projection in Germany

5.5.4 Revenue

Once the PV power plant is installed, it will generate electricity continually during the sunny hours. This electricity will be sold to grid operator or electricity supplier through the grid and thereby revenue will be generated. The potential annual revenue from the PV plant, R_n, is given by:

$$R_n = P_{el,n} E_n \qquad [5.14]$$

The revenue of any year is determined by multiplying the electricity price and amount of electricity generation in the same year. While annual energy yield degradation rate is assumed less than annual electricity price growth rate in this study, the annual revenue will increase yearly. The annual revenue has to be discounted by a discount rate to the base year in order to get its present value. The present value of total revenue from PV plant throughout its operation period, R_t, is given by:

$$R_t = \sum_{n=1}^{n=N} P_{el,n} E_n \frac{1}{(1+d)^n} \qquad [5.15]$$

Replacing the values of cumulative energy yield and electricity price from equations 5.13 and 5.14, equation 5.15 for the total revenue calculation becomes:

$$R_t = P_{peak} Q \frac{G}{I_{stc}} P_{el,w} \sum_{n=1}^{n=N} \frac{(1+r)^{n-1}(1-s)^{n-1}}{(1+d)^n} \qquad [5.16]$$

The calculated annual revenue from solar PV system using the data given in table 5.1 for PV system with 25 years of life time is given in figure 5.7.

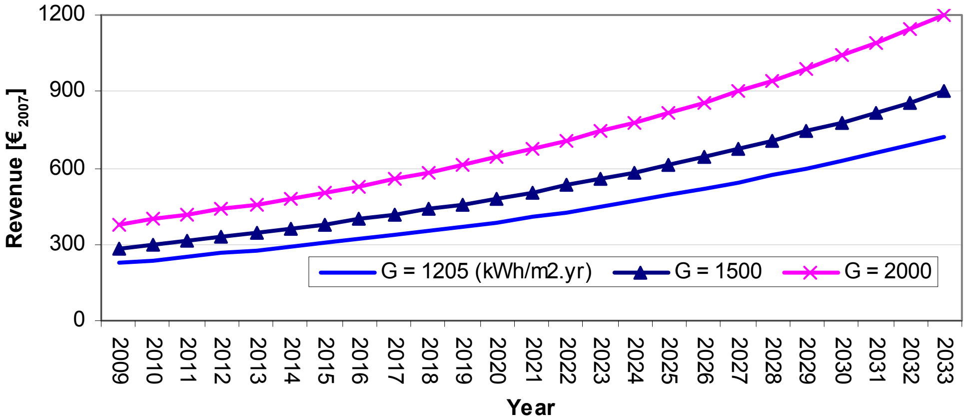


Figure 5.7: Annual revenue from PV power plant (grid connected)

As shown in figure 5.7, annual revenue is highly affected with the available global radiation on the site.

Avoided external cost by PV power plants over conventional power plants is not calculated separately so as to avoid double counting. This is assumed that the annual increase in grid electricity price will already include the external cost of conventional power plants.

5.6 Results

The economic analysis results are given in the following sections.

5.6.1 Cost Benefit Analysis (CBA)

The main result of the economic analysis has been considered the cost benefit analysis in this study. The net present value[3] (termed as net present benefit, *B*, in this study) of the PV power plant is given by:

$$B = R_{t,NPV} - C_{t,NPV} \tag{5.17}$$

If the value of *B* is positive, the investment in the project is worthwhile, if the value is zero, the project is indifferent and if the value is negative, the project brings loss if it is executed, meaning it is wise not to invest in the project. This is the major indicator that helps in decision making on whether to invest in the grid connected PV power plant or not, under given market conditions. The results obtained from the calculations using default values (table 5.1) as input parameters for the grid connected solar PV system in Germany are given in figure 5.8.

[3] Net present value is computed by assigning monetary values to benefits and costs, discounting future benefits and costs using an appropriate discount rate, and subtracting the sum total of discounted costs from the sum total of discounted benefits. Discounting benefits and costs transforms gains and losses occurring in different time periods to a common unit of measurement.

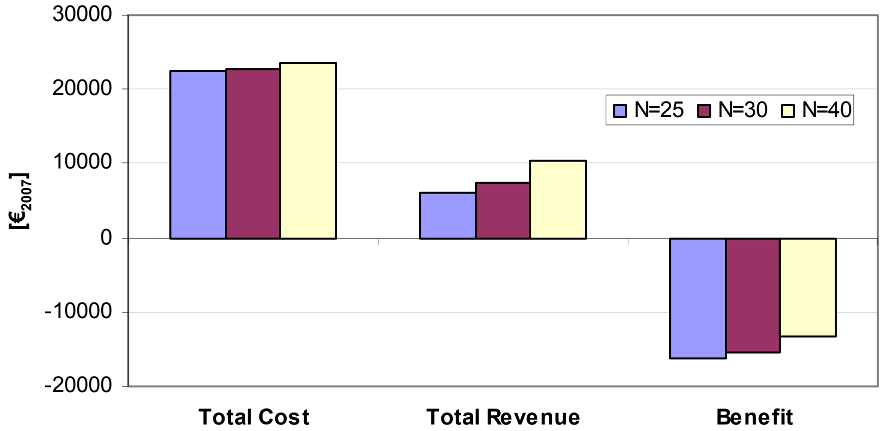


Figure 5.8: Cost benefit analysis results (electricity price growth rate = 6 %)

From the results shown in figure 5.8, it can be concluded that under existing market and climatic conditions in Germany, the electricity generated from grid connected solar PV system can not compete with the electricity generated from conventional power plants. The present values of costs are almost the same for all system life times, but the revenues are different. This is because the system size, which is same in all three cases, determines the total costs, but the system life time decides the cumulative energy yield, which affects the revenue. Although, increasing the system life time will help to increase the cumulative energy yield and to generate additional revenue, its present value is relatively low because of a discount rate considered to calculate the present value of the future revenue.

As a more optimistic scenario, the CBA results for annual wholesale electricity price growth rate of 9 % are shown in figure 5.9. Even if there is an annual growth rate of 9 % in the wholesale electricity price, PV systems are still not market competitive.

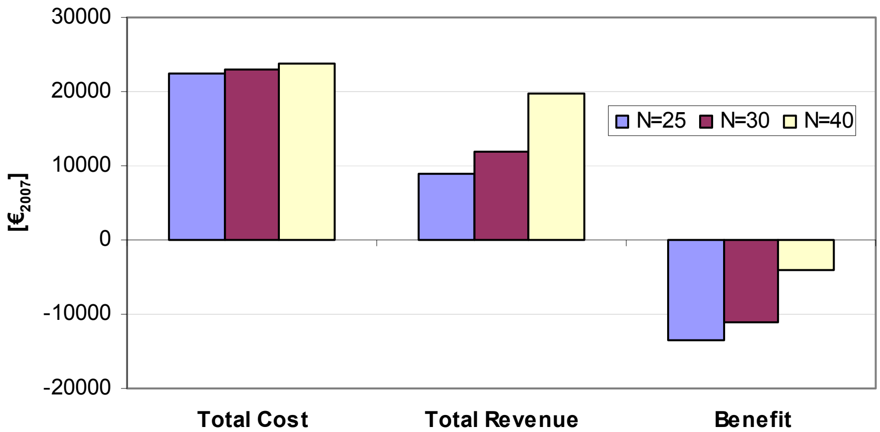


Figure 5.9: CBA results (electricity price growth rate = 9 %)

Recently the thin film PV modules are coming in the market and they are relatively cheaper. For example, the modules produced by FirstSolar costs about 1000-1500 €/kW$_p$ [USSEC, 2009]. Because of the fact that the technology is new, its performance, degradation of energy yield and life time is not studied as much as that for the conventional silicon modules. Also, if the technology is already so cheap, perhaps there is not much space for the price decrease in the future following the experience curve progress ratio as high as 80 %. To get answers to such doubts, some more years has to be awaited. Considering the price of these modules to be 1000 (1500) €/kW$_p$ as of today, the cost benefit analysis has been made and the obtained values for the benefit (in €) are found to be about -808 (-4265), 443 (-3085) and 3174 (-482) for the systems with a life time of 25, 30 and 40 years, respectively.

In the following sections of this study, the market price data for the conventional silicon modules (figure 4.5) have been considered, unless otherwise specified.

5.6.2 Breakeven Analysis

In economics, the net present value of the project should be equal to zero for any project to be at breakeven condition. The breakeven equation is given by:

$$B = R_{t,NPV} - C_{t,NPV} = 0 \qquad [5.18]$$

Using equation 5.18, different scenario analysis can be carried out by varying the range of input parameters, and their sensitivity to the overall project results can be analysed. For the PV system discussed here, the breakeven values obtained for module price and wholesale electricity price are given in figure 5.10. Both values are given for two different scenarios of annual wholesale electricity price growth rate of 6 % and 3 % and for systems with three different system life time of 25, 30 and 40 years.

These breakeven values for module price or electricity price in figure 5.10 mean that the supposed PV power plant would have been at breakeven point, if either PV modules were already available at the given price or current wholesale electricity price was already at the value shown in the figure.

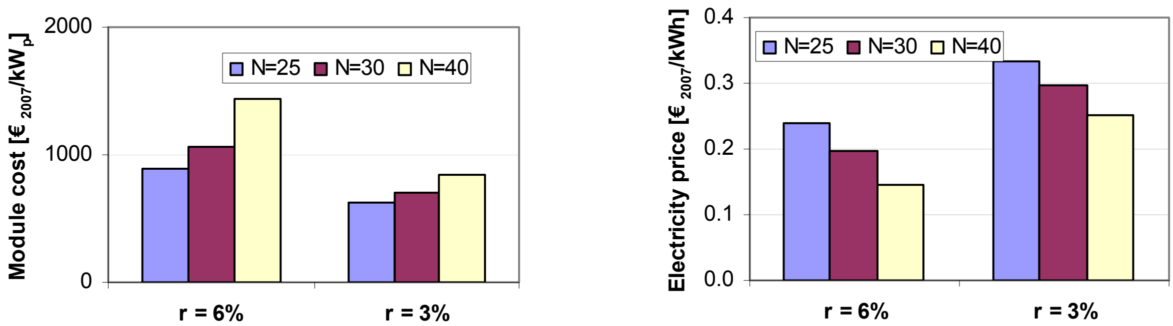


Figure 5.10: Breakeven module and electricity prices

5.6.2.1 Breakeven Year

Breakeven year is the year when solar PV system will be at its breakeven point, i.e. the value of B in equation 5.18 is zero. It has already been discussed in the previous section that there are certain conditions (e.g. module price or electricity price in figure 5.10) that should be fulfilled so as to be the PV systems at breakeven. For the systems to be installed in coming years there will be decrease in total system price because of decreased module and BOS cost driven by learning rate and there will be increase in total revenue caused by wholesale electricity prices increase driven by raising fossil fuel prices, including some other factors. Compounded with this situation, it will lead to a time point when investing in the PV systems will be economically worthy. Figure 5.11 shows that such time point (breakeven year) will occur in around 2019-2020.

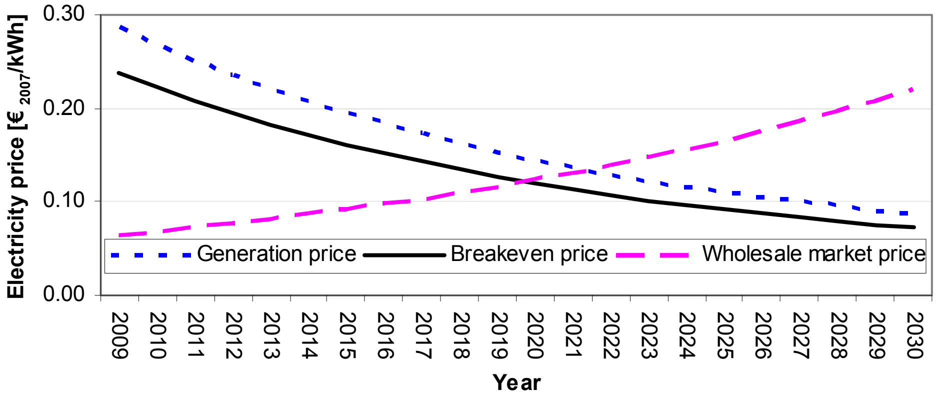


Figure 5.11: Breakeven year ($N = 25$)

Likewise, PV electricity generation cost per kWh has also been calculated. This is done by dividing the total system cost given in equation 5.10 by cumulative electricity yield from installed PV system throughout its life time as given in equation 5.12. This kWh generation price of PV can be compared with the same from other conventional electricity generation technologies. The condition when both the generation prices are equal is called as grid parity (detail in section 5.6.3). As given in figure 5.11, breakeven year will occur around two years before the grid parity year. This means it is not necessary to wait for investment in solar PV systems until it reaches the grid parity. If the value for electricity price growth rate and discounting rate were same (and the revenue was considered to be generated in the beginning of the year), both lines - generation and breakeven prices - would have been coincided.

The breakeven year will occur sooner if the system life time is longer. The results are shown in figure 5.12. It can be seen that breakeven years, in reference to wholesale electricity prices, will be nearly in 2019, 2018 and 2015 for the systems with life times of 25, 30 and 40 years, respectively.

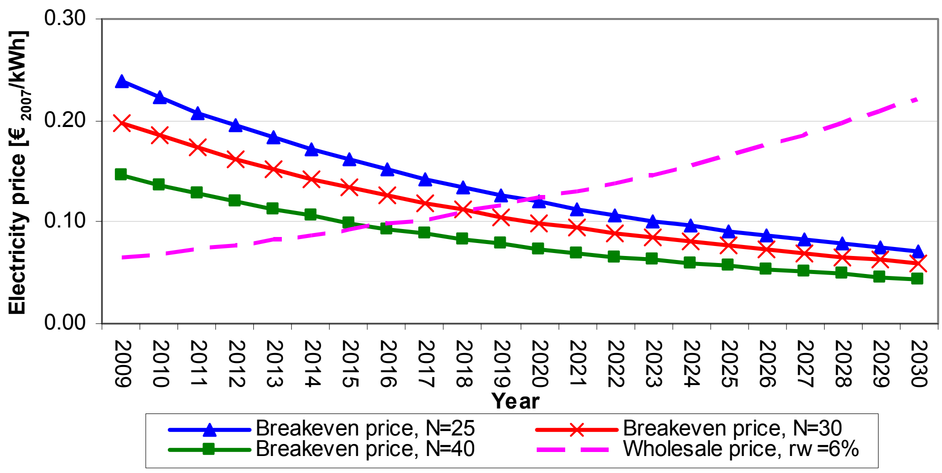


Figure 5.12: Breakeven year (electricity price growth rate = 6 %)

The year is; however, dependent on the growth rate of the wholesale electricity price in electricity market. The pessimistic scenario for its lower growth rate of 3 % is shown in figure 5.13. In this case, the breakeven years occur later, i.e. around in 2028, 2026 and 2024 for the system life times of 25, 30 and 40 years, respectively.

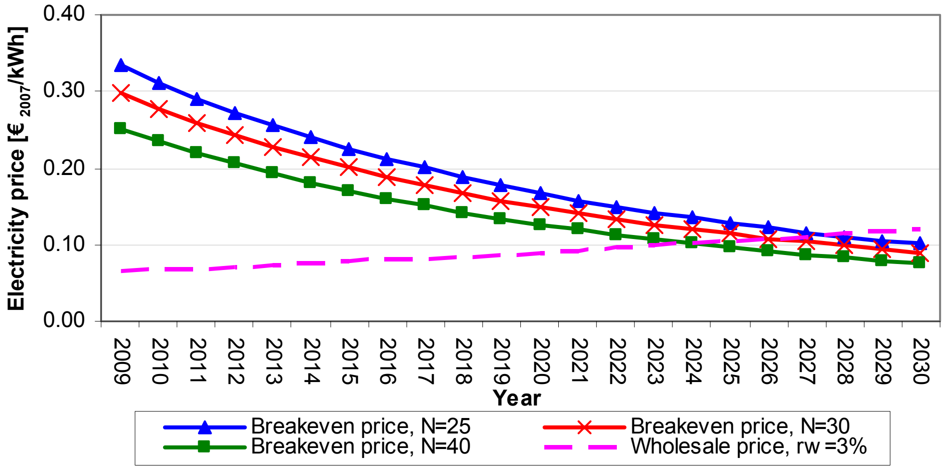


Figure 5.13: Breakeven year (electricity price growth rate = 3 %)

5.6.2.2 Breakeven Module vs. Electricity Prices

Different combinations of solar PV module price and base year wholesale electricity price for grid connected PV systems in Germany are shown in figure 5.14. It can be seen that for the same electricity price, PV systems in sunny locations would have been at breakeven albeit the module prices were higher. Coordinates of each point in the line are the values of module prices and necessary base year electricity price for the systems to be at breakeven conditions.

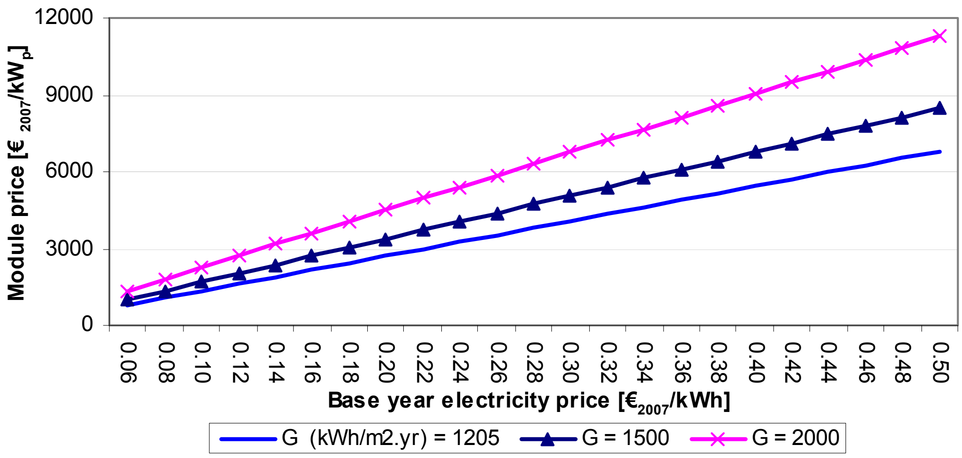


Figure 5.14: Breakeven module price and electricity price ($N = 25$)

5.6.3 Grid Parity

Grid parity is a term popularly used in solar PV sector to explain the time point when a kWh electricity generation cost using solar PV becomes equal to a kWh electricity price in the grids. Grid electricity has two diverse prices, one at wholesale market and one at end use or household consumer market. Many authors consider the grid electricity price for household consumer while calculating the grid parity; however, both cases are discussed in this study.

Considering yearly module price in Germany to be similar to yearly module prices worldwide for the coming years (figure 4.7) and using the other parameters as in default values given in table 5.1, grid parity for wholesale and end use electricity market in Germany has been calculated and the corresponding results are presented in the following sections.

Figure 5.15 shows grid parity for wholesale and end use electricity prices. If the household intends to sell the electricity to the grid, it will receive the wholesale electricity price as revenue. And grid parity, in this case, it will be a meeting point of generation price curve and wholesale electricity price curve, i.e. in around 2021. If a household installs a grid connected solar PV system at house premises and intends to use 100 % of the generated electricity at house, it will save the money that would have been paid as retail price for the utility. In such circumstance, grid parity will be the meeting point of generation price and end use price, i.e. year 2011-2012 in figure 5.15.

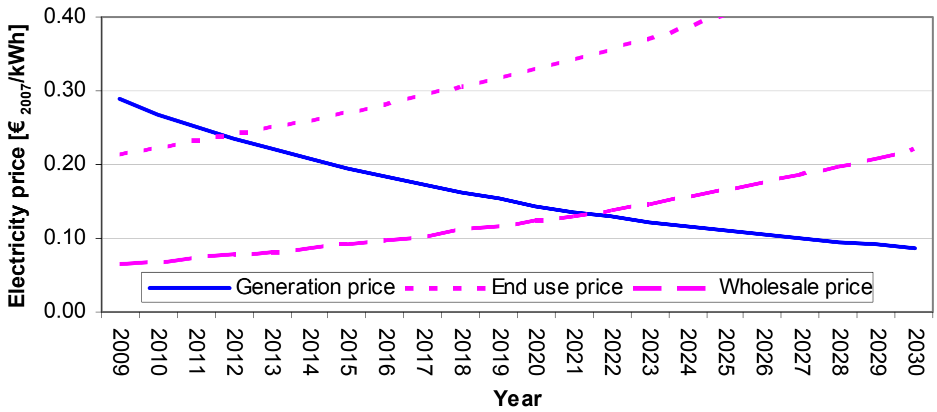


Figure 5.15: Grid parity – wholesale and end use electricity price

However, in practice, household may decide to install the system and partly use the electricity generated at home and sell the surplus to the grid. This will result grid parity year in between of these two cases discussed in figure 5.15. This is discussed in the following section 5.6.3.1.

5.6.3.1 Grid Parity for Mixed Case

The main idea behind this discussion is to assess how much electricity from solar PV can be used at household at the time of generation without any electricity storage systems in use. It is obviously worthy to use the PV electricity as much as possible at the time of its generation, because it will replace the expensive electricity that would have been consumed from the grid in the absence of PV systems. The electricity that is not consumed at household can be fed into the grid and revenue based on wholesale electricity tariff can be obtained. For this assessment, the possible shortest time scale electricity consumption and generation profile (e.g. second or minute profile) should be analysed for accurate results, but such data are very hard to obtain. In this study, an hourly profile for one year has been analysed. Figure 5.16 shows the hourly average electricity consumption profile of a reference German household with annual electricity consumption of 3500 kWh. Electricity demand data are taken from VDEW [2008] and they are processed to obtain the results shown in the figure 5.16.

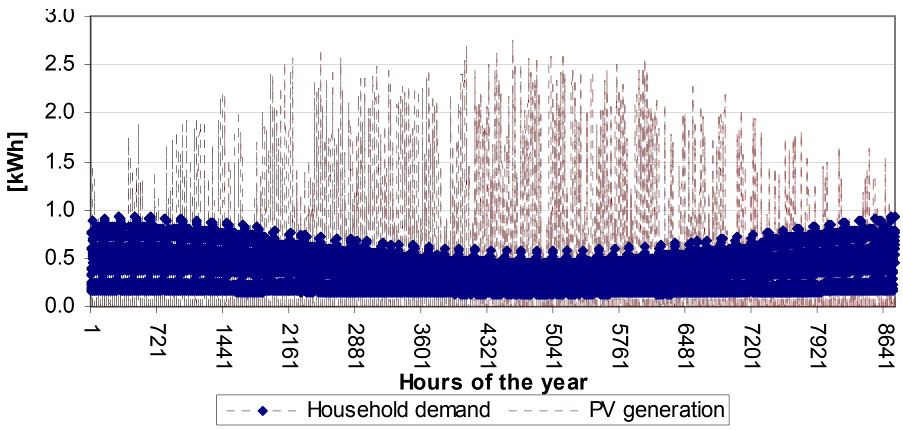


Figure 5.16: Hourly electricity consumption and PV electricity generation

The dotted line (dark red) depicts the average hourly electricity generation from a PV system with module size of 3.874 kW_p for climate data of Cologne, Germany (climate data are taken from PVSOL 2.6). It is clear from the figure that during summer, hourly electricity generation from PV surpasses the hourly electricity demand at household. It reverses during winter. Based on those hourly values of consumption and generation pattern, possible portion of household consumption at the time of PV electricity generation has been calculated. It was found that about 42 % of the electricity from PV can be consumed at the time of generation, and rest 58 % has to be supplied to the grids (figure 5.17), at the reference site in Cologne. This share will be different to other locations with different climate data or different electricity consumption patterns. The results would be more accurate if the electricity demand and generation profile for shorter than hourly interval (e.g. each seconds) were considered; however, this has not been done here because of the fact that no such data could be obtained.

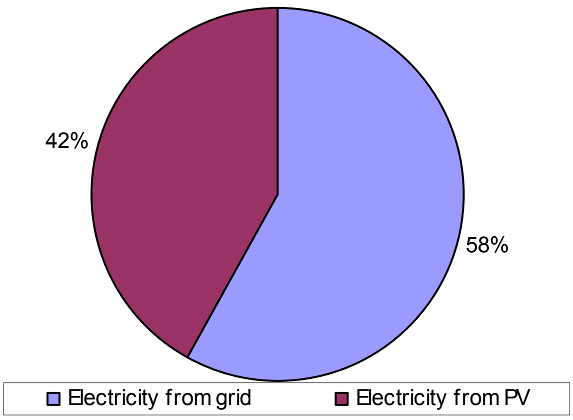


Figure 5.17: Share of PV electricity consumption at the time of its generation

This result can be transferred to estimate the electricity price that a household will virtually get from the each kWh electricity generated from PV. This price has been represented in figure 5.18 by solid pink line, in between of wholesale and end use electricity prices.

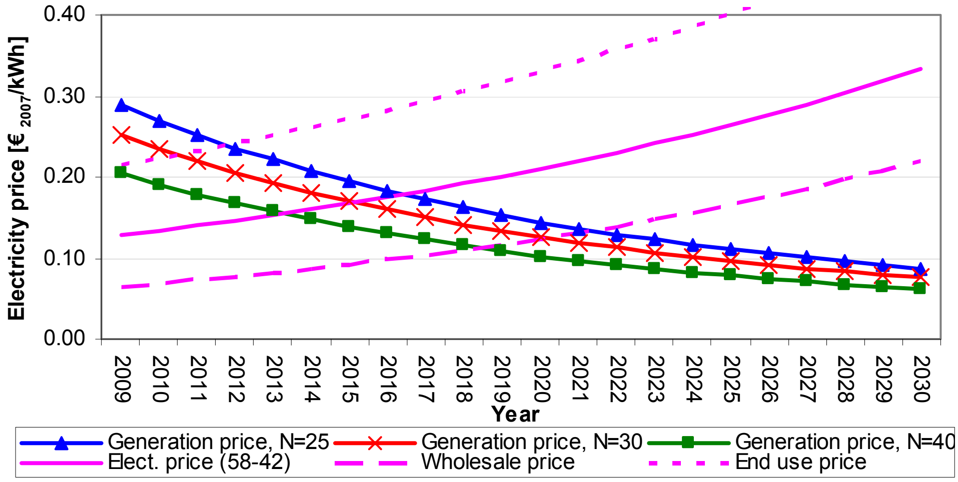


Figure 5.18: Grid parity for mixed case

It can be concluded that the grid parity in practice will occur between the years 2017 and 2013 for PV systems with the life time ranging from 25 to 40 years. Also the use of smart metering (in future) will be helpful to calculate the revenue based on real value of PV electricity (assuming PV generation during the mid day (peak hours for demand) will be higher and the grid electricity price will also be higher). And, this might make PV systems market competitive in advance.

The following sub sections discuss the effect of varying different parameters in determining the grid parity years (sensitivity and scenario analyses).

5.6.3.2 Effect of Global Radiation

Not surprisingly, the available global radiation has an important role for the electricity yield from PV system. In the sunny areas yield will be higher and thereby high revenue will be generated. This will ultimately near the grid parity year compared to less sunny regions and it has been clearly shown in figure 5.19.

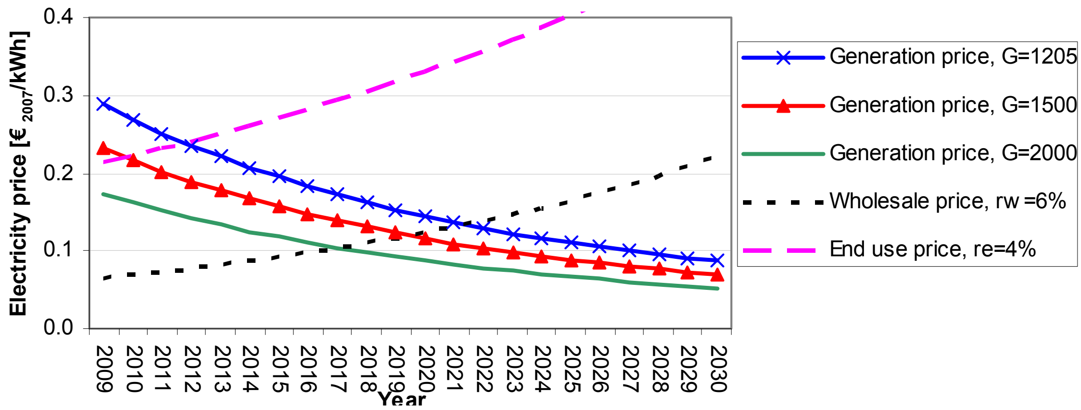


Figure 5.19: Grid parity – different global radiation and wholesale electricity price

By varying average annual global radiation from 2000 kWh/m^2.yr (e.g. value for Nepal) to 1205 kWh/m^2.yr (e.g. value for Germany) grid parity year will shift from 2021 to 2017.

5.6.3.3 Effect of Interest Rate

The effect of different bank interest rates in sooner or later occurrence of grid parity is shown in figure 5.20 for wholesale and end use electricity prices.

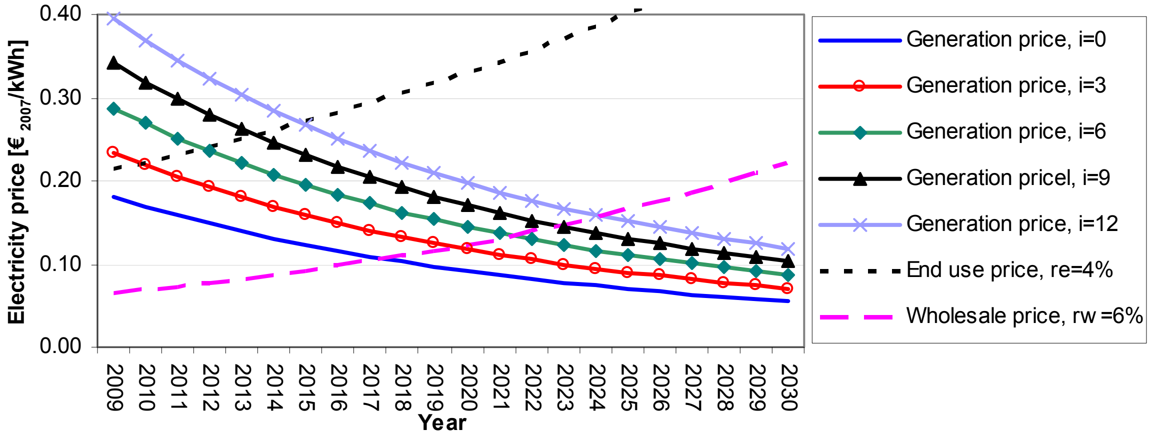


Figure 5.20: Grid parity – different interest rate and electricity price

If the bank interest rate is low, the overall cost of the project will decrease and hence the grid parity will occur sooner. In many countries, it might be possible to get a bank loan for lower interest rates for renewable energy projects like solar PV. As given in the figure 5.20, the grid parity will occur between the years 2017 and 2024 for wholesale electricity price and before year 2015 for end use electricity price by varying the bank interest rate from 0 to 12 %.

5.6.3.4 Effect of System Life Time

Longer the system life time the more is the cumulative electricity generated from it throughout its operating life time. While the initial investment cost at the time of system execution is the same for same size irrespective of system life time (financial and variable costs might differ), a lower cost per kWh electricity generation will apply for the systems with longer life time. This will ultimately cause the sooner occurrence of grid parity. This phenomenon is shown in figure 5.21.

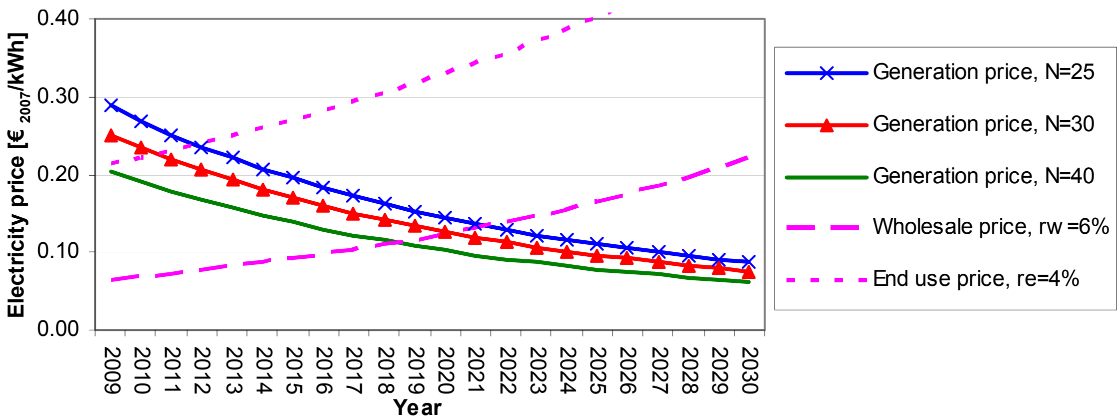


Figure 5.21: Grid parity – different system life time

As shown in figure 5.21, grid parity will occur between the years 2021 and 2018 for wholesale electricity price (annual growth rate of 6 %) and between the years 2012 and 2009 for end use electricity prices (annual growth rate of 4 %).

5.6.3.5 Effect of Progress Ratio

Influence of progress ratio in module and system price reduction has been discussed in chapter 3. This cost reduction pattern will have direct impact on the competitiveness of solar PV. Figure 5.22 shows the sooner or later occurrence of grid parity for different progress ratios ranging from 75 % to 90 %. For the wholesale electricity price growth rate of 6 %, range of grid parity year is between 2019 and 2028 for PRs between 75 % and 90 %, respectively.

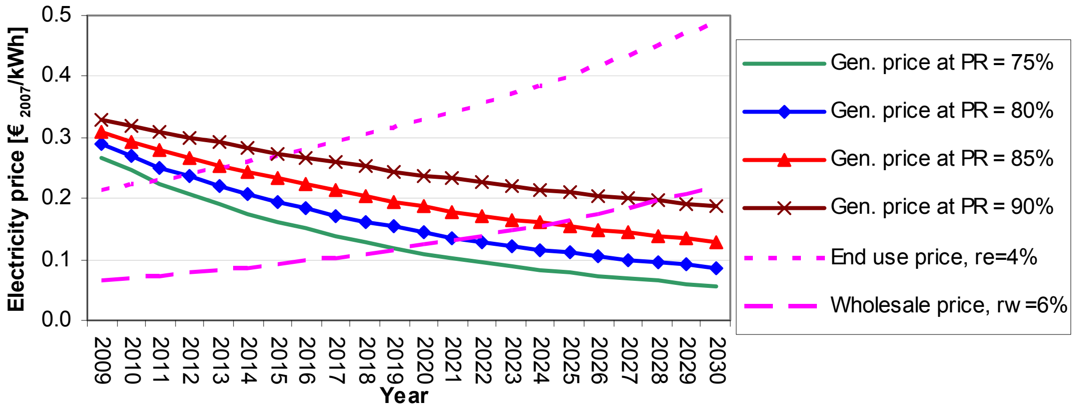


Figure 5.22: Grid parity – different progress ratio

5.6.4 Learning Investment and Win Point

Based on the assumption made in this study there will be certain GW_p PV installations needed in Germany until the PV systems becomes at breakeven point (not at grid parity). Until the breakeven year, market price of modules will be higher than breakeven price of modules; therefore, every system installed until the breakeven year will cause some losses. The cumulative amount of loss from year 2009 until breakeven year is termed as learning investment in this study. However, the systems that are installed after breakeven year will generate profit. The year when the cumulative loss before breakeven year equals to the cumulative profit after breakeven year is termed as win point. After this year, solar PV systems will have largely positive impact in overall national economy.

Considering the figure 5.11, breakeven year for Germany will be in around 2019 (which is shown also in figure 5.23). By the corresponding year, estimated cumulative installations will be around 29 GW_p (around 100 GW_p cumulative installations worldwide) and this will need a learning investment (2009-2019) of around 23 billion Euros in German PV sector. Win point will occur somewhere in around 2027 (figure 5.23). The corresponding cumulative installation by that time will be about 57 GW_p (around 381 GW_p cumulative installations worldwide), making cumulative net present value zero in this year.

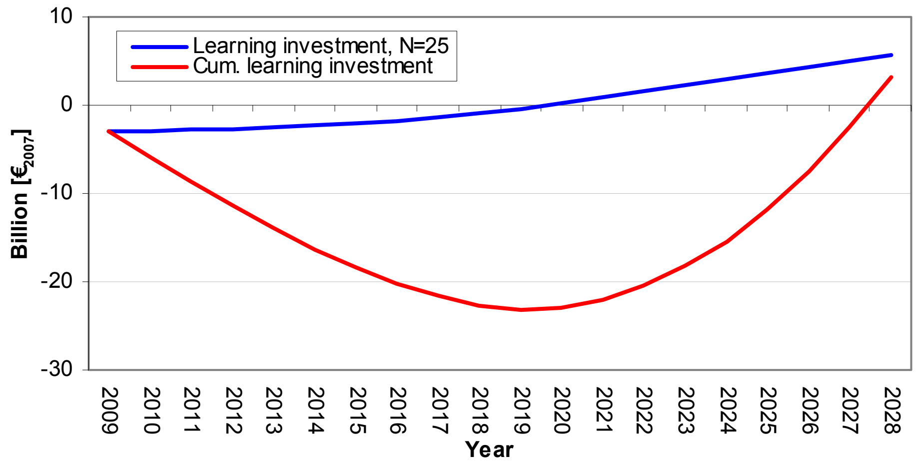


Figure 5.23: Learning investment and win point for *N* = 25

However, the results seem optimistic, if the analysis is carried considering the PV systems having longer system life time of 30 years. Under this condition, breakeven year will be sometime in around 2018. By this year, in Germany, a cumulative installation of about 25 GW_p (around 82 GW_p cumulative installations worldwide) and a learning investment of around 17 billion Euros will be needed. The win point will occur in around 2024 (around 46 GW_p cumulative installations in Germany and 238 GW_p worldwide).

Remarks over Similar Studies

Staffhorst [2007] calculated that the grid connected PV will be at breakeven with the conventional grid electricity (EEX price scenario) before 2033 and most likely around 2025 in his (pessimistic to optimistic) scenarios. Considering PV system installations in niche markets, he estimated that breakeven year will improve from 2025 to 2017. As already discussed, in current study, the breakeven year has been calculated to occur in around 2019-2020 in wholesale electricity market. The grid parity year has been calculated to be around 2021 and 2012, for wholesale and end use electricity market, respectively. The differences in breakeven values between these two studies are difference in the assumption in input parameters, e.g. global radiation, electricity price growth rate, discount rate, variable cost factor, annual PV installation growth rate, etc.).

5.7 Concluding Remarks

A reference household in Cologne, Germany consumes an average annual electricity of 3500 kWh. Use of a PV system with a capacity of about 3.9 kW_p will make such household as zero electricity household. The electricity yield from a PV system depends on the incident solar radiation on the module's plane. An optimal module inclination angle should be designed in order to ensure the maximum electricity yield throughout the year, especially in the cases where module tracking mechanisms are not used. A fixed module inclination angle of 30 ^{o} is generally considered to be optimal for Germany.

Major costs associated with the installation of solar PV systems are fixed costs, i.e. initial expenses for buying the module as well as BOS components. Operating costs (e.g. repair maintenance costs) are minimal. The revenue is based on the amount of electricity yield from the system. Therefore, the grid connected systems are the best options over stand alone systems because 100 % of the PV generated electricity can be sold to the grid. Furthermore, the initial investment to these systems is lower because there is no need for a storage unit.

In this study, an economic analysis of a solar PV system has been carried out. Besides, the breakeven and grid parity analysis of PV systems under different market and climatic conditions have been analysed. The cost benefit analysis results depict that grid connected PV systems are still not economically feasible in Germany under the boundary conditions used in this study. PV systems might become economically feasible if the cheaper solar modules (e.g. thin film) are introduced in the market. The breakeven analysis features that the systems would have been at breakeven as of today if the module price was as low as 0.88 €/W_p or the base year electricity price was as high as 0.24 €/kWh. Breakeven year is calculated to be in around 2019 for the systems with life time of 25 years. In this year the module price will be around 1.71 €/W_p and the base year wholesale electricity price is projected to be around 0.12 €/kWh. The learning investment for PV systems between year 2009 and breakeven year 2019 is calculated and the value is found to be around 23 billion Euros. This loss will be covered by the installations after this year and a win point is expected to occur in 2027.

The grid parity year for wholesale electricity price may fall around in 2021 and by considering the end use electricity price it has been calculated to occur around in 2012. These years may shift if there are different market trends than assumed in the calculations, e.g. progress ratio, annual growth rate of cumulative installation, price growth rate, etc.

For the available hourly average solar radiation in Cologne, it has been found that a zero electricity household can supply annually about 42 % of the electricity generated from PV at the time of its generation and about 58 % of the household demand has to be supplied with grid electricity. Therefore a kWh electricity price that has to be paid to the grid by a household with a PV system on rooftop has been corrected and it is used for real grid parity determination. In this way, real grid parity years have been found to occur around in 2017, 2015 and 2013 for PV systems with life times of 25, 30 and 40 years, respectively.

If the rate of consumption of electricity at the time of its generation can be increased, the PV systems will be economically more feasible. This can be done, for example, by applying demand side management approaches at household level or by using plug in hybrid electrical vehicles that are expected to enter market in near future. Recent food shortage debates related with bio fuels use in vehicles can be avoided using electric vehicles. However, more public awareness programmes should be launched by the stakeholders at national and international levels. PV systems should be promoted vigorously in the countries with higher annual average solar radiation, where those systems are already at breakeven. Installations in those sites will help doubling the cumulative installation worldwide and it will ultimately help to reduce module prices worldwide being PV module a global product.

6 STAND ALONE PV SYSTEMS

The idea behind this study of stand alone PV systems is to supply the household electricity demand by generating it at household premises using solar PV systems. Electricity demand is different at different household and it is dependent on many factors, such as on the consumer behavior, number of residents in a household, consumer incomes, electrical appliances in use, weather/climate influences, etc. From the economic point of view, it is important to make the PV system size as small as possible; however, at the same time electricity supply from such system must secure the demand throughout the year. Therefore, it is important to assess the household electricity consumption (demand) pattern in details, on smaller time interval e.g. seconds, minutes or hours, if possible.

After the demand data is assessed, the second step is to process the climate data and obtain the solar radiation available in the site. It would be better to have radiation data on the same interval to that of electricity consumption data. Unlike consumption data, the climate data for small time interval are possible to get online from many weather stations (e.g. NASA). Another climate parameter needed is number of consecutive no sun days in the given time period (e.g. in one week). This will help in sizing the electricity storage system (e.g. battery). Once climate data and electricity demand data are processed, system size (size of modules, BOS, battery) can be designed. System size translated into corresponding market price will determine the initial investment of the PV system. Other parameters, e.g. bank interest rate, variable cost, component replacement costs, etc. will determine the total system cost.

Once a stand alone system is installed at house to supply the electricity, one can get free form the grid electricity use and no electricity bills have to be paid to the utilities afterwards. This opportunity cost (saved electricity bills payment) is considered as the imputed revenue in this study. If there is a newly built house, initial costs associated with the grid connection arrangements between the house and the grid (named grid access costs in this study) can also be avoided. Finally, avoided electricity bills and avoided grid access cost will make total revenue. However, if an existing house (already connected to grids) prefers to go for stand alone generation, revenue will consist only avoided electricity bills, because grid access cost is already paid and it is not refundable.

6.1 Principle

It would be worthy to supply electricity to a household from stand alone PV system, when the total cost associated with its installation and operation is at the most equal to the sum of the imputed revenue to be generated from the system throughout its life time and the cost related to grid access.

Electricity demand in household, end use market price for grid electricity and climate data are different from country to country, and sometimes they are even different in the regions within the country. This is why it is difficult and indeed impossible to design a common system that applies everywhere. As an alternative to this problem, a model has been developed separating those uncertain parameters as input variables that can be used for different range of input values. This model can be used for each individual houses to design the solar PV system size and to carry out the economic analysis. The results discussed in the following sections are for the existing market conditions and climate data of Cologne, Germany (50 ^{o} 56 ” N and 6 ^{o} 59 ” E).

6.2 Model in the Block Diagram

The economic analysis model to analyse the stand alone solar PV system for urban areas is described in a block diagram in figure 6.1.

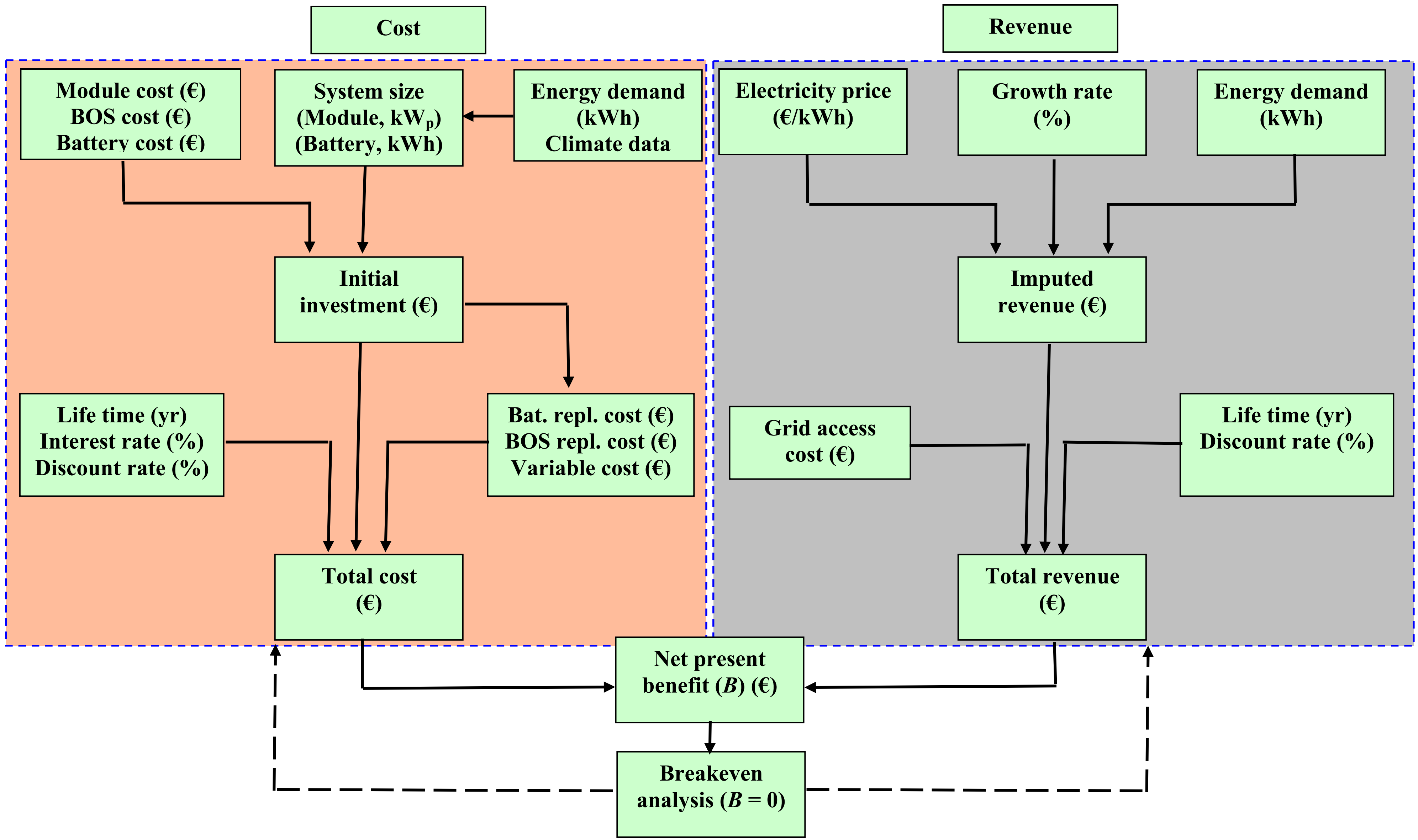


Figure 6.1: Economic analysis model for stand alone solar PV systems

6.3 Household Electricity Demand in Germany

Figure 6.2 shows the average daily electricity consumption pattern of a reference household with an annual consumption of 3500 kWh [VDEW, 2008]. It is obvious that there is variation in consumption in different seasons, highest consumption in winter and the lowest consumption in summer. There are peaks in weekends, most likely this is because people stay at home and consume more electricity in weekend compared to that in working days.

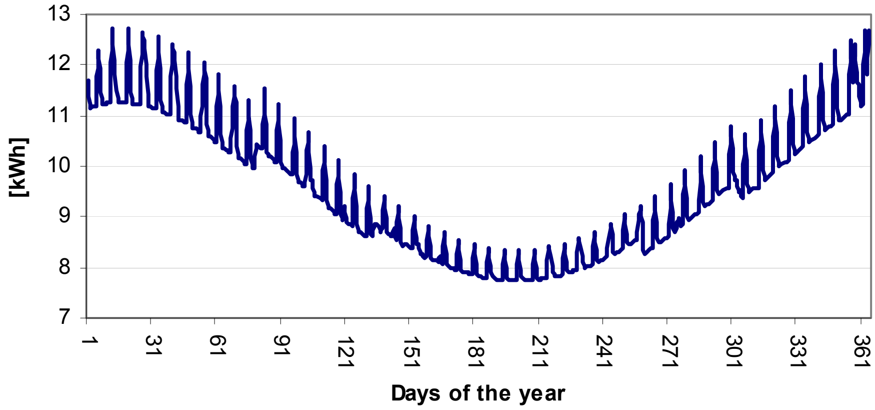


Figure 6.2: Daily electricity consumption of a reference household, Germany

Variation in consumption is big not only in seasons, but also in different hours of a day. Figure 6.3 shows an hourly variation for four days in different seasons of the year. In all these curves there are two peaks, one during mid day when people are supposed to make their lunch and the other in the evening, when they have their dinner and also lighten their home.

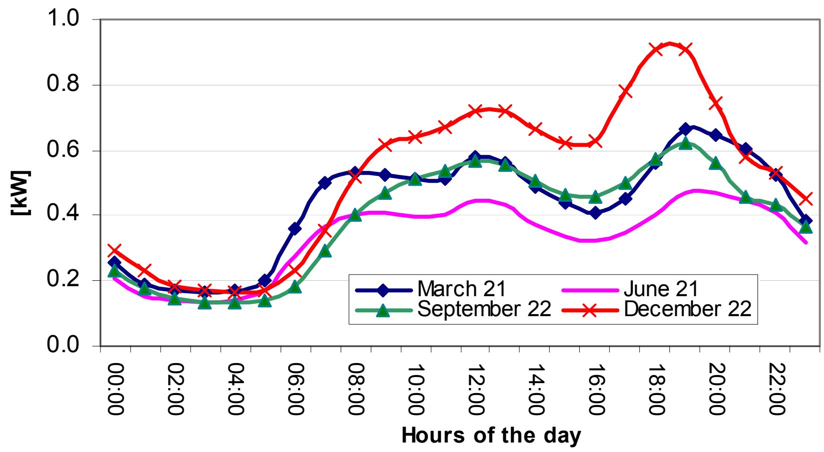


Figure 6.3: Hourly variation in electricity consumption in Germany

6.4 Assumption

The following assumptions are made to analyse the stand alone PV system for urban areas:

- Electricity demand of a household is fully covered by the PV system
- Avoided electricity bill is the imputed revenue from the PV system
- New houses will have additional imputed revenue from grid access cost avoidance
- PV system has a standard life time of 25 years (unless otherwise mentioned)
- Non battery BOS components will be replaced in the middle of the system life time

Energy demand at household is considered to be met by the same PV system throughout the system operation period. Degradation in energy yield is not considered in the calculation, and it is thought to be compensated with the use of energy efficient devices in the coming years. Effect of this degradation in imputed revenue is neglected to avoid complexity in the calculations. The solution might have been to oversize the system with certain factor, so that the electricity yield after degradation will still meet the demand at home. It will; however, increase the initial expenditures. This is why the system has not been oversized in this study.

6.5 Default Values

The following default values (table 6.1) have been used in the calculations.

Table 6.1: Default values – stand alone PV system, Germany

Description	Symbol	Unit	Value
Electricity demand, annual	E_d	kWh/yr	3500
Global radiation on inclined surface (74^o)	G_i	kWh/m^2.yr	1118
Quality factor	Q	%	40
Effective energy consumption days in a year	D	days	365
Number of autonomous days	D_a	days	4
Maximum depth of discharge	DOD	%	80
Battery energy conversion factor [a]	η_b	%	80
Module price	C_m	€$_{2007}$/kW$_p$	3238
BOS cost factor (excluding battery)	k_{mbos}	%	30
BOS replacement cost factor	$k_{mbosrpl}$	%	70
Battery price	C_b	€$_{2007}$/kWh	100
Battery replacement cost factor	k_{brpl}	%	100
Discounting rate	d	%	4
Real interest rate	i	%	6
Variable cost factor	k_v	%	1
Electricity price from grid	$P_{el\text{-}e}$	€$_{2007}$/kWh	0.2143
Annual $P_{el,e}$ growth rate	r_e	%	4
Cost of grid access	C_{iga}	€$_{2007}$	1180
Project life time	N	yr	25
BOS (except battery) replacement year	N_r	yr	12
Battery replacement year	n_b	yr	5

[a] It is also called battery energy conversion efficiency or ageing factor

A reference household with an annual electricity consumption of 3500 kWh is often used to make the calculations easier. In fact, individual electricity consumption depends on a large number of factors such as number of persons, usage habits or age and number of electrical appliances. For example, household electricity consumption can range from nearly 1800 kWh for a single person household to 5300 kWh for households with five or more persons. Households that are well equipped with efficient appliances and make sparing use of energy may nevertheless keep their annual consumption down to as little as 2000 kWh for four persons [BMU, 2008b].

Grid access cost can be excluded for the houses which are already connected to grids, but this must be considered for the new houses to be built. In some cases, the grid access cost is comprised of not only of electricity, but also of gas, district heating and water supply and sewage systems. In this case, it might be difficult to give monetary value for grid access cost that only reflects for electricity. The value given by the utility has been used in this study. No salvage value or disposal cost after system life time is over has been considered.

6.6 System Sizing

System sizing is the most important step because it is a reference that determines the guaranteed supply of electricity to household throughout the year and overall costs of the PV system. There might be different approaches of system sizing employed for stand alone solar PV system and two of them - statistical approach and energy balance approach - are discussed below.

6.6.1 Statistical Approach

Sizing of stand alone PV systems can basically be done using analytical method or simplified method [Benatiallah et al, 2005]. The analytical method needs relatively complex input data set for statistical analysis, but it gives the information about supply reliability. The level of supply reliability is expressed in terms of loss of load probability (LLP). LLP is the ratio of the energy deficit to the total energy demand for a period of time in question [Celik, 2002]. The zero LLP means a 100 % reliable supply. LLP affects the system size and thereby per unit electricity generation cost. If all the energy produced in the system is used either to satisfy the load demand or used in another application (e.g. supply into the grid), the unit cost of electricity is the least at $LLP=0$ [Celik et al, 2008], but the unit cost varies considerably for different location with different climate and market data. However, if the excess energy after satisfying the load has to be dumped (the case of stand alone PV systems in most of cases), the unit cost of electricity is least at the particular LLP level, and not necessarily at zero LLP. For example, Celik et al [2008] found this level between 0.16 and 0.21 for five different cities in Turkey.

Simplified method generally uses energy balance equation for the worst month (least production, highest demand) and average meteorological data [Markvart et al, 2000]. However, designing the system for the worst month does not necessarily mean a LLP of zero, e.g. for Turkey, Celik [2006] calculated LLP value of 0.93 for a PV system with battery storage, whose design was based on worst month and corresponding ratio for average monthly energy production to load was 1.53. Sizing based on energy balance is probably the simplest of the sizing methods, and because of its transparency, it is widely used [Markvart et al, 2000]. This method has also been used in this study using the energy balance equation for the worst month (December).

6.6.2 Energy Balance Equation

Size of the system is dependent on energy demand of the household and climate data of the site (solar radiation and number of consecutive no sun days). The module size in terms of watt peak is given by:

$$P_{peak} = \frac{E_d \; I_{stc}}{Q \, G} \qquad [6.1]$$

Size of the storage battery is given by the equation:

$$B_c = \frac{D_a \; E_d}{DOD \, \eta_b \; D} \qquad [6.2]$$

where,

B_c is battery capacity [kWh]
D_a is number of no sun days the battery has to supply the electricity [days]
D is number of electricity demand days in a year (i.e. 365 days in general) [days]
DOD is depth of discharge rate of the battery [%]
η_b is battery energy conversion factor (ageing factor) [%]

6.6.3 Solar Radiation and Module Inclination Angle

If a household is supposed to be supplied with electricity from stand alone solar PV systems, a big problem exists due to seasonal variation. In summer, when there is high potential for PV electricity generation, household demand is low. But unfortunately, in winter, when household demand is high, potential of PV generation is very low. Figure 6.4 shows the average daily solar radiation for Cologne, Germany.

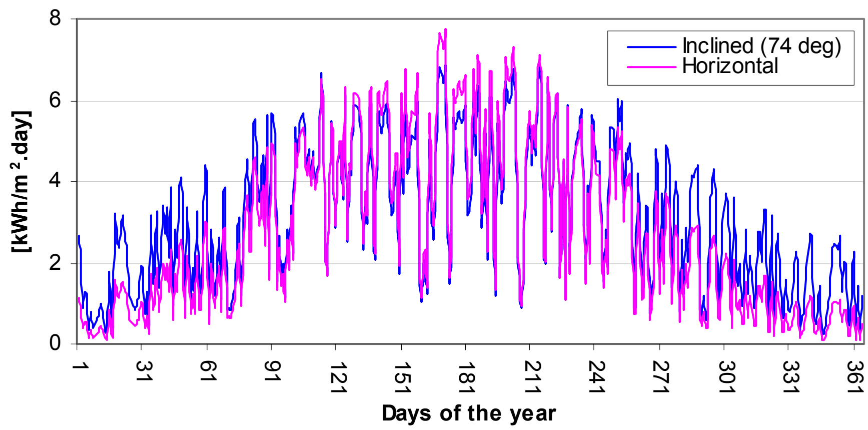


Figure 6.4: Average daily global radiation - Cologne, Germany

As shown in the figure 6.4, two values of global radiations are presented, one for horizontal surface (PVSOL 2.6) and another for inclined surface (calculated). It can be seen that the global radiation for inclined surface is higher in winter months and lower in summer months in comparison for the horizontal surface. An optimal angle of inclination of modules can lead to a smaller system size in order to supply the same amount of electricity. The calculated values for system size (using equation 6.1) needed to secure the annual amount of electricity demand in Germany for different angles of module inclination is given in figure 6.5.

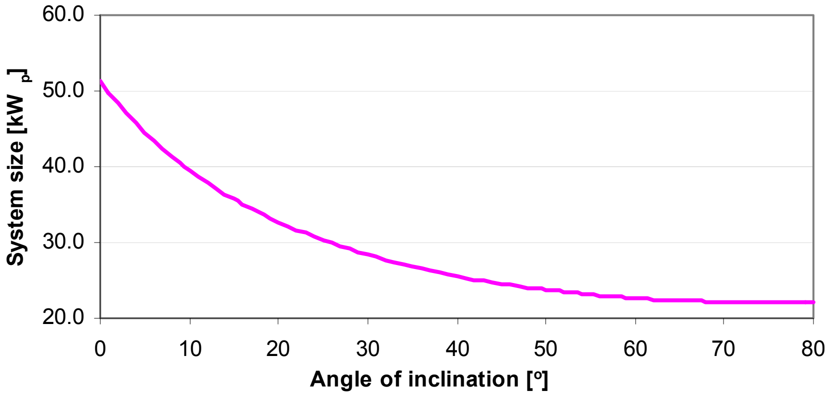


Figure 6.5: Stand alone PV system size at different module inclination angle

By looking at figure 6.5, it can be perceived that a module inclination angle of around 74 ^{o} will lead to the smaller system size. This value is higher than the optimal inclination angle used for the grid connected systems in chapter 5. This is because a stand alone system should be designed in such a way that its smallest size can cover the highest household demand even in the worst month for available solar radiation (i.e. December in Germany).

6.6.4 System Size

Figure 6.6 gives the stand alone PV system sizes needed each month in order to secure the household electricity demand. Naturally, in summer months, when the available solar radiation is high and monthly demand is relatively low, the required system size is very small in compared to winter months. It can also be seen that system size can be drastically reduced if an optimal angle of inclination for modules (74 ^{o} in this case) could be chosen.

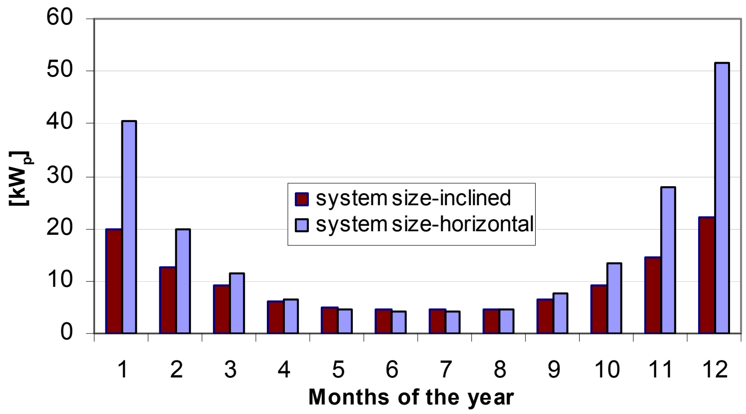


Figure 6.6: Stand alone PV system size for monthly electricity supply

For the given climate data and electricity demand data, the system size calculated for Cologne, Germany is the module size of 22.1 kW_p and the battery capacity of 71.8 kWh (details in figure 6.7). As noted in figure 6.7, in most of the months, energy generated is more than the energy demand. This is because the system has to be designed for the worst month, i.e. December in this calculation, to secure the sufficient electricity demand throughout the year. Daily average solar radiation is at minimum in December, but the electricity demand is at maximum leading to an enormous system size. This is the biggest problem for stand alone systems in the regions where seasonal variation in available global radiation is high. Battery is supposed to supply power for the house for four autonomous days (number of consecutive no sun days in one week [NASA, 2008]) even if there is no sun shine at all.

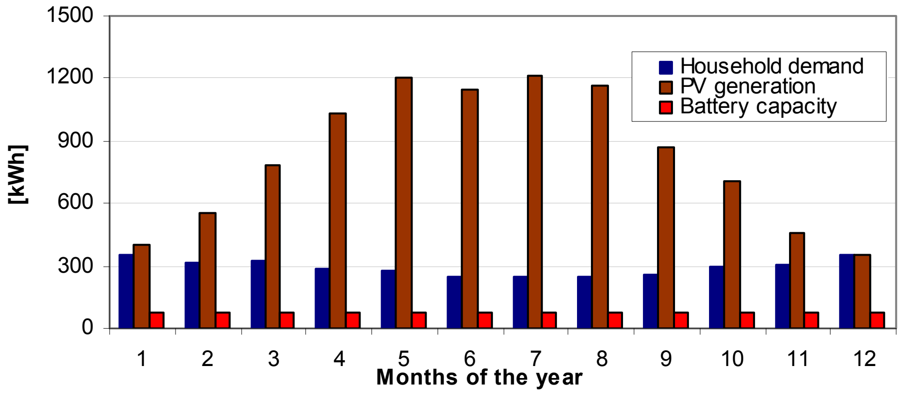


Figure 6.7: PV system size for a reference household (SA-Germany)

6.6.5 Production to Load Ratio

Production to load ratio ($R_{P/L}$) is the ratio of amount of electricity generated to load in the given period of time. For off grid (stand alone) systems, a higher value of $R_{P/L}$ means higher amount of electricity loss. However, for grid connected systems, this value is unity, because all of the electricity generated can be supplied to grid.

The monthly average values of $R_{P/L}$ for stand alone PV system designed in this study are shown in table 6.2. System is designed to meet the electricity demand in December, and therefore, $R_{P/L}$ is unity (for system size of 22.1 kW_p) in this month. The average monthly $R_{P/L}$ has been calculated as 2.38 (ranging from 1.0 in December to 5.0 in July). This high ratio means an enormous system size, but relatively low LLP level.

Table 6.2: Production to load ratio

Months	**$R_{P/L}$ (system size = 22.1 kW_p)**	**$R_{P/L}$ (system size = 19.7 kW_p)**	**$R_{P/L}$ (system size = 14.7 kW_p)**
January	1.12	**1.00**	0.74
February	1.78	1.59	1.18
March	2.41	2.15	1.60
April	3.54	3.16	2.35
May	4.39	3.91	2.91
June	4.67	4.16	3.10
July	5.00	4.45	3.31
August	4.68	4.17	3.10
September	3.38	3.02	2.24
October	2.42	2.16	1.60
November	1.51	1.34	**1.00**
December	**1.00**	0.89	0.66
Whole year	**2.83**	**2.52**	**1.87**

For comparison purpose, system design results for covering the electricity demand only in eleven and ten months have also been shown in the same table 6.2. If the energy balance equation for the second worst month (January) is considered in design, the average monthly $R_{P/L}$ would have been reduced to 2.52 (unity in January), requiring a smaller system size of 19.7 kW_p. This would have, however, increased the LLP level making system less reliable, but unit cost for PV electricity generation would have been less. Similarly, for a PV system to cover full demand only throughout ten months, $R_{P/L}$ has been calculated to be 1.87 (unity in November) requiring a smaller system size of 14.7 kW_p.

Figure 6.8 shows the monthly energy demand and monthly PV electricity generation from the system sizes that are enough to cover electricity demand for 12, 11, and 10 months in a year, respectively.

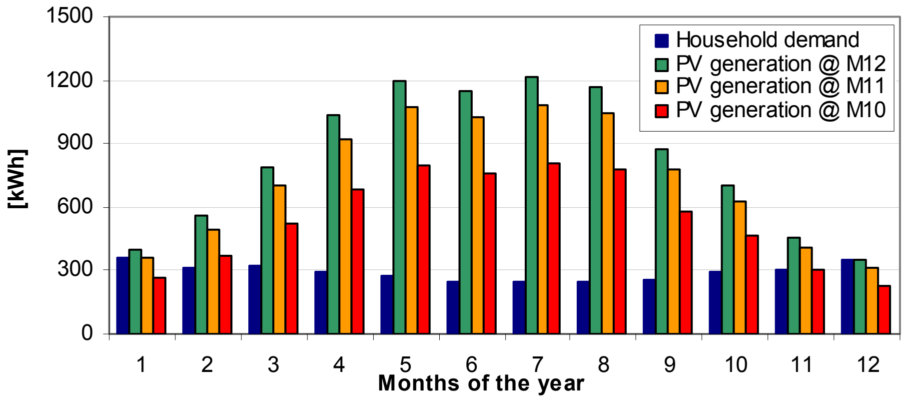


Figure 6.8: Electricity generation with different system size

Installing a smaller size will be cheaper, but it will cause certain blackouts in some days a year. Therefore, it is a decision of a household whether to save some extra expenses by allowing some black out days. Practically, people in developed countries, who are enjoying a reliable electricity supply, might not be ready to accept some black days. However, for people in developing countries, where even the grid electricity black out is not a surprise, installation of relatively smaller sizes and accepting some black days might be the right choices (an economic decision).

6.6.6 System Size – No Seasonal Variations

If there were no seasonal variation in available global radiation in Germany, which is though the hypothetical scenario, the system size would be quite smaller. Although the case of NSV seems hypothetical in Germany, there are regions in other countries lying near to the equator which have more or less no seasonal variations in climate throughout the year. No variation in seasons (i.e. daily average sun shine hours throughout the year to be the same) generally means that there is also no variation in average daily energy consumption throughout the year (the average daily temperature to be the same in all days). The comparison of module and battery size to fulfill the same energy demand for actual German climate data and for no seasonal variation (NSV) in available global radiation and electricity demand is shown in figure 6.9.

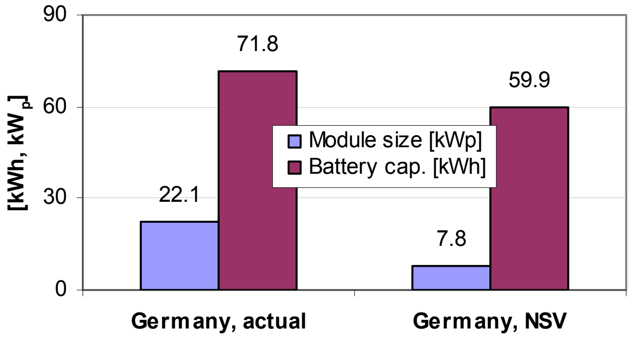


Figure 6.9: Stand alone PV system – actual and with no seasonal variation (NSV)

There is a big difference in module size and relatively small difference in battery size. This is because of two reasons. The first is the autonomous energy supply days for both cases are considered to be the same value (i.e. 4 days). The second is the effect of seasonal variation in climate will be very high in available global radiation that determines the PV electricity generation. However, this effect will be quite low in average daily electricity demand that determines the battery size.

6.7 Economic Analysis

System cost and other economic parameters are discussed in the subsequent sections. Unless otherwise mentioned, the calculations are based on the default values presented in table 6.1.

6.7.1 System Cost

The total system cost in its present value, C_t, (for the base year 2009) is given by:

$$C_t = C_{mt} + C_{mbos} + C_{bt} + C_{mbosrpl} + C_{brpl} + C_v \qquad [6.3]$$

where,

C_{mt} is present value of module expenditure [$€_{2007}$]

C_{mbos} is present value of initial BOS expenditure (excluding battery) [$€_{2007}$]

$C_{mbosrpl}$ is present BOS replacement cost (excluding battery) [$€_{2007}$]

C_{bt} is present value of initial battery expenditure [$€_{2007}$]

C_{brpl} is present value battery replacement cost [$€_{2007}$]

i. Module Expenditure

Like in the case of grid connected systems, initial investment for modules is supposed to be borrowed from the bank. This loan will be paid to the bank through annual instalment principal and interest payment. Module expenditure is the sum of annual payment of principal and interest on loan to the bank. The present value of module cost is given by:

$$C_{mt} = C_m P_{peak} \left\{ \sum_{n=1}^{n=N} \frac{(1 + i(N - n + 1))}{N(1 + d)^n} \right\} \qquad [6.4]$$

ii. BOS Expenditure

Initial BOS expenditure is sum of annual principal payment and interest payment to the bank loan that will be borrowed to buy the BOS components during the system installation.

The present value of BOS expenditure (excluding battery) is given by:

$$C_{mbos} = C_m P_{peak} k_{bos} \left\{ \sum_{n=1}^{n=N_r} \frac{\left(1 + i\left(N_r - n + 1\right)\right)}{N_r \left(1 + d\right)^n} \right\} \quad [6.5]$$

iii. BOS Replacement Cost

Non battery BOS components are supposed to last for twelve years after the installation and they will have to be replaced at the end of twelfth year (for system life time of 25 years). Cost needed for replacement is supposed to be covered from own savings that are made on the electricity bills, which would have been paid to electricity supplier if there was no stand alone PV system. The present value of BOS replacement cost is given by:

$$C_{mbosrpl} = C_m P_{peak} k \left\{ \frac{k_{bos} k_{bosrpl}}{\left(1 + d\right)^{N_r}} \right\} \quad [6.6]$$

where,

$k = \dfrac{C_{m(n+N_r)}}{C_{m(n)}}$ is module price reduction factor

iv. Battery Cost

Like in module and BOS cost calculation, initial battery expenditure is sum of annual principal and interest payment to the bank loan borrowed to buy the batteries during the system installation period. The present value of initial battery expenditure is given by:

$$C_{bt} = \frac{E_d \ D_a \ C_b}{DOD \ \eta_b \ D} \sum_{n=1}^{n=n_b} \frac{\left(1 + i\left(n_b - n + 1\right)\right)}{n_b \left(1 + d\right)^n} \quad [6.7]$$

where,

n_b is battery life time [years]

Batteries are supposed to have life time less than system life time, and therefore they have to be replaced periodically (5, 6 and 10 years for system life times of 25, 30 and 40 years, respectively). Battery replacement cost is supposed to be covered from own savings over avoided electricity bill payment. The present value battery replacement cost is given by:

$$C_{brpl} = B_c \ C_b \ k_{brpl} \left\{ \frac{k_1}{\left(1 + d\right)^{r_1 n_b}} + \frac{k_2}{\left(1 + d\right)^{r_2 n_b}} + \frac{k_3}{\left(1 + d\right)^{r_3 n_b}} + \frac{k_4}{\left(1 + d\right)^{r_4 n_b}} \right\} \quad [6.8]$$

where,

$r_1 \ldots r_4$ is replacement number, 1…4

$k = \dfrac{C_{b(n+rn_b)}}{C_{b(n)}}$ is battery price reduction factor (derived using learning curve)

iv. Variable Cost

Variable cost is assumed to be a certain portion (1 %) of initial investment. The present value of the variable costs is given by:

$$C_v = C_m P_{peak}\left\{k_v\left(1+k_{bos}\right)\sum_{n=1}^{n=N}\frac{1}{\left(1+d\right)^n}\right\} + \frac{E_d\ D_a\ C_b}{DOD\ \eta_b\ D}\sum_{n=1}^{n=N}\frac{k_v}{\left(1+d\right)^n} \qquad [6.9]$$

v. Total Cost

Replacing the individual cost components of equation 6.3 from equations 6.4-6.9, the present value of total cost of stand alone solar PV system will be:

$$C_t = C_m P_{peak}\left[\begin{array}{l}\left\{\sum_{n=1}^{n=N}\frac{\left(1+i\left(N-n+1\right)\right)}{N\left(1+d\right)^n}\right\} + k_{bos}\left\{\sum_{n=1}^{n=N_r}\frac{\left(1+i\left(N_r-n+1\right)\right)}{N_r\left(1+d\right)^n}\right\} \\ + \left\{\frac{k.k_{bos}k_{bosrpl}}{\left(1+d\right)^{N_r}}\right\} + \left\{k_v\left(1+k_{bos}\right)\sum_{n=1}^{n=N}\frac{1}{\left(1+d\right)^n}\right\}\end{array}\right] +$$

$$\left[B_c C_b\left\{\sum_{n=1}^{n=n_b}\frac{\left(1+i\left(n_b-n+1\right)\right)}{n_b\left(1+d\right)^n} + \sum_{n=1}^{n=N}\frac{k_v}{\left(1+d\right)^n} + \sum_{n=nbr}^{N}k_{brpl}\left\{\frac{k_1}{\left(1+d\right)^{r_1 n_b}} + \frac{k_2}{\left(1+d\right)^{r_2 n_b}} + \frac{k_3}{\left(1+d\right)^{r_3 n_b}} + \frac{k_4}{\left(1+d\right)^{r_4 n_b}}\right\}\right\}\right] \qquad [6.10]$$

The present values of individual component costs for systems with different life time and with and without seasonal variation are given in figure 6.10. The present values are presented for the base year 2009 in the currency of €$_{2007}$.

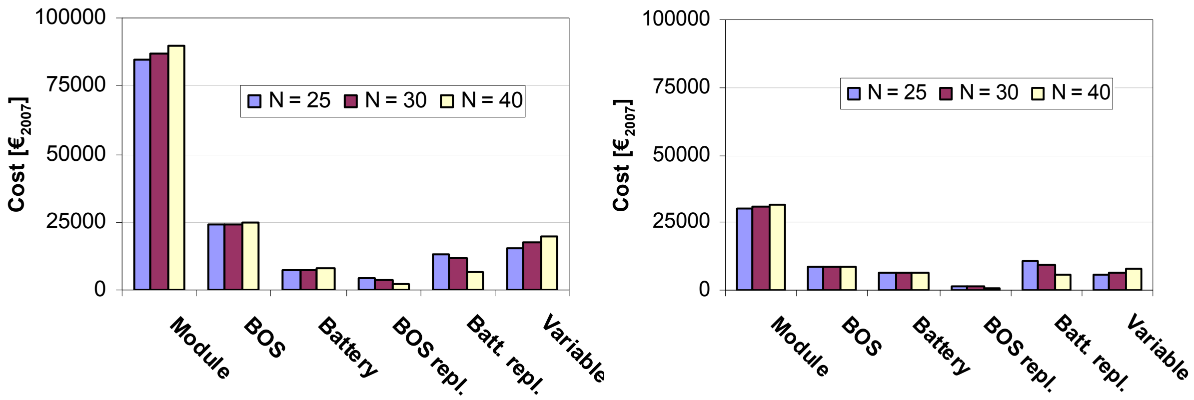


Figure 6.10: Individual cost components – actual case (left) and NSV case (right)

Due to smaller PV system size, the cost values for no seasonal variation case are far below compared to the actual case. All other component costs, except to those of replacement costs, are in increasing trend with boost in system life time, like in the case of grid connected systems. Learning effect on BOS components and battery has contributed to the decrease in those replacement costs, being lower at the later time period.

6.7.2 Revenue Calculation

Although there is no direct revenue gained from PV system; however, PV electricity will help saving the money that would have been paid to utilities in the absence of PV system. This saving is named as opportunity revenue and it is given by:

$$R_t = R_i + C_{ga} \qquad [6.11]$$

where,

R_i is imputed revenue [€$_{2007}$]

C_{ga} is grid access cost [€$_{2007}$/hh]

Imputed revenue is calculated by multiplying electricity demand of the year multiplied by the end user electricity price of the same year and is given by:

$$R_i = E_d P_{el,n} \tag{6.12}$$

The present value of this annual revenue will be obtained after its discounting with a discount rate d. It is given by:

$$R_{in} = E_d P_{el,n} \frac{1}{(1+d)^n} \tag{6.13}$$

It is assumed that the electricity grid has longer life time (about 50 years) than PV system life time. Therefore, a proportionate value of grid access cost (for the equal period to that of PV system life time) is included in total revenue calculation. The present value of grid access cost is given by:

$$C_{ga} = C_{iga} \sum_{n=1}^{n=N} \frac{(1+i(N_g - n + 1))}{N_g (1+d)^n} \tag{6.14}$$

where,

N_g is grid life time [years]

End use electricity price is supposed to increase every year with yearly growth rate, r_e. Hence the present value of total revenue is given by:

$$R_t = E_d P_{el,e} \sum_{n=1}^{n=N} \frac{(1+r_e)^{n-1}}{(1+d)^n} + C_{iga} \sum_{n=1}^{n=N} \frac{(1+i(N_g - n + 1))}{N_g (1+d)^n} \tag{6.15}$$

6.7.2.1 Grid Access Cost

Grid access cost includes the cost charged by utilities for the arrangement between house and nearby grid node (connecting wires, accessories and construction work) to access the electricity at house. The cost is different from place to place. An example of those costs for three German cities is given in figure 6.12.

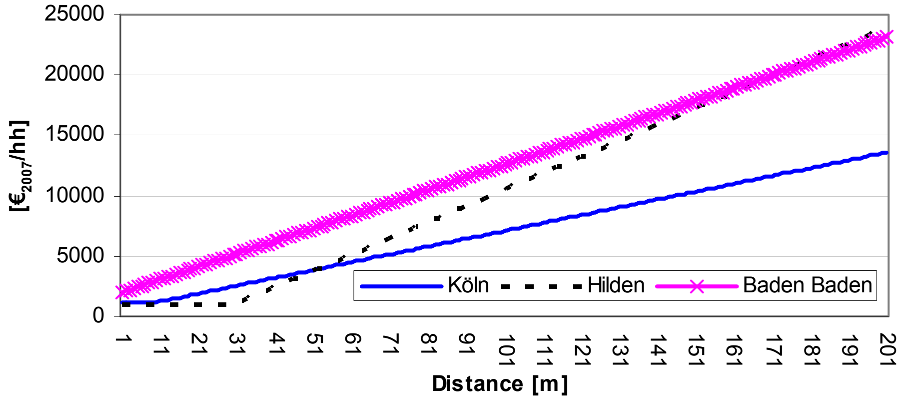


Figure 6.11: Grid access cost, Germany

Obviously, the grid access cost will increase proportionally with the distance between house and nearby grid access node. However, if the distance is too long, e.g. hundreds of meters of even some kilometers, grid access costs might not be proportionate. In this case, analysis of grid extension is necessary rather than mere grid access costs.

6.8 Results

Two different aspects, actual case and no seasonal variation in available solar radiation and energy demand case, have been analysed and the results obtained for both cases are discussed in the following sections.

6.8.1 Cost Benefit Analysis (CBA)

The calculated values for benefit (loss in this case) are given in table 6.3. Since the system size is too big (module 22.1 kW_p and battery 71.8 kWh) compared to a small amount of electricity demand (3500 kWh/yr), definitely the losses from the system will be very high, if the project is executed.

Table 6.3: CBA results – stand alone PV systems

CBA results	Actual case			No seasonal variation case		
	N=25	*N*=30	*N*=40	*N*=25	*N*=30	*N*=40
Total cost ($€_{2007}$)	149584	150783	150970	63448	63176	61067
Total revenue ($€_{2007}$)	19284	22984	30311	19284	22984	30311
Benefit (loss) ($€_{2007}$)	-130300	-127799	-120660	-44165	-40192	-30757

As pointed out in table 6.3, the systems are not economically feasible under existing market conditions, even under hypothetical case of no seasonal variations, as characterized by the negative values of benefit (loss).

6.8.2 Breakeven Analysis

Breakeven scenarios have been calculated by equaling the equations 6.10 and 6.15. The breakeven values for module price, electricity price, battery price and grid access cost, which would have been required to make the PV system economically feasible under the market conditions are given in table 6.4.

Table 6.4: Breakeven conditions of stand alone PV system

Breakeven values	SAG			SAU-NSV		
	N=25	*N*=30	*N*=40	*N*=25	*N*=30	*N*=40
C_m, $€_{2007}/kW_p$	-64	65	346	77	419	1156
P_{el}, $€_{2007}$/kWh	1.76	1.48	1.11	0.74	0.61	0.44
C_b, $€_{2007}$/kWh	-497	-527	-661	-142	-136	-132
C_{iga}, $€_{2007}$/hh	131553	129147	122122	45418	41539	32219

(SAG: stand alone systems in Germany under actual climatic conditions, SAU-NSV: stand alone systems in urban areas but with no seasonal variation)

The negative signs for module and battery price indicate that the system would only worth if those negative signed amount were provided to the owner of the system for generating the electricity from PV in the form of subsidy or similar scheme. If one of the values shown in table 6.4 were true, the PV system would have been at breakeven condition. The grid access cost given in table 6.4 for system life time of 25 years reflects a distance of 2.1 km between nearby grid and house in Cologne. However, avoiding seasonal variation this distance will be very short, i.e. 690 m.

The breakeven battery value for SAG case (table 6.4) is lower with increase in system life time. This is because of the lower value of battery replacement costs (equation 6.8) in the later time driven by the learning effects. Additionally, for the systems with longer life time, the battery life time is assumed to be also higher, and this leads to decrease in replacement frequency. Ultimately the overall battery costs (and total kWh purchase) will be lower and thus the breakeven cost becomes lower.

6.8.2.1 Effect of Energy Demand

Energy demand at household will determine the system size (module and battery) and thereby overall system cost. Energy demand will also affect the imputed revenue (avoided electricity bill) that would increase with higher demand. Figure 6.12 shows that if the electricity demand is low (e.g. 500 kWh/yr), it will contribute to a smaller system size and thereby overall generation costs. This will eventually invite sooner occurrence of breakeven year.

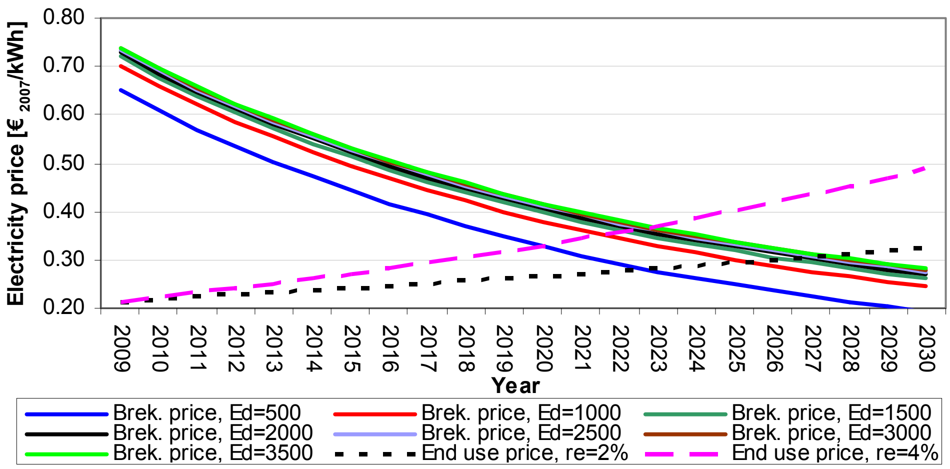


Figure 6.12: Effect of annual household electricity demand ($N = 25$)

However, when the demand is high (e.g. 2000, 3000, 3500 kWh/yr) there will be no significant effect in breakeven results. This is because a small increase in electricity demand will lead to larger system size requirement and it will ultimately lead to higher generation cost. But increase in imputed revenue due to insignificant increase in electricity demand is negligible compared to generation cost increased due to bigger system size to fulfil the additional demand. This is why the breakeven electricity price lines in figure 6.12 almost coincide to each other for higher electricity demand cases.

6.8.2.2 Breakeven Module vs. Electricity Price

The combination of module price and end use electricity price for breakeven condition are presented in figure 6.13. It will be almost impossible that these conditions of very high electricity price or very low module price would be met in the coming decades. This ultimately means that no stand alone systems will be widely installed in the country in coming years. Although the results are far better if the seasonal variation is avoided, the conditions are still not realistic in the current German market.

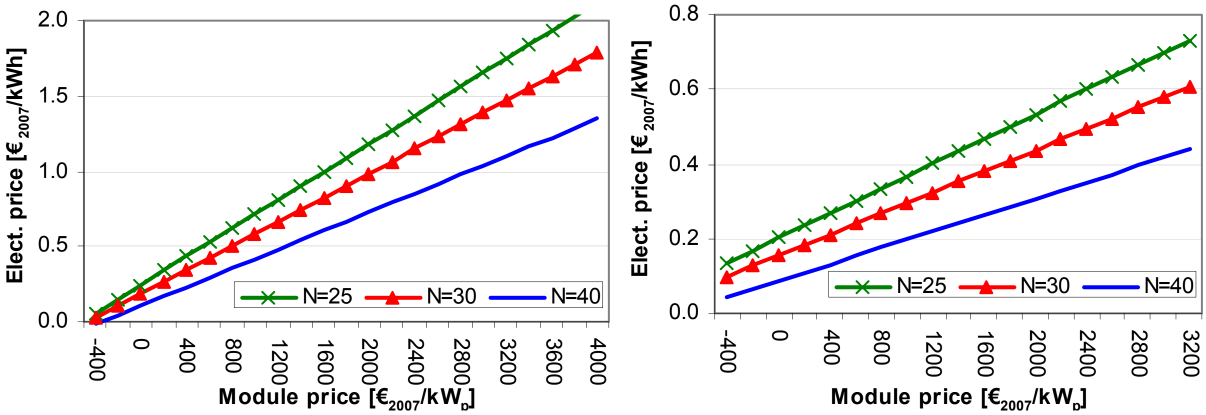


Figure 6.13: Breakeven prices – actual case (left) and NSV case (right)

6.8.2.3 Breakeven Year

Breakeven values for different parameters discussed in table 6.2 are as of base year (2009). Those values are "either or" which means the values are as if there will be change in only one parameter while remaining all other constant over time. This will, however, not be true in real case because all the parameters will change together with time. This is why the break even conditions for different parameters considering the module price decrease and the electricity price increase at the same time are discussed here.

Under the module price decrease in accordance with the values given in figure 4.7, and end user electricity price increase at the yearly growth rate of 4 % from base year price (21.43 €ct/kWh), stand alone PV system in German household will not be economically at breakeven within next decades as shown in figure 6.14.

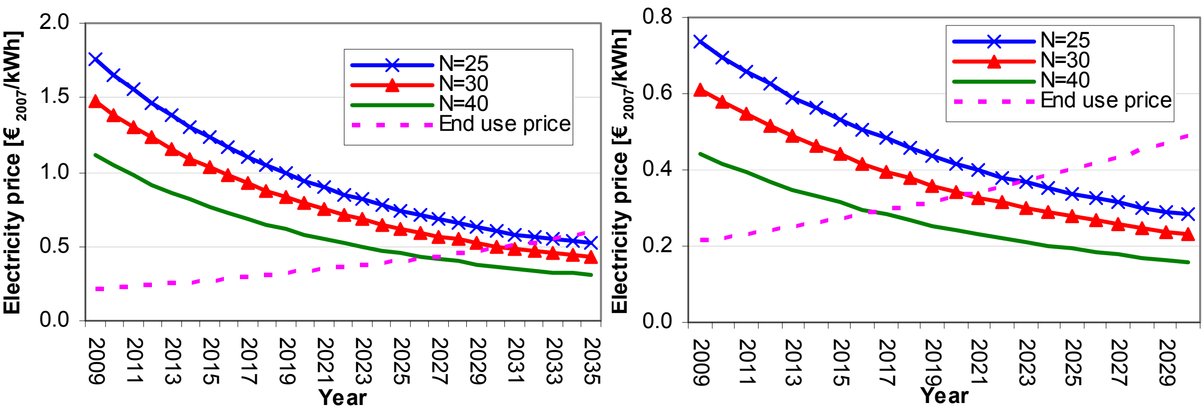


Figure 6.14: Breakeven year – actual case (left) and NSV case (right)

Provided the conditions of the assumption of this study come true, stand alone solar PV systems in Germany will be economically at breakeven point in the year 2034, 2030 and 2026 for systems with life time of 25, 30 and 40 years, respectively. However, the results are very positive for the hypothetical case of no seasonal variations. In this case, as shown also in figure 6.14, the breakeven years will be between years 2016 and 2023 for the systems with different life times.

6.8.2.4 Breakeven Module Price

Figure 6.15 illustrates the breakeven module price for different years and different system life time. For a system having shorter life time to be at breakeven, module price in the market should fall very low compared to that for the systems with longer period. Ironically, it will make sense to invest in solar PV system in Germany as of today if solar modules are not only free of cost available but also an extra amount is paid for using these modules. This situation will change with time and by year 2025, even if module price are in the range of 0.5 €/W_p, the systems will be economically feasible even for the system life time of 25 years.

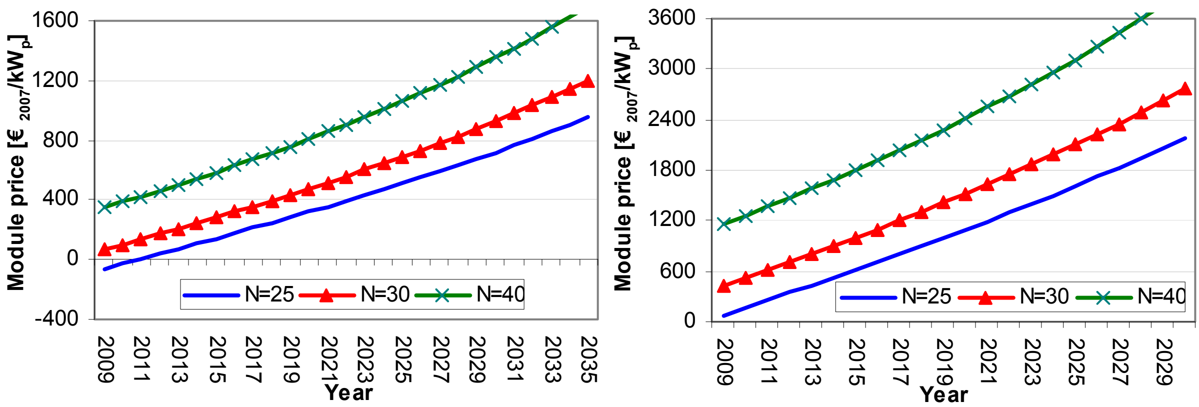


Figure 6.15: Breakeven module price – actual case (left) and NSV case (right)

A comparison for no seasonal variation case is given in the same figure 6.15. In this case, even if the module price in market are quite high, in the range of 1.6 €/W_p, PV system will be economically feasible by 2025. Effect of variable system life time on breakeven module price can also be seen very clear.

6.8.2.5 Breakeven Battery Price

One of the problems for using solar PV system as an autonomous electricity supplier at household is the need for electricity storage system. Batteries used for storing the electricity from solar PV systems comprise a big expense as described earlier in the cost calculation section. Figure 6.16 shows the market price for batteries that would have been required to make stand alone solar PV system economically feasible.

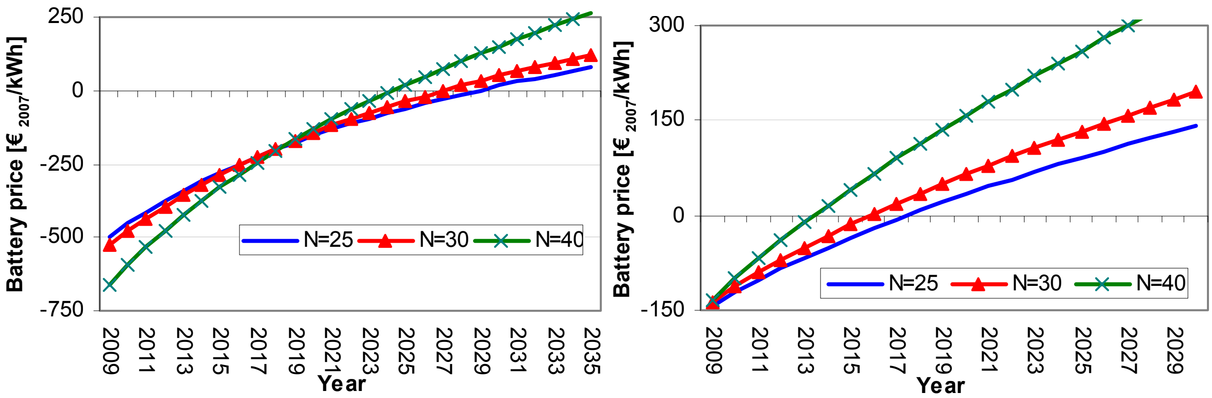


Figure 6.16: Breakeven battery price - actual case (left) and NSV case (right)

For coming many years, buying a battery will not be a good choice if economically feasible PV system is expected regardless of its operating life time. One point to be noted in figure 6.16 is that the systems with shorter life time have better performance up to certain future time point. This is because the battery life time is assumed to be longer for the systems with longer life time. There is annual decrease in battery price in the market driven by learning curve effect. For the systems with longer life time, battery replacement will occur at the later time point and this replacement cost will have less value when it is converted to its present value due to its discounting. However, when the battery price is looked for the period up to overall system breakeven years, systems with longer life time will obviously achieve the breakeven year earlier.

6.8.2.6 Breakeven Grid Access Cost

The breakeven grid access costs, which means that the systems would have been at breakeven if the mentioned costs were incurred for grid access purpose, are given in figure 6.17.

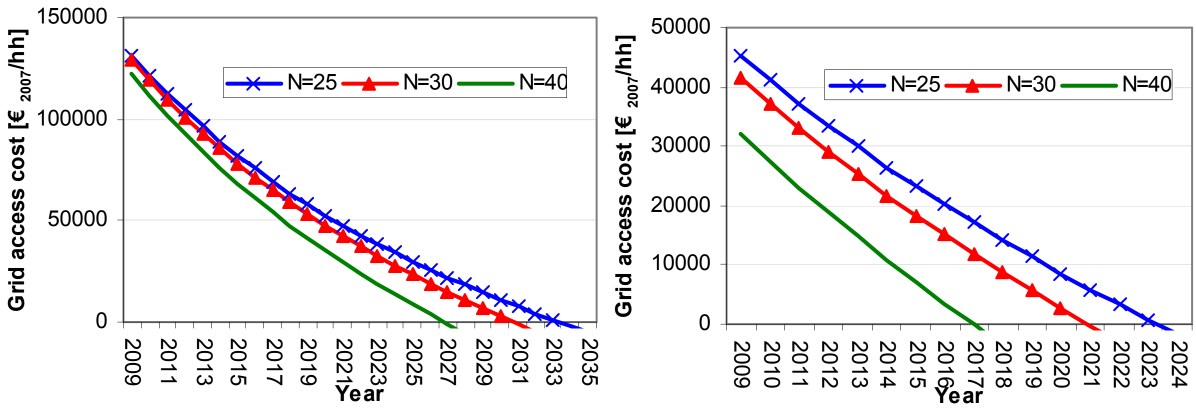


Figure 6.17: Breakeven grid access cost – actual case (left) and NSV case (right)

Similar to the effect of other factors mentioned earlier, effect of grid access cost in actual case and no seasonal variation cases have been shown and the results for no seasonal variation case are noticeably encouraging.

6.8.2.7 Breakeven Grid Access Distance

The grid access cost given in figure 6.17 has been transferred to the corresponding grid access distance for Cologne. Breakeven grid access distance over the time is given in figure 6.18.

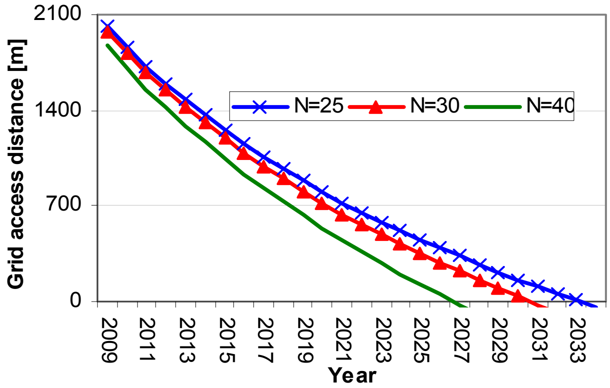


Figure 6.18: Breakeven grid access distance, Cologne

The distance shown in figure 6.18 is for a single house. However, if there is more than one house in the mentioned distance, practically the same grid access way (tunnel/wiring, etc) could be used for extra houses as well, and thus grid access costs per household could be reduced drastically.

6.8.3 Grid Parity

Grid parity between a kWh electricity generation price from PV system and a kWh grid electricity price for household customers has been analysed. Two different annual electricity price growth rate scenarios of 4 % and 2 % are presented for each case representing optimistic and pessimistic scenario. Figure 6.19 shows the grid parity year for Germany under market as usual conditions. It can be seen that even if system life time is longer as 40 years, grid parity will not occur before the year 2026. For shorter system life time of 30 and 25 years, the grid parity year will be in around 2030 and 2033-2034, respectively.

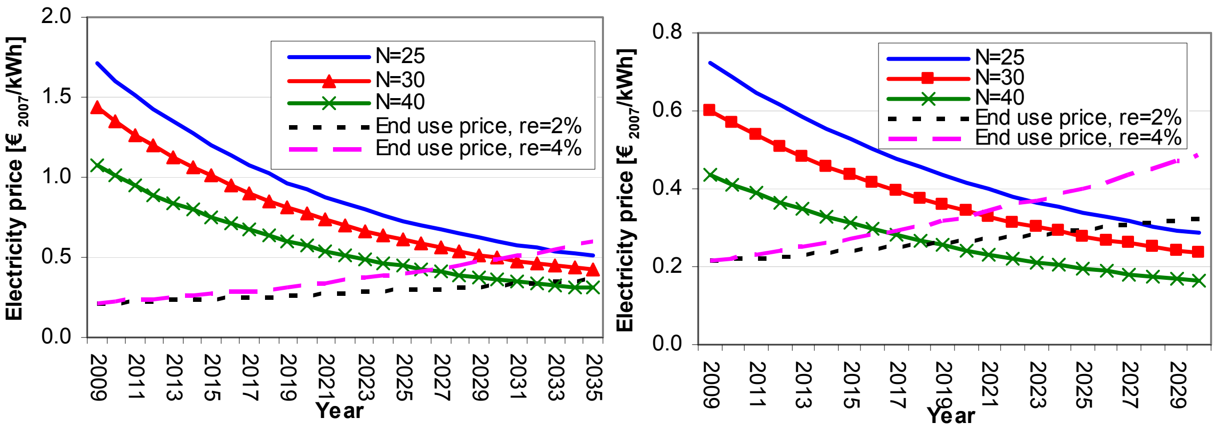


Figure 6.19: Grid parity (SAG) – actual case (left) and NSV case (right)

This implies that a German household customer will benefit by using the electricity at household from grid instead of installing a solar PV system for the same purpose for almost next two decades. However, if there is any drastic development in the solar cell technology or its price, it might not take such long time. Also, if the system is designed only to cover the electricity demand of 11 or 10 months, the system size will decrease significantly and thereby grid parity year will be earlier. This is not impossible to do by compromising certain welfare for the period of two months and by applying different energy management measures. The results for grid parity will look like completely different but positive (figure 6.19, right), if there were no seasonal variations. Details of grid parity calculation by omitting seasonal variations are given in the following sections.

6.8.3.1 Without Seasonal Variation

Effects of different input parameters in grid parity analysis under no seasonal variation case are independently described as below.

i. Effect of Global Radiation

Not surprisingly, as shown in figure 6.20, grid parity year will be sooner in sunny locations and later in less sunny locations. This is because, if the location is sunny, a smaller system size is needed to supply the same electricity at household. In this case, overall system cost will shrink significantly, but the imputed revenue will be the same because the electricity demand at household is considered to be the same.

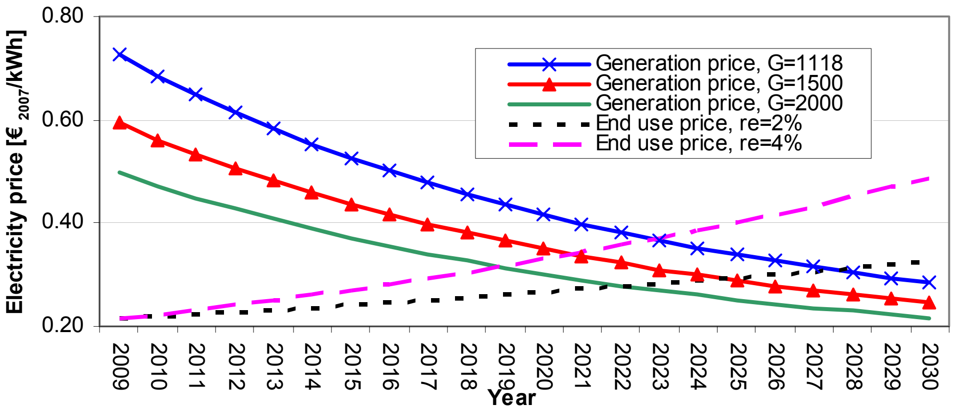


Figure 6.20: Effect of global radiation in breakeven year ($N = 25$))

This illustrates that the people living in tropical countries, where demand for electricity for lighting purpose is high, could get benefit of this effect.

ii. Effect of Autonomous Days

Number of consecutive no sun days has direct effect in the electricity storage system, because the storage system should be able to supply the electricity to household during these days. If these days are more, bigger battery size will be needed and it will increase overall system cost pushing the occurrence of grid parity year later. This can be seen in the figure 6.21.

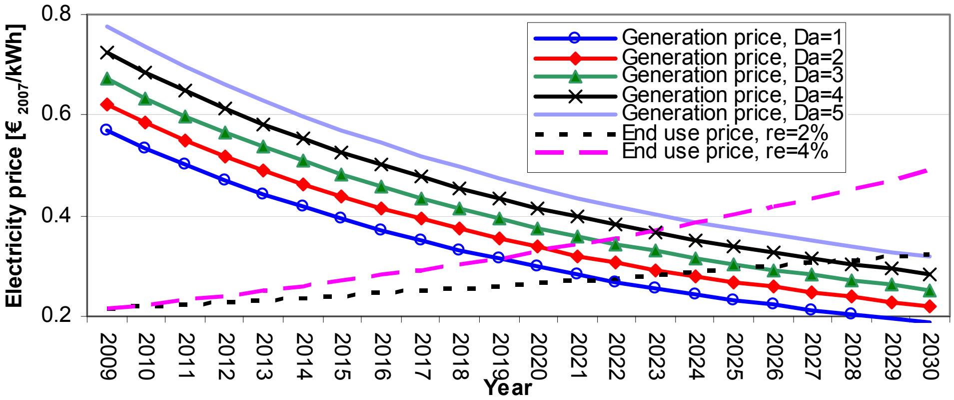


Figure 6.21: Effect of number of consecutive no sun days ($N = 25$)

However, the supply for less autonomy days means that a less reliable supply. Therefore, it is the decision of owner whether to have 100 % reliable supply system or to have less reliable supply system at low prices.

iii. Effect of Interest Rates

Figure 6.22 shows the effect of interest rate. Obviously the higher interest rate will result poor economic performance and vice versa.

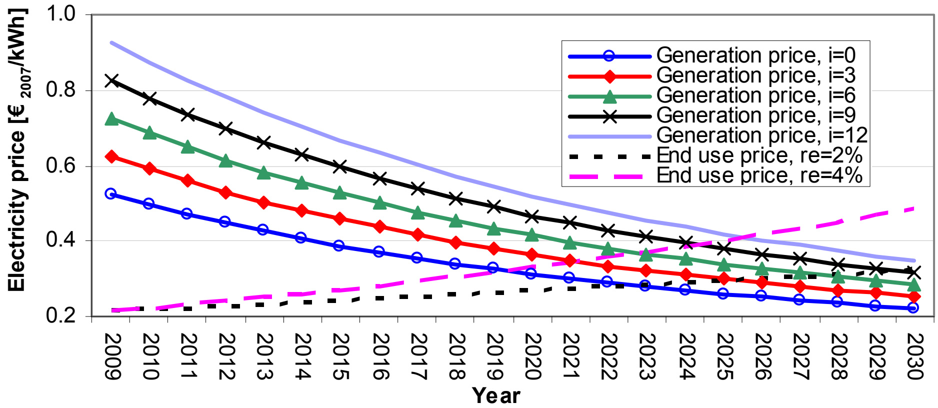


Figure 6.22: Effect of different bank interest rates ($N = 25$)

The effect is narrowed down in the later years because of low amount of investment needed due to decreased module and battery prices. This low initial investment will result low financial expenditures.

iv. Effect of Battery Price

The lower the battery price is, the lower will be the overall system cost and thereby a kWh electricity generation price will be less. This will ultimately bring the grid parity year earlier as shown in figure 6.23.

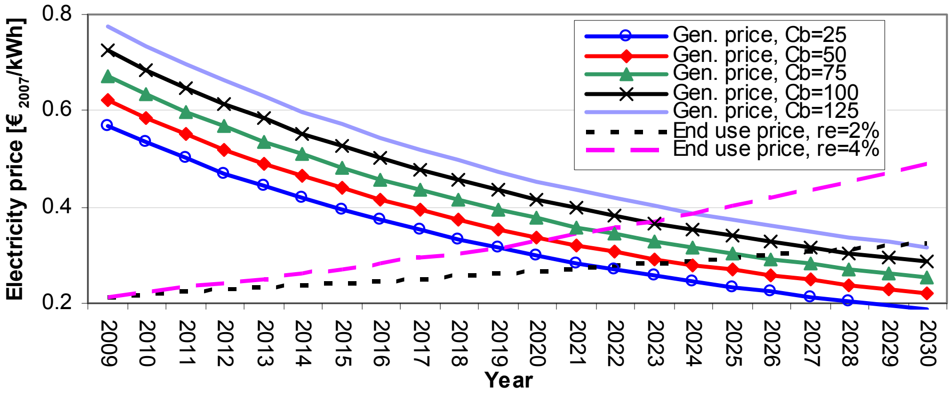


Figure 6.23: Effect of variable battery price ($N = 25$)

The analysis made in this chapter 6 was for the climate and market conditions of Cologne, Germany. It might be interesting to compare these results with a different country with different climate and market conditions. This comparison has been carried out in the next chapter (chapter 7) with reference location of Nepal.

6.9 Concluding Remarks

Electricity price for German household customer in January 2008 was 21.43 €ct/kWh. Out of which, the major part of bill does not fall under electricity production or wholesale price, but transmission, distribution and different taxes on electricity. If stand alone generation is opted, these major expenses of bill can be avoided. These avoided expenses can be used to invest in stand alone PV systems securing reliable and environment friendly electricity.

An off grid PV system, however, is not prone to its demerits. The first problem of having no grid is a need for electricity storage system because there is no coincidence in time of household electricity demand and time of solar PV electricity generation. The avoided expenses by avoiding grids have to be transferred to an electricity storage device, normally a big battery bank, so as to ensure the household supply in no sunshine hours. The need for an oversized PV system is the next problem due to seasonal variation in available global radiation in the countries at high latitude like Germany. As PV generator is the most expensive component of PV systems, it will increase overall system cost significantly, making a kWh electricity generation cost very expensive.

Someday occurrence of grid parity year will be determined by the variables used in cost and revenue calculation equations. Not surprisingly, some variables have major influence than the others. The study shows that stand alone solar PV systems are not economically viable to German households at present. Household customers will benefit by buying the electricity from grids instead of installing a solar PV system for at least the next two decades. This is mainly because of high investment costs needed for a big system size that is required to ensure electricity supply in all seasons of the year. Therefore, the only way to make a kWh PV electricity cheaper is to reduce the system size. Other variables used in the calculations, e.g. bank interest rate, discounting rate, monthly average solar radiation, etc. are site specific, and also solar PV sector (or users) have no manipulation in altering their values.

The biggest problem for stand alone systems in the countries like Germany is seasonal variations that cause major fluctuations in monthly average solar radiation. This will ultimately result an enormous PV system size in order to ensure continuous electricity supply to households in all months of the year. However, if the system is designed to cover the full electricity demand of only 11 or 10 months and the partial demand of one or two months, the system size will decrease significantly and thereby a kWh PV electricity generation cost could also be very less. Due to seasonal variations in available solar radiations in Germany, only 35 % of generated electricity can be used and 65 % of generation is a loss (35 % is using the performance ratio of 40 % and inclination of 74 ^{o}, this will be indeed as low as 18 % if the performance ratio of 75 % and inclination of 30 ^{o} as in the case of grid connected PV system is considered). This loss can be avoided in grid connected PV systems, where 100 % of the generated electricity can be fed into the grids and thereby revenue can be generated making grid connected systems economically more attractive. This is why replacing or avoiding grid is not possible in the context of Germany.

Once a kWh PV electricity cost decreases, it will bring breakeven and grid parity years sooner. If low latitude locations of the world are considered, there is less or no seasonal variation in monthly average solar radiation, which leads to a smaller module size and the costs for a kWh electricity generation are less.

Moreover, stand alone PV systems might be the right choices as of today in the locations without any existing grids, for example in black forests of south Germany. If the distance between a house and nearest grid in Cologne is more than 2.1 km, installing a stand alone solar PV system will be cheaper than extending the grid. However, even in today’s scenario, there is no argument that stand alone PV system has no other better alternative to provide electricity in the rural areas of many countries in the world.

Very late occurrence of breakeven year (around 2034) might suggest that households would never shift to autonomous solar PV systems in Germany in order to supply their electricity needs. This is because of the possibility that other cheaper technologies might already be available in the market prior to the occurrence of abovementioned breakeven years.

7 PROSPECTS OF SOLAR PV IN NEPAL

Electricity plays a vital role in socio-economic development of a country. Economic growth and improved living standards of people are directly or indirectly related to the increasing trend of energy consumption. Nepal has a large number of remote villages that do not have electricity supplies. Linking rural areas to national electricity grid would be very difficult because it would require a lot of time and budgetary investments [NPC, 2007]. However, renewable energy technologies might be the lower cost options in rural Nepalese villages, where population and load density are low. Development and promotion of alternative energy sources in rural areas would help to enhance the quality of rural life by saving time to be spent in fuel wood collection, creating additional employment opportunities, health improvement and increasing access to education for children. Additionally, the promotion of alternative energy sources contributes to reduce the green house gases emissions that help for the possible carbon trading in global market under the clean development mechanism (CDM) of Kyoto Protocol. The earned fund can be invested in the alternative energy projects.

Despite having vast potential of techno-economically viable hydro resources, Nepal is facing a huge shortage of electricity supply. Due to the rough physical terrain and scattered human settlement in rural areas, the grid extension to those areas, especially to remote hill districts, seems next to impossible in the foreseeable future [NEA, 2006]. Thus, the decentralized energy service provision may be an effective alternative energy service option to meet the growing energy demand of rural people in the aforementioned circumstances. Among the various decentralized energy service technologies, solar PV is one of the proven and potential technologies for rural electrification [NEA, 2007] and that is the focus of this study.

About 10 million people, out of Nepal's estimated population of 28.5 million (at the end of 2006), live in such remote locations (5-18 days walk) that neither a road nor the national electricity grid will reach them for decades to come [Zahnd and Kimber, 2009]. More than half of country's population is still deprived of electricity. The cost of grid extension will be prohibitive for a number of villages in the high mountainous areas; and the local mini/micro grids from micro-hydro power plants are not viable in many of these areas [Rai, 2004]. Biogas production (for cooking and lighting purpose), in these high hilly areas, is not feasible because of very low temperature (below 10 ^{o}C) [Gautam et al, 2009]. This bitter fact compels Nepal to look for other off grid electricity sources. Solar PV technology has been proven to be a viable option because of its modular size, small weight, ease of installation, etc. Also, adverse physical characteristics of rural areas do not hinder much the dissemination of solar PV systems [Rai, 2004]. The need of electricity is not only for rural areas, but the grid connected locations are also seeking the reliable electricity supplies because of big load shedding problem.

7.1 Overall Energy Situation in Nepal

Energy sources have been categorized under three broad types in Nepal: traditional, commercial and alternative energy sources [WECS, 2006]. Traditional energy sources include biomass fuels - particularly fuel wood, agriculture residue and animal waste used in the traditional way (i.e. direct combustion). Commercial sources of energy are fossil fuels (coal and petroleum fuels) and electricity from large hydropower plants. Alternative energy sources incorporate new, renewable and non conventional forms of energy (e.g. solar, micro-hydro, wind, biogas, briquettes, etc).

Biomass, hydropower and solar energy are three major energy resources in the country. Besides these, there exist some sporadic deposits of natural gases and coal reserves, which are very small in quantity and are not yet exploited commercially. The country is spending a major share of export earnings to import petroleum products. Total energy consumption of the country is largely dominated by the use of traditional energy sources. In 2005, the share of traditional forms of energy in total energy consumption was estimated to be about 88 %. The remaining 12 % of consumed energy came from commercial and alternative energy sources, and the share of electricity in total energy use was less than 2 % [WECS, 2006]. Figure 7.1 shows energy consumption pattern of the country by energy source type in 2005.

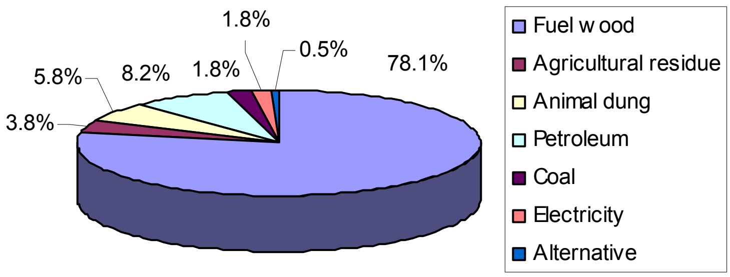


Figure 7.1: Energy consumption in Nepal in 2005 by source type

If the present energy consumption pattern (by source type) is compared with the same pattern from a decade ago, there is hardly any significant change. The country has not been able to get rid of its high dependence on biomass to meet the energy demand. Figure 7.2 shows the change in the energy consumption pattern by source type for the period of 1995-2005. Although the use of alternative energy resources has increased by almost five times in the given period, this has still negligible share in total energy consumption.

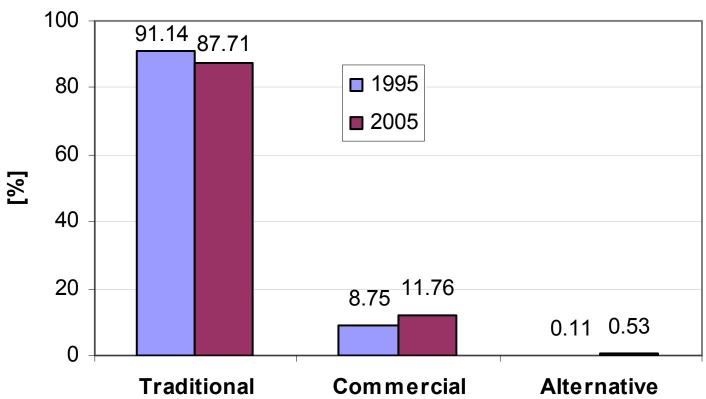


Figure 7.2: Energy consumption by source type in Nepal in 1995 and 2005

Unlike in developed countries, almost 90 % of total energy consumption has been used in residential sector as shown in figure 7.3. In rural areas, major residential energy consumption is for cooking and sometimes for livestock food preparation. The traditional biomass sources, especially fuel wood and agricultural residues, are major cooking fuels. Exploitation of fuel wood from the forest has become the major cause of deforestation. In urban areas, kerosene and natural gas meet cooking fuel demands. So far, the major use of electricity in residential sector is limited to lighting and operating household appliances (e.g. television, refrigerator, etc.). Industrial sectors use electricity and fuel oil. Petroleum products (i.e. diesel and petrol) are the major transport fuels; however, there are very few vehicles operated also with electricity (i.e. batteries) and natural gas. Although about 81 % of the country's population depends on agriculture [IAAS, 2009], there is hardly any modernization in this sector. This is why the agro-sector consumes much less energy, i.e. only about 0.8 % [WECS, 2006].

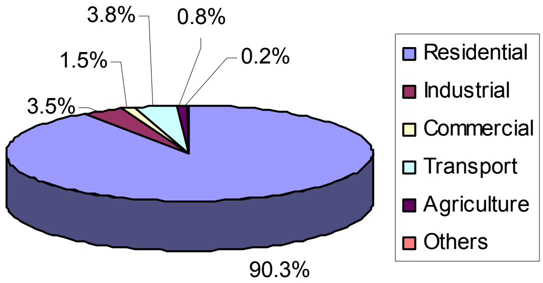


Figure 7.3: Energy consumption by sector in Nepal in 2005

Though Nepal has a huge potential of hydropower generation, its exploitation is minimal. Various studies depict that the feasible potential is about 83 GW, of which about 42 GW is considered as technically and economically viable [Shrestha, 1966]. The actual generation capacity of hydropower is limited to only 0.64 GW [NEA, 2008], due to the lack of necessary investment. Besides hydropower, there is a thermal generation capacity of about 53 MW, which is not in regular operation though. The national electrification rate, in 2006, was around 44 % with a very uneven regional and urban/rural distribution. However, the access to grids does not necessarily imply that there is a reliable electricity supply to meet the needs of the people. The electricity demand is more than the supply capacity and there are frequent blackouts. During the winter of 2008-09, the load shedding period was up to 16 hours a day [NEA, 2009]. This might be slightly less during rainy season when the run of river type power plants could generate their full capacity.

Nepal Electricity Authority (NEA), a sole government utility responsible for national electrification (generation, transmission, and distribution), has forecast the future electricity demand as shown in figure 7.4. There are no big hydropower plants in the construction phase up to date. Past experiences explain that it takes at least 4-5 years for the construction of a new hydropower plant that can generate electricity. This clearly shows that the black out situation will not improve in the near future. This will virtually stop any grid extension plans in new locations.

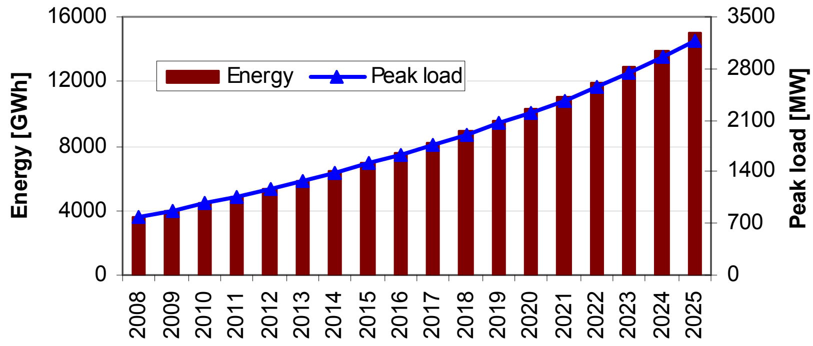


Figure 7.4: Load forecast [NEA, 2008]

As shown in table 7.1, the biggest portion of total electricity generated by NEA has been consumed by domestic customers, mainly for lighting purpose [NEA, 2008]. Lighting is the key sector, where solar photovoltaic can also fulfill the electricity demand.

Table 7.1: NEA electricity distribution by user types

User group	% of total no. of consumers	Sales (%)	Revenue (%)
Domestic	95.92	40.20	40.30
Non-commercial	0.74	4.50	6.25
Commercial	0.44	6.13	8.33
Industrial	1.77	39.23	36.33
Others	1.13	9.94	8.79

7.2 Renewable Energy in Nepal

Traditionally, Nepal's rural population has been meeting their energy needs from conventional sources like fuel wood and other biomass resources. This is neither sustainable nor desirable from environmental considerations as well as from the perspective of the effort to improve the quality of life [CES, 2000]. Therefore, there is a need to substitute as well as supplement the traditional energy supply system by modern forms of energy. Because of the country's dependence on imported fossil fuels, the high cost of grid connection and low and scattered population density, a decentralized energy supply system becomes the natural choice. Decentralized new and renewable energy systems like micro hydro, solar photovoltaic, biogas, improved cook stove etc. provide feasible and environmental friendly energy supply options in rural areas.

Biomass is the major renewable energy source available in the country if it is used in a sustainable way. As an agricultural country, Nepal produces substantial amounts of agricultural and forestry processing residues such as rice husk, rice straw, bagasse, cotton stalk, jute stick, almond shells, sawdust, etc., however, a small fraction of the residues is converted into useful energy. The major limitation in utilizing them for energy is their low bulk densities and high moisture content. In the domestic sector, biomass is primarily used in cooking stoves, which have low efficiency. There is a huge potential for biomass technologies like improved cook stove, gasifier, briquetting, and biogas. There are several locations where a huge potential of biogas exists but penetration is still low. Furthermore, biogas is still within the relatively rich people and it has to reach to the poorer strata of population in future.

Another promising renewable resource available in the country is water resource. Large, mini, micro and pico hydropower plants are in use. The country receives ample solar radiation with an average of 3.6-6.2 kWh/m^2.day, and the sun shines for about 300 days a year [MOF, 2002]. However, the resource has not yet been well used using modern technologies. So far, the major solar applications are water heating, PV, cooking and drying. Wind is still one of the non-harnessed energy resources in Nepal. It is not yet known on the national scale how big its potential in the country is. There are no proven geothermal resources, which are suitable for large power generation. However, only very little studies have been made on 40 hot springs found in different regions within the country. Some of the hot springs are partially used as therapeutic purposes and recreation purpose only [CES, 2000].

Needless to state that technically feasible, economically viable, and environment friendly renewable energy technologies (RETs) are the major option for rural people in Nepal in order to access the modern needs of energy. Nepal does have some successful implementations of RETs such as biogas, micro-hydro, solar thermal and photovoltaic, etc. In Nepali context, there exist a large potential of renewable energy resources to be exploited for the future use. It is important that further R & D works be made for exploitation of the immature technologies such as wind, geothermal etc. In addition, local capability development in terms of RETs awareness and technical backup know-how is crucial for sustainability of RETs.

7.3 Solar Photovoltaic Status

Most of the villages in Nepal are isolated from modern means of energy supplies. The major electricity demand, at the moment, in these villages is for lighting. Villagers light their homes either by kerosene lamps or by wooden flames, which cannot provide sufficient light and are also problematic in terms of health, safety, hygiene. The kerosene is not easily available and is very much costly due to additional transport costs in remote areas [IEA, 2002; ITDG, 2004]. This is why the solar PV sector is very popular among rural dwellers. Fortunately, the country receives an ample amount of solar radiation with an average of 3.6-6.2 kWh/m^2.day, and the sun shines for about 300 days a year [MOF, 2002]. The development of solar energy technology is, thus, reasonably favourable in many parts of the country. The exact date of the first use of solar PV in Nepal cannot be ascertained, but it is said that the first PV module was used in 1963 in an airport for navigational purpose [AEPC, 2003]. Recorded use of solar PV for domestic electrification started only in 1991-92 [Shrestha et al, 2003]. By now, the major user of solar PV systems is the residential sector. Based on their application areas, the solar PV systems in Nepal are categorized in the following four types [AEPC, 2008].

7.3.1 Solar Home System (SHS)

SHS is defined as the household electricity supply system with solar PV panel of capacity 10 W_p or more, battery, charge controller and appropriate number of DC lights. It is the most widespread application of solar PV technology in Nepal. By December 2007, a total number of about 115,000 SHSs had been installed throughout the country with the total installed capacity of 3.5 MW_p. Figure 7.5 shows the SHSs installation trend in Nepal during 1992-2007.

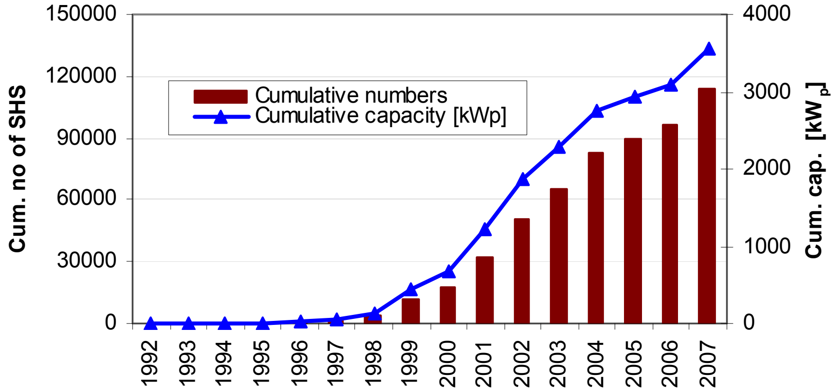


Figure 7.5: SHS installation in Nepal, 1992-2007

The annual growth rate of SHS installations was an increasing trend until 2002. The growth rate fluctuated in 2003 and 2004, and decreased thereafter. This might be due to discontinuation of government subsidy (due to suspension of donor support citing then political situation of the country). After the resumption of subsidy as per *Subsidy for Renewable (Rural) Energy 2006* [AEPC, 2006], many SHSs were installed in 2007, and such trends are expected to continue in coming years as well. Individual capacity of installed SHSs ranges between 10 W_p and 120 W_p. Figure 7.6 shows the percentage distribution of SHS installations by system size.

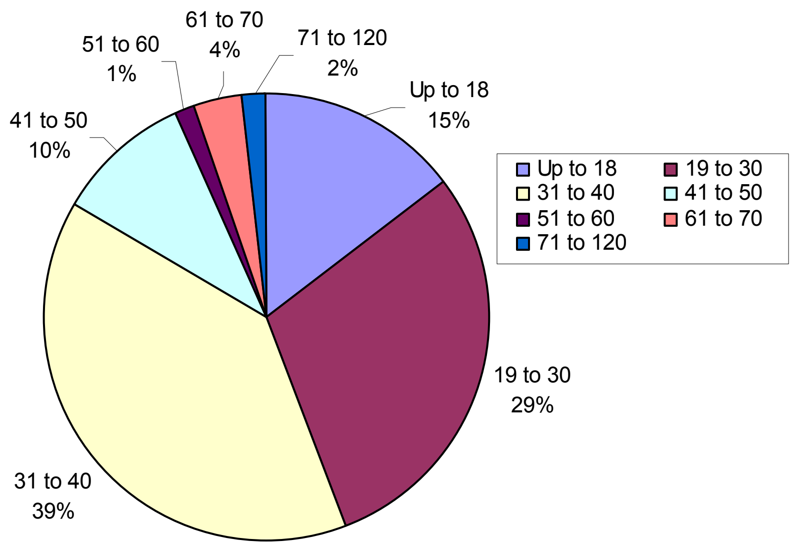


Figure 7.6: SHS installations by system size, W_p

It can be clearly seen in figure 7.6 that about 83 % of the installed systems are smaller than 40 W_p capacity. This is a clear indication that SHSs are mainly used for lighting. Usually, a 40 W_p system is used to supply three DC lights.

7.3.2 Small Solar Home System (SSHS)

Popularly known as *Solar Tuki* among local folks, SSHSs have module size between 2.5 W_p and 10 W_p, battery, battery charge controlling mechanism, and appropriate number of white light emitting diodes (WLED). WLED is an electronic component that emits near to white light when connected to a DC source. A popular version of *Solar Tuki* consists of one 3 W_p solar panel and two WLED lamps of 0.4 W_p. By the end of 2006, about 6000 SSHSs were installed [AEPC, 2008].

7.3.3 Community Solar PV System (CSPS)

Solar PV powered water pumping system is the main application under this category. Those systems have been used for pumping water for drinking as well as irrigation purposes. By the end of 2006, about 64 such pumping systems were installed with total installed capacity of 116 kW_p. Individual systems are of various sizes ranging between 130 W_p and 40 kW_p. Another application of CSPS is for lighting in community owned institutions such as, community building, community battery charging centres, lodge, and campsites, etc. By the end of 2006, about 31 such lighting systems were installed with a total capacity of about 5.3 kW_p [AEPC, 2008].

7.3.4 Institutional Solar PV System (ISPS)

Applications using solar PV in facilities such as schools, health clinics, religious buildings (e.g. monasteries), government buildings, etc. fall under ISPS. By December 2006, the total number of ISPS installations had reached to about 210 with a total installed capacity of about 42 kW_p. The individual system capacity of ISPS ranges between 34 W_p to 6.5 kW_p [AEPC, 2008].

7.3.5 Government Initiatives

In Nepal, both the government and the private sectors are involved in promotion of solar PV sector. The government is actively involved in functional areas such as, quality control assurance, and is a major source of financial incentives to the beneficiaries. The Alternative Energy Promotion Centre (AEPC), formed in 1996 under the Ministry of Environment, is the apex body for coordinating national level activities and programmes on renewable energy including solar PV. Government plans the further expansion of solar PV sector and the following quantitative targets have been set in ongoing interim plan, 2007-2010 [NPC, 2007]:

- Installation of 90000 units of solar PV systems in 73 (out of 75) districts to provide electricity at the household level
- Distribution of 140000 units of *Solar Tukis* in 75 districts
- Development and commissioning of 50 solar water pumping systems for drinking and irrigation purpose in 30 districts
- Installation of 810 institutional solar PV systems in 30 districts.
- Installation of 1500 units of solar dryer/cooker in 40 districts.

In order to promote solar PV sector further, the government provides subsidy with financial support from foreign donors. The present subsidy scheme for different village development committees (VDC) is as shown in table 7.2. Additionally, import duty and value added taxes on PV systems are also exempted.

Table 7.2: Solar PV subsidy scheme [AEPC, 2009]

Category	Very remote VDCs	Remote VDCs	Accessible VDCs
Solar Tuki (solar lantern) (%)[a]	50	50	50
10-18 W_p (thousand NRs)[b]	7	6	5
>18 W_p (thousand NRs)[b]	10	8	6
Public welfare organization (%)[c]	75	75	75
Solar Pumps (up to 1 kW_p) (%)[c]	75	75	75

[a] 50 % of total cost, but not exceeding NRs 1250.

[b] 1 Euro = 106 Nepalese Rupees (NRs) as of May 04, 2009.

[c] 75 % of total cost

7.3.6 Beyond the Subsidy

Although solar PV is a very fascinating technology for rural electrification, not surprisingly, its high investment cost has been largely hindering the widespread dissemination worldwide. Without subsidy and similar incentive schemes, PV systems can not yet sustain in electricity market in most countries. Nevertheless, the PV system costs are decreasing over the past years at a learning rate of 20 % for each doubling in cumulative production and this trend is expected to follow in the coming years [Beneking, 2007; Schaeffer et al, 2004]. Thus, PV system will have an important role in the electricity mix worldwide in coming years.

In the remote and isolated Nepalese villages, there is no convincing alternative to solar PV for electricity generation. Hydropower, even for small power plants, needs big investment that is beyond the affordability of many rural households. Although there is no proper wind mapping data available, performed studies show that the wind energy is not sufficient for electricity generation in many places [Gewali and Bhandari, 2005]. Unfortunately, rural people can not afford full cost of solar PV systems at their own and once the donor supported subsidy scheme is over, solar PV spread might also stop. This should be considered by government in its development plans. The following sections of this study discuss the future role of solar PV systems in electrification of urban and rural areas of Nepal.

7.4 Urban Areas

As discussed earlier, the urban areas in the country are already provided with the grid electricity, but the supply is unreliable. Installation of stand alone solar PV could provide the reliable electricity to a household. However, a question arises: are the stand alone solar PV systems economically feasible without any subsidy schemes, and will the urban households having access to the grid easily adapt them? These questions have been answered through a cost benefit analysis in the following sections. Once the PV systems are economically feasible, most likely many households will shift from grid use towards solar PV installation in order to avoid the frequent blackouts. In this case, an urban household is supposed to install a solar PV system at home premises and meet the household electricity demand solely from PV electricity. Possibility of grid connected solar PV systems has not been discussed, because there is no mechanism so far for the regulation of grid connected solar PV, unlike in many developed countries. Therefore, only off grid stand alone systems have been considered in the analysis. The analysis has been made using the same model discussed in chapter 6 for stand alone systems in Germany using the default values given in table 7.3.

Table 7.3: Default values for stand alone solar PV system for urban areas in Nepal

Description	Symbol	Unit	Value
Electricity demand, annual	E_d	kWh/yr	1000
Global radiation	G	kWh/m^2.yr	2014
Quality factor	Q	%	40
Effective energy consumption days in a year	D	days	365
Number of autonomy days	D_a	days	4
Maximum depth of discharge	DOD	%	80
Battery energy conversion factor	η_b	%	80
Module price	C_m	€$_{2007}$/kW$_p$	3238
BOS cost factor (excluding battery)	k_{mbos}	%	30
BOS replacement cost factor	$k_{mbosrpl}$	%	70
Battery price	C_b	€$_{2007}$/kWh	100
Battery replacement cost factor	$k_{bbosrpl}$	%	100
Discounting rate	d	%	4
Real interest rate	i	%	6
Variable cost factor	k_v	%	1
Electricity price from grid	P_{el}	€$_{2007}$/kWh	0.08
Annual electricity price growth rate	re	%	4
Cost of grid access	C_{iga}	€$_{2007}$	50

Based on practical experiences on site, a typical urban household has an annual electricity demand of around 1000 kWh/yr. Solar radiation data for the site (27 ^{o} 44 ’ N and 83 ^{o} 22 ’ E) are taken from NASA website. Nepal does not manufacture solar modules or batteries; instead it imports them from abroad. Therefore, the similar values of German market price data for solar modules and batteries are used in the calculations assuming those items already being global products. Although bank loan interest rates in developing countries are normally pretty higher than in Germany because of high risk of investment, this might not be the case for renewable energy projects. Therefore, a low interest rate of 6 % has been used. Annual growth rate in electricity price has been assumed to be 4 %, which is fewer compared to the price increase in other commodities. However, in the real case scenario, there is no increase in electricity price since 2001. This is not because the utility has been making profit even without increasing the price, but because of many political reasons. Any increase in electricity price in present context might invite anti-governmental protests and political unrest because the government owns the utility. However, this stagnant price is assumed to be temporarily; there could be sudden increase in this price as soon as a stable government is in power.

Therefore, an annual price growth rate of 4 % has been assumed in order to calculate the long term economic scenarios.

7.4.1 System Sizing

In order to make an energy autonomous house, an optimal system sizing is necessary. Monthly available solar radiation plays an important role in the sizing of the system as discussed in the previous chapter. Daily average global radiation data on horizontal surface have been retrieved from NASA website and they are converted into tilted surface using the equation 5.9. A comparison of radiation on horizontal surface and on tilted surface has been shown in figure 7.7. The minimum radiation is available in July because of rainy season.

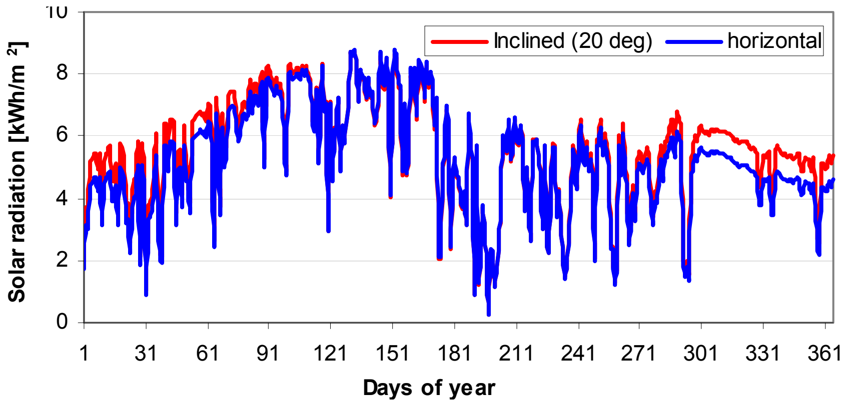


Figure 7.7: Global radiation in Nepal

As shown in figure 7.7, radiation value in some months during the summer time is lower than during the winter time. Therefore, the system should be designed for covering the summer (worst) months. This means, a lower value of tilt angle might be necessary unlike in many other locations at the similar latitude, where designs are mainly based for winter month loads because of the lowest value of global radiation. System size needed in order to supply the energy demand in July has been calculated for inclination angles from 0 ° to 45 °, and it has been shown in figure 7.8.

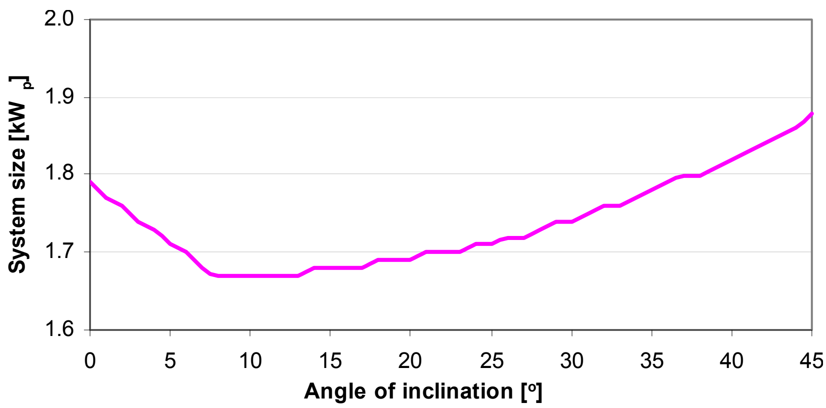


Figure 7.8: PV module size at different angle of module inclination

As shown in figure 7.8, the smallest system size (1.67 kW_p) would be able to cover the energy demand at a module inclination angle of 8 °. This value will increase up to 1.69 kW_p, if the inclination angle is increased from 8 ° to 20 °. If the inclination angle is very less, the module will be relatively flat, and there is risk of dust and other foreign material deposition on the module surface. It will significantly decrease the module performance. Also, in case of rain, inclined modules could be automatically cleaned with rainwater. Keeping those factors in mind, a module inclination angle of 20 ^{o} has been chosen, and thereby a module size of 1.69 kW_p has been designed. Batteries have been designed to supply the electricity demand up to 4 autonomous days, and the battery size has been calculated to be 17.1 kWh. The battery size is proportional to the number of autonomous days; hence the less autonomous days will make the smaller battery size. However, these days are not decreased in the calculations because the numbers of consecutive no sun days during monsoon are higher. While calculating the battery size, the daily electricity demand throughout the year is assumed to be the same. This is practically true for the mentioned site, because use of electricity demand is considered to be only for household electronics and lighting, excluding heating and cooling devices. A non luxury household in the capital city, Kathmandu, basically does not use any space heating and cooling systems because of no extreme weather changes throughout the year.

An average monthly electricity demand and the electricity production with the system size of 1.69 kW_p have been shown in figure 7.9.

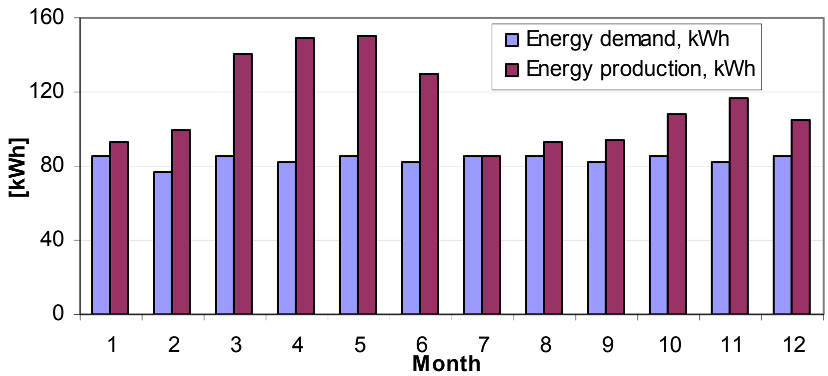


Figure 7.9: Monthly electricity demand and PV generation, Nepal

Because of less variation on average monthly solar radiation throughout the year, $R_{P/L}$ is smaller (1.36) compared to that of Germany in chapter 6 (2.83). Monthly values of $R_{P/L}$ have been shown in figure 7.10.

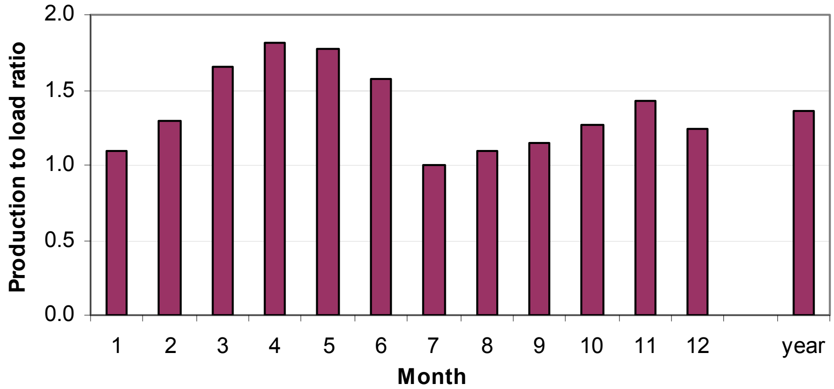


Figure 7.10: Production to load ratio - stand alone PV system in Nepal

Looking at figure 7.10, it can be said that annual electricity generation with the PV system will be 1364 kWh (for the performance ratio of 40 %), out of which only 1000 kWh will be used by household (using battery storage systems, not the electricity consumption at the time of its generation) and the rest is a loss.

7.4.2 Economic Analysis

The total cost has been calculated for the default values (table 7.3) by using the same procedure used as in German stand alone systems (equations 6.3-6.10). The present value for total revenue is calculated using equation 6.14. The results of the cost benefit analysis are given in the table 7.4. Apparently, there is no prospect for stand alone solar PV system in Nepalese urban locations under the current market condition.

Table 7.4: Cost benefit analysis results - stand alone PV system in Nepal

Cost benefit analysis results	**Stand alone PV – urban areas**		
	***N*=25**	***N*=30**	***N*=40**
Cost, $€_{2007}$	14971	14828	14109
Revenue, $€_{2007}$	1976	2365	3139
Benefit (loss), $€_{2007}$	-12995	-12463	-10970

By equalling the equations for net present cost and revenue, breakeven analysis has been carried out. Breakeven values for module price, electricity price, and grid access cost are presented in table 7.5. Either of them would be required to make the PV system economically feasible as of today under existing market conditions.

Table 7.5: Breakeven values for PV system components - stand alone PV system in Nepal

Breakeven values	**Stand alone PV – urban areas**		
	***N*=25**	***N*=30**	***N*=40**
C_m, $€_{2007}/kW_p$	-1069	-809	-200
P_{el}, $€_{2007}/kWh$	0.62	0.51	0.37
C_b, $€_{2007}/kWh$	-149	-156	-190
C_{iga}, $€_{2007}/hh$	13048	12520	11032

The negative signs for module price indicate that the investment would only be worthy if those amounts were rewarded to the owner of PV system in a form of subsidy or similar schemes for generating electricity from PV.

The solar PV breakeven year is shown in figure 7.11. Attributed to learning rate of 20 %, PV system price will decrease every year and a kWh grid electricity price will be in increasing trend. It can be seen that the break even year will occur somewhere between 2026 and 2036, depending upon operating life time of PV system.

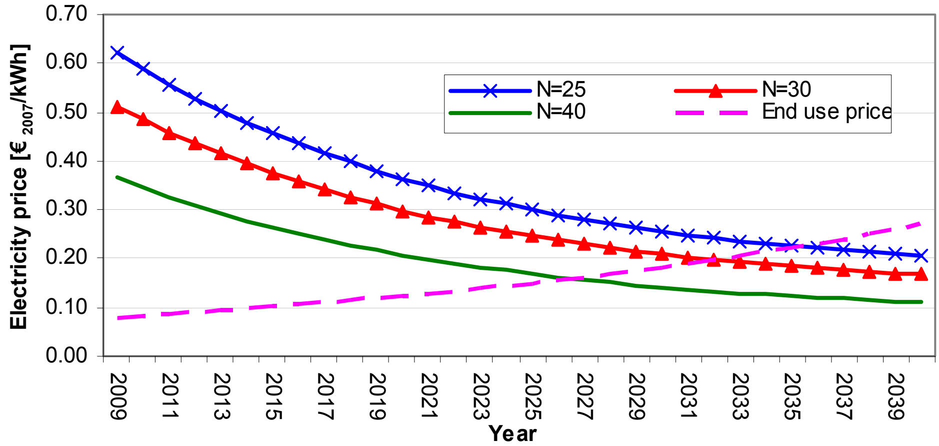


Figure 7.11: Breakeven year - stand alone PV system in Nepal

The results for break even year in figure 7.11 are quite pessimistic, if they are compared with grid parity or break even years of grid connected PV systems in other countries, e.g. Germany. In grid connected systems, 100 % of the electricity generated can be utilized, which is not the case in stand alone systems (figure 7.10). The expensive components of solar PV systems (modules, inverters, batteries) are more or less already global products and their price is comparable worldwide. Therefore, a kWh PV electricity generation costs for the location with similar climate conditions does not differ much. In contrast, the conventional grid electricity price differs highly from country to country, due to national policies, subsidies, fuels used for electricity generation, etc. In Nepal, grid electricity price is cheaper than other developed countries because almost all electricity in national grid is generated by hydro resources. In this case, the solar PV electricity is compared indeed with the grid electricity from another renewable source for calculating the break even year. Time series module and battery costs to make the systems at breakeven have been presented in figure 7.12.

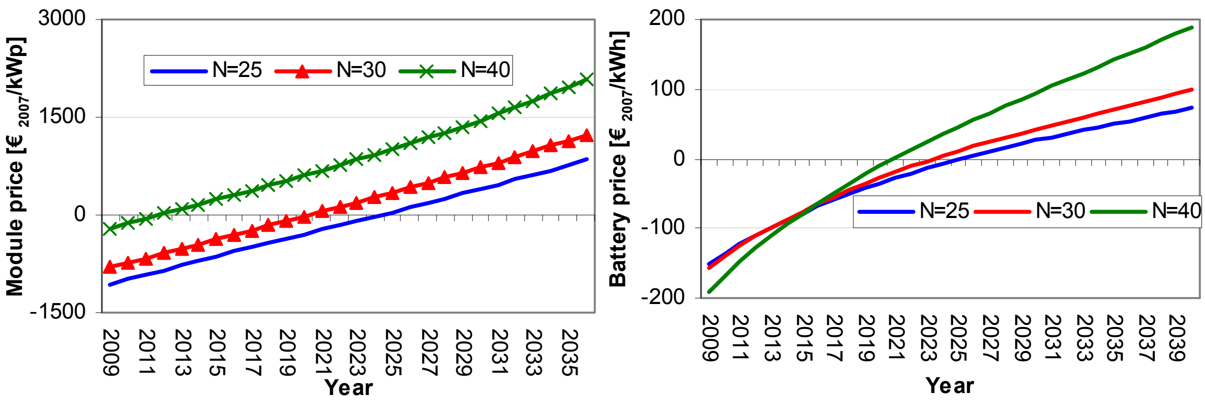


Figure 7.12: Breakeven module and battery price - stand alone PV system in Nepal

7.4.2.1 Grid Parity

The year when the PV electricity generation price will be equal to that of grid electricity price is shown in figure 7.13. It can be seen that the grid parity will occur somewhere between years 2026 and 2035 depending upon operating life time of PV system. However, if the annual growth rate of grid electricity price is low (2 %) grid parity year will occur later i.e. after the year 2032 even for the systems with 40 years of life time.

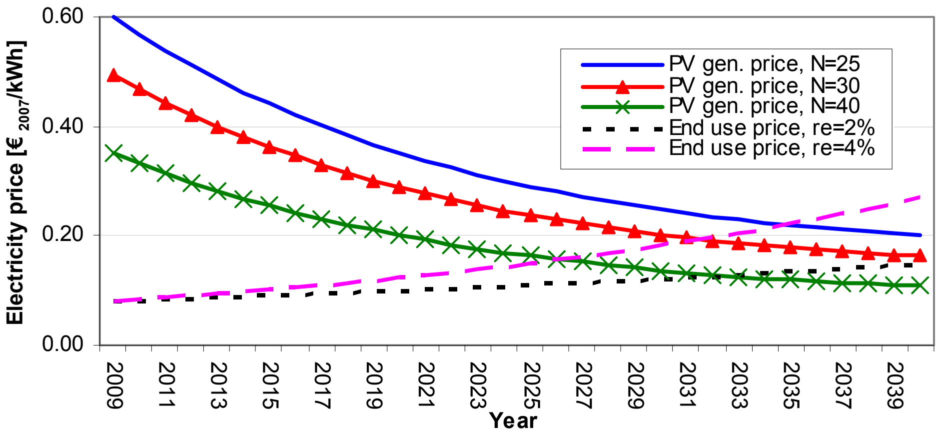


Figure 7.13: Grid parity – stand alone PV system in Nepal

In reviewing the above results (tables 7.4-7.5 and figures 7.11-7.13), it is not rational for the government to provide subsidy and encourage people to invest in solar PV systems in Nepalese urban areas. All the subsidies and the investment will simply go into the uneconomic and unproductive sector, simply for expensive household electrification. Instead, the focus should be paid in investing the subsidy money in productive sectors (which might also be in electricity generation sectors but using cheaper technologies, e.g. hydropower), which will eventually uplift the economic growth of people. The country can wait for urban area PV sector investment until the price for solar PV system becomes low enough to make its installation economically competitive, caused by mass installations in many parts of the world, where solar PV is already or near to its break even condition.

7.5 Rural Areas

The solar PV systems discussed so far were for urban population, mainly in developed countries (chapters 5-6) that already have a well developed grid infrastructure. Solar PV systems for rural people, who live especially in developing countries and do not have access to any means of electricity at present, is discussed under this section. The study will focus on either rural people should be supplied with stand alone solar PV systems or with grid electricity through grid extension from existing nearby grid node. For reference, climate and market data of the Nepalese village are undertaken.

7.5.1 Principle

It would be advisable to supply electricity to a household from stand alone solar PV system, when the total cost associated with its installation and operation is at the most equal to the sum of imputed revenue generated from it throughout the life time of the system, cost for grid access and cost for grid extension.

If the location is far-off from the available grid node, or if the demand is too low (due to small number of households on the site) it might not be wise to extend the grid. In this case, solar home systems might be the proper option to supply the electricity. The electrification approach differs from site to site depending upon many factors and this is not a problem that sees a single and perfect solution. First of all, the location of the site is very important. How far is the available nearest grid, if the grid extension has to be considered? Is the available grid capable of supplying the load in the new location? Is the existing grid electricity reliable? How much is the demand in the proposed location? How does the daily load (demand) curve look like? How is the climate data e.g. annual average solar radiation, seasonal variation in solar radiation, etc? Is the demand intended for AC or for DC supplies? How can the investment be arranged, is there any banks that are ready to grant loans for this purpose? How much is the bank interest rate and the loan payback period? How is the potential future demand in the site - increasing, decreasing or constant? These are some of the pertinent questions that have to be analysed thoroughly before a rural electrification approach is proposed for any site. Based on these factors, economic aspects of the stand alone solar PV system for a reference rural Nepalese village has been discussed here.

7.5.2 Reference Village (RV)

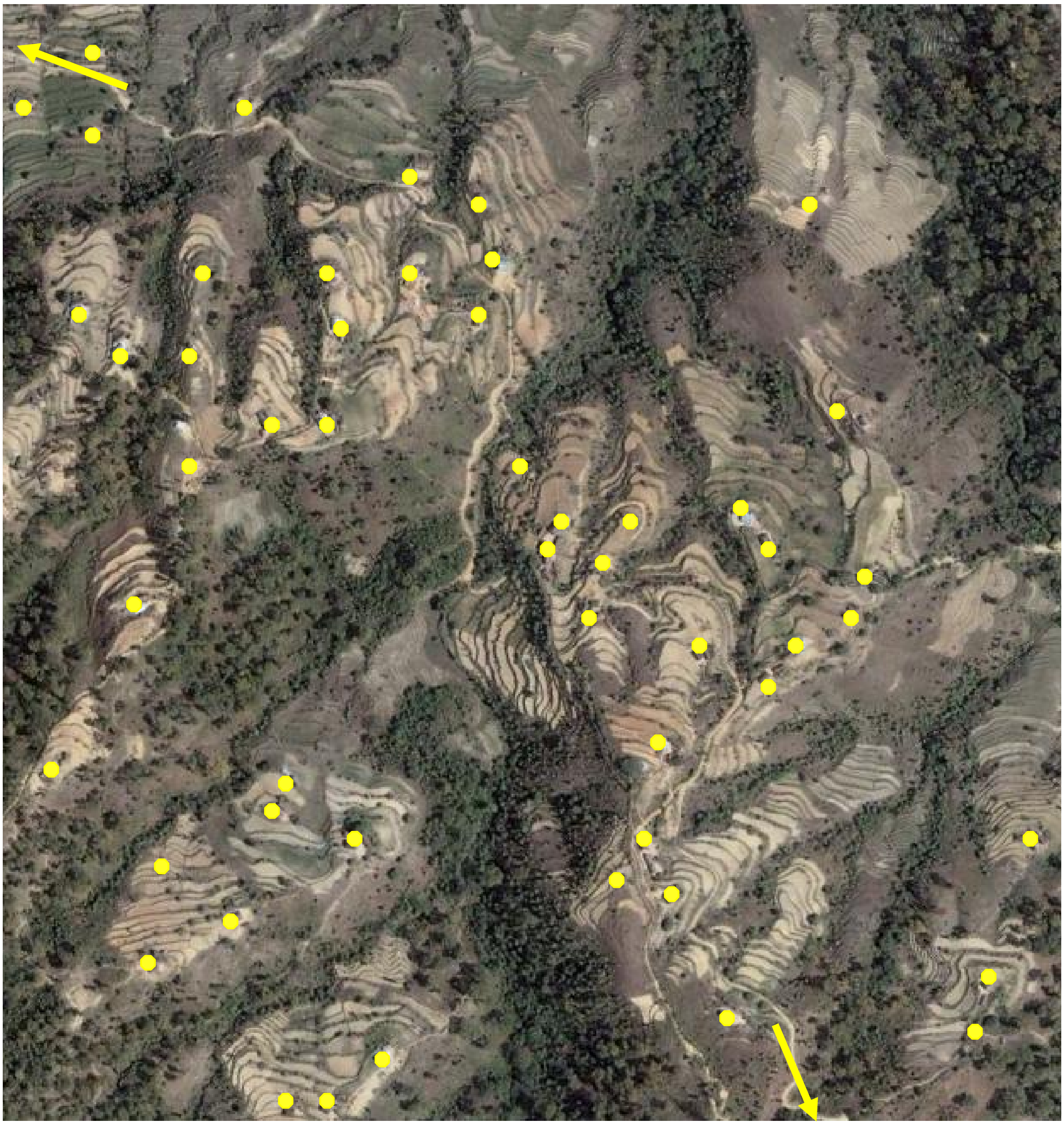


Figure 7.14: Aerial view of the centre of Jhingamara village (Google earth view)

The reference village (27 ° 45 ' N, 83 ° 22 ' E) is mountainous and is not far from plain land of Terai (around 10 km), where the electricity transmission grid exists. The village has an estimated 100 households, which have no means of electricity supply. Kerosene lamp is the basic means for lighting. Fuel wood is almost exclusively used for cooking. This is one of the typical villages of its kind among thousands of such villages in Nepal.

Table 7.6 gives the estimated daily appliances in use and electricity demand for two different types of households. Household type-1 (HH 1) is low or no income family households and Household type-2 (HH 2) is relatively higher income family in comparison to HH 1. Generally, single household consists of 4-6 family members. In the village, about 60 households are supposed to be of HH 1 types and 40 households of HH 2 types.

Table 7.6: Expected electrical load in individual households

Household type – 1 (HH 1)				
Appliances	**Number**	**Rated capacity (W)**	**Daily use (hours)**	**Daily energy demand (Wh)**
Lamp (kitchen)	1	15	3	45
Lamp (main room)	1	15	2	30
Lamp (outside)	1	15	1	15
Lamp (toilet)	1	15	1	15
Radio	1	10	4	40
Cassette player	1	30	2	60
Household type – 2 (HH 2)				
Appliances	**Number**	**Rated capacity (W)**	**Daily use (hours)**	**Daily energy demand (Wh)**
Lamp (kitchen)	1	15	3	45
Lamp (main room 1)	1	15	2	30
Lamp (main room 2)	1	15	2	30
Lamp (outside)	1	15	1	15
Lamp (toilet)	1	15	1	15
Lamp (cattle house)	1	15	1	15
Radio	1	10	4	40
Cassette player	1	30	2	60
Television	1	45	3	135

The daily load profile of individual households is given in figure 7.15. As shown in the figure, there is electricity demand in the morning, a peak between 6 am and 7 am, when people wake up and use light in their kitchen as well as turn on their radios in order to follow the national news and other informative programmes. Light will go off at 7 am, but the radio continues until 8 am. HH 2 will shift from radio to his TV around 8 am to follow news and musical programmes. Generally after 9 am, people go to their farm/fields for working during the day, children go to school, and there is no energy demand during the day. When people come back home in the afternoon, HH 2 will turn on cassette player for two hours at 4 pm and HH 1 for one hour at 5 pm. Both households will turn on their radio from 6 pm until 8 pm. Also the households will turn on their lamps in main rooms and kitchen at 6 pm until 8 pm. Light at outside home and in toilet will not be lit continuously, but it is estimated that they will be used about an hour a day. The time has been put at 7 pm for outside lamp and 8 pm for toilet. Additionally, HH 2 will light the lamp at cattle house at 6 pm for about one hour. HH 1 will turn on cassette player before going to sleep at 8 pm for about one hour. Similarly, HH 2 will turn on TV at 8 pm for about 2 hours. This electricity demand pattern is supposed to follow throughout the year. This will give an annual electricity demand value for HH 2 around 140 kWh/yr and for HH 1 around 75 kWh/yr.

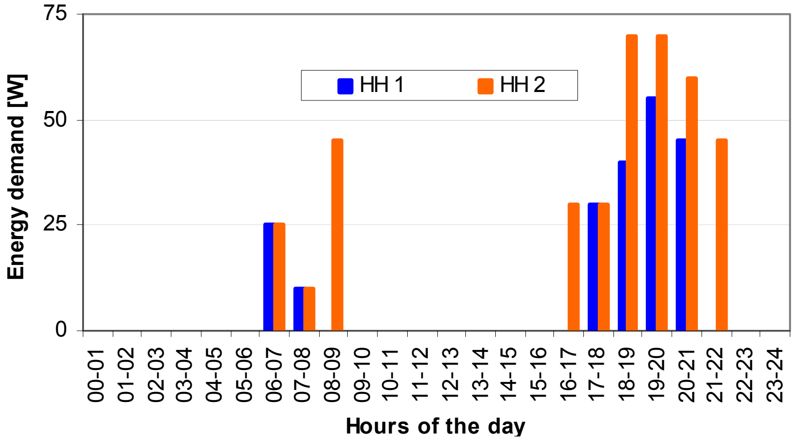


Figure 7.15: Daily load profile of individual household

The information about the village could be used accurately if on site survey would have been held. This has not been made in this study because of time and financial constraints. The data are collected from personal observation and past experience of the author in his home village, a similar village in another part of the country. This study presents the reference village as an example. However, in real project implementation cases, it is very important to make the accurate survey by visiting the corresponding sites.

Regarding the electrification of this village, there are three potential options – grid extension, on site generation, or the combination of both. The possible energy sources for on site generations are very limited. There are no hydropower resources nearby, and the nearest river is at relatively far distance (many kilometres). Even if a hydropower plant is installed in that river, there are other many dwellings nearby, and the chances to supply hydro electricity up to this village are almost negligible. Another option could be wind turbine installation, but the available wind speed for the site is very low, with an average annual wind speed of about 2.9 m/s (derived using Meteonorm software), which is not sufficient for the electricity generation in a reliable and an economic way. Other options e. g. operation of diesel generator or gas turbines has been opted out because these fuels are not renewable, are scarce and very expensive on site. The only reliable resource available on site is solar radiation, with an annual average global radiation of around 2000 kWh/m^2.yr. Therefore, in order to electrify the village, two approaches have been taken for further considerations. The first is utility's prospective - grid extension, and the next is users' prospective - stand alone solar PV systems.

7.5.3 Utility's Prospective

Under this case, the village could be supplied with the electricity if the utility decides to extend the grid to the village. If the electricity is supplied to the villagers, they will pay the monthly electricity bill, equal to a kWh unit price paid by other grid electricity users in urban locations. Utility's decision of grid extension will mainly be influenced by the amount of electricity demand in the whole village and the grid fee amount, which is a portion of electricity bill paid for a kWh by consumers. This case has been analysed with the help of economic analysis and the breakeven conditions for different input parameters are calculated. Table 7.7 shows the input data used as default values in the calculations.

Table 7.7: Default values – utility's prospective

Appliances	Symbol	Units	Values
Number of households	H	-	100
Average annual household electricity consumption	E	kWh/yr	100
Average distance	L	km	10
Cost of grid extension per unit distance	C_{gt}	€/m	1
Grid life time	N_g	yr	40
Electricity price	P_{el}	€/kWh	0.08
P_{el} growth rate	r	%	4
Grid fee (% of electricity price)	f	%	20
Bank interest rate	i	%	6
Variable cost factor	k_v	%	2
Discounting rate	d	%	4

Calculations are made with the assumptions that the village will have basically constant amount of electricity demand every year in the future. The grid extension distance of 10 km is from the existing grid node until the village entry point. Local inter-village grid connection costs are supposed to be included in grid access cost for individual household and they are not considered in the calculation here. Transmission line is likely to have voltage level of 220 V. This is supposed that 220 V line could be extended in the range of this distance. Theoretically, transformers could be used at both ends and the electricity at higher voltage could be transmitted, it will then increase the overall costs. The grid extension cost is assumed to be 1 €/m in average, which is relatively very low if it is compared with high voltage transmission lines especially in developed countries like Germany. The reason is that the transmission poles are supposed to be either made of concrete or wood. Based on practical experiences on site, the cost of grid extension will be enough for those poles, cable, and manpower. Grid fee has been estimated to be around 20 % of electricity bill because there is no exact data available from the utility. Household electricity demand is supposed to be around 100 kWh in a year. This value has been derived with an assumption that the village has 60 households of HH 1 types and 40 households of HH 2 types (this brings the annual demand value to 101 kWh, but it has been rounded to 100 kWh for the ease in presentation and the calculation).

The initial investment, financial, and repair maintenance costs are summed up to calculate the project cost. The theoretical revenue has been calculated by multiplying the annual village electricity demand and grid fee portion of a kWh electricity price. Present values of cost and revenue of the project for grid life time period of 40 years have been calculated. The equations to calculate of present values of total cost (C_t) and total revenue (R_t) are given by:

$$C_t = C_{gt} L \left[\left\{ \sum_{n=1}^{n=N} \frac{1 + i(N - n + 1)}{N(1+d)^n} \right\} + \left\{ k_v \sum_{n=1}^{n=N} \frac{1}{(1+d)^n} \right\} \right] \qquad [7.1]$$

$$R_t = E_d \; H \; P_{el} \; f \sum_{n=1}^{n=N} \frac{(1+r)^{n-1}}{(1+d)^n} \qquad [7.2]$$

The results for present value for total cost and total revenue are found to be 16484 € and 6154 €, respectively. This means grid extension is not an economically sound option for the utility and perhaps no grid will be extended to the region in the near future. The breakeven analysis has been made by making the benefit of the project zero (*total cost = total revenue*). Results from the breakeven analysis have been shown in figure 7.16.

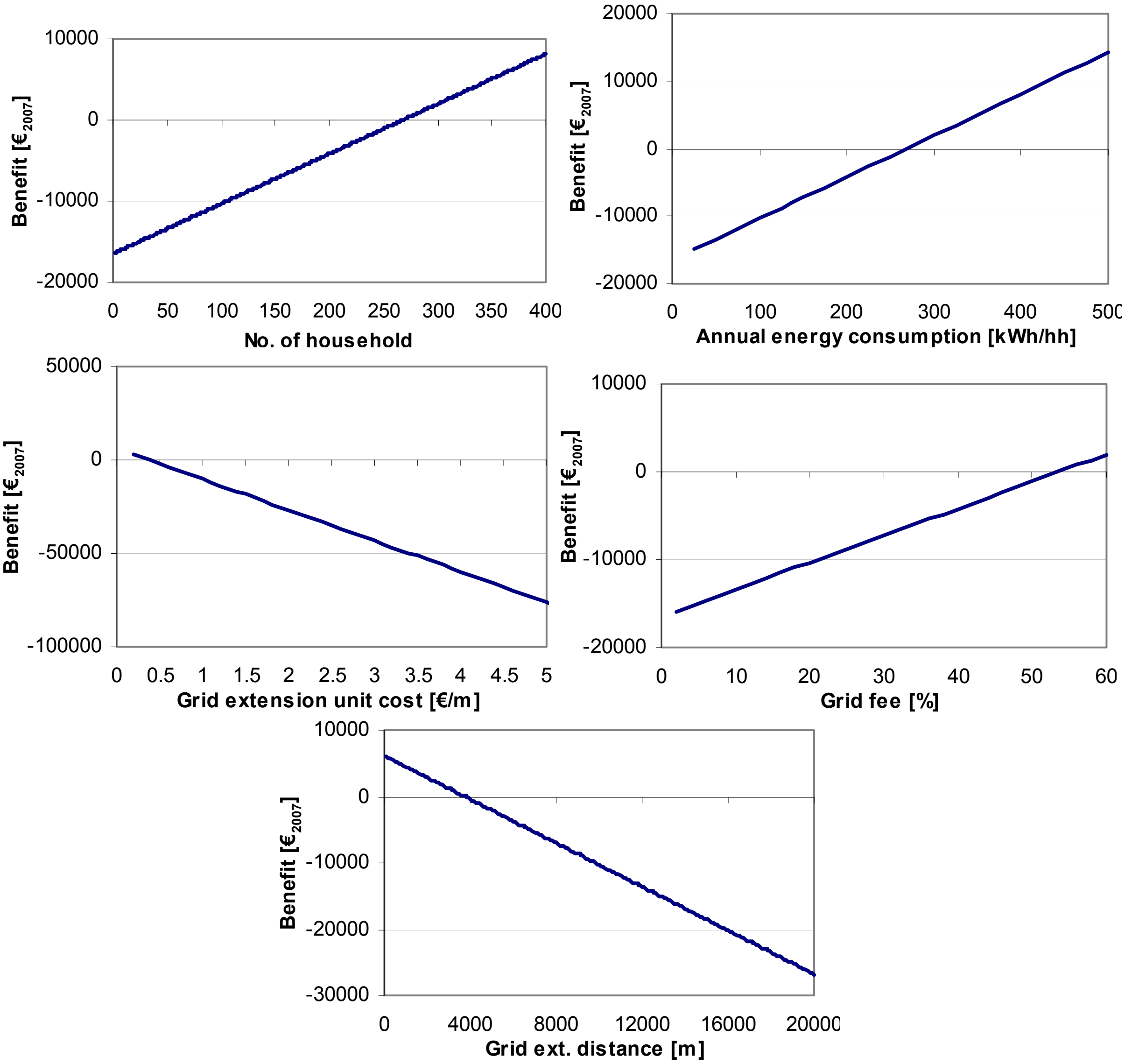


Figure 7.16: Breakeven conditions for grid extension

As shown in figure 7.16, the grid extension project is not economically laudable project from utility prospective under existing market scenarios. The project would only worthy if the village had more than 268 households, or annual energy consumption of individual households in average was about 268 kWh, or grid extension unit cost was less than 0.4 €/m or the portion of greed fee in a kWh electricity price was about 54 % or grid extension distance below 3.7 km. From the cost calculation, it can be said that the net present unit cost for grid extension would be about 165 €/hh (4.12 €ct/kWh).

7.5.4 User's Prospective

If the household itself has to decide the means of electrification, independent of government's (utility's) plans, it will see the economics of stand alone solar PV system (as discussed earlier, other options of village electrification in this site are not applicable). In this case, household will prefer a solar PV system in order to cover the annual electricity demand. The system size has been calculated to be around 123.5 W_p, using the same equation used for urban areas (equation 6.1). Battery size has been calculated to be around 701 Wh (equation 6.2). A DC supply will be used and no inverter is needed. This is why the BOS cost component has been considered to be only 5 % of the module cost. The input parameters used in the calculation as default values are given in table 7.8.

Table 7.8: Default values – user's prospective

Description	Symbol	Unit	Value
Electricity demand, annual	E_d	kWh/yr	100
Global radiation	G	kWh/m^2.yr	2014
Quality factor	Q	%	40
Effective energy consumption days in a year	D	days	365
Number of autonomous days	D_a	days	4
Maximum depth of discharge	DOD	%	80
Battery energy conversion factor	η_b	%	80
Module price	C_m	$€_{2007}$/kW$_p$	3238
BOS cost factor (excluding battery)	k_{mbos}	%	5
Battery price	C_b	$€_{2007}$/kWh	100
Discounting rate	d	%	4
Real interest rate	i	%	6
Variable cost factor	k_v	%	1
Electricity price from grid	P_{el}	$€_{2007}$/kWh	0.08
Annual electricity price growth rate	r	%	4
Cost of grid access	C_{iga}	$€_{2007}$	50
PV system life time	N	years	25

Considering the system life time of 25 years, the cost and imputed revenue from the system has been calculated. Time series of installation cost has been calculated using the module price decrease in the future and it has been found to be 758 €/hh (30 €ct/kWh). The cost for the systems to be installed in the coming years will decrease driven by learning rate (20 %), the total cost for a stand alone solar PV system will be as shown in figure 7.17.

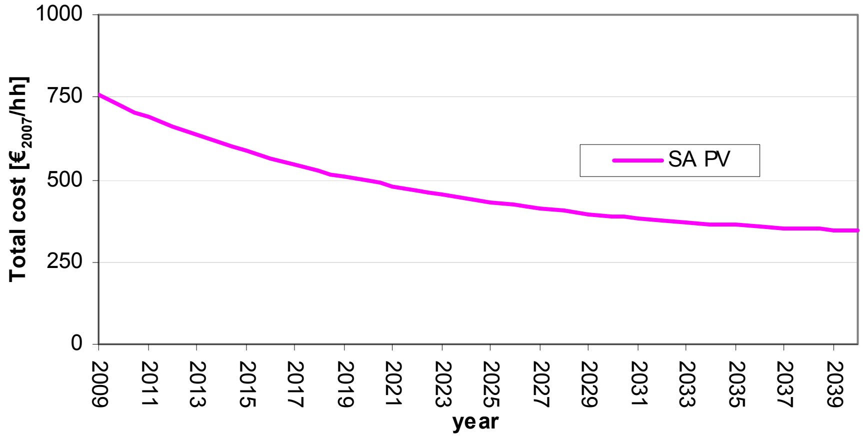


Figure 7.17: System cost of a stand alone PV system in rural Nepal

Under the hypothetical case that there is grid electricity and if the users would have to choose between grid electricity and solar PV systems, the economic benefit by using the solar PV system over the next years (taking into account the avoided electricity bill and the grid access costs as revenue) has been shown in figure 7.18. The net present loss by installing the stand alone PV system as of today has been calculated to be around 510 € for average household consuming 100 kWh electricity annually.

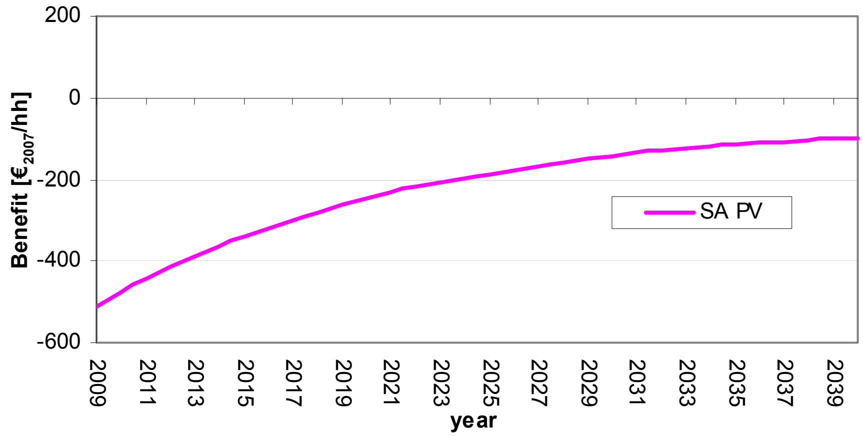


Figure 7.18: Benefit (loss) from stand alone PV system in rural Nepal

It can be seen in the figure 7.18 that stand alone PV system will not be an economic options in Nepal's rural areas until the coming decades under the current market conditions.

However, there are many social benefits of electricity, from indoor health quality improvement to better learning environment for children. Therefore, in decision making, economic analysis should not be the sole criteria, but other social dimensions should also be considered and the people indeed should be supplied with the electricity.

7.5.5 Solution

Under this sub-section, the role of government for rural electrification approach has been discussed. In developed countries, access to electricity and safe drinking water is considered as a basic human right, which is not yet the case in developing countries like Nepal, especially in rural areas. However, government might launch the rural electrification programme for the region (not necessarily for the reference village mentioned before, but the other villages which have similar characteristics). In this case, among others, economic facet is one of the most important components. The cost for grid extension and the costs for stand alone solar PV dissemination have been calculated and both of the options are compared in figure 7.19. It is assumed that the grid extension cost will be the same, irrespective of the number of households (1 or 100).

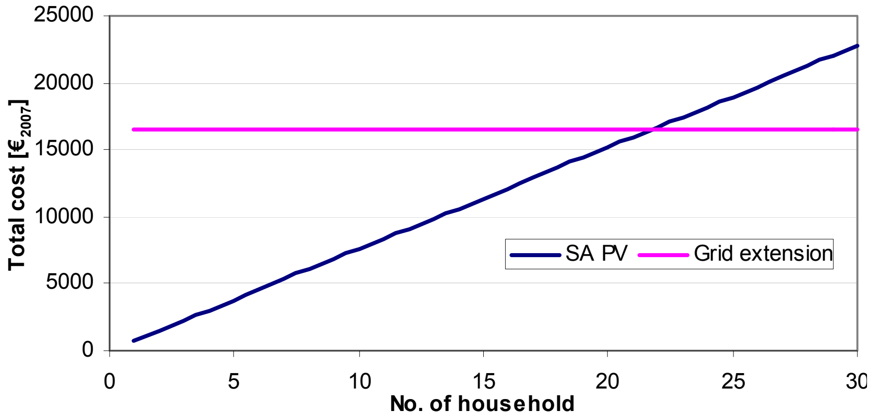


Figure 7.19: Stand alone PV vs. grid extension (with number of household)

As shown in figure 7.19, if the village has number of household less than 22, choosing the stand alone solar PV will be a reasonable option over the grid extension.

Similarly the results based on the grid extension distance have been shown in figure 7.20. Neglecting the transportation costs, stand alone solar PV system cost for individual household will be the same irrespective of distance (0 or 50 km) from the existing grid. Looking at the total cost results in figure 7.20, it can be said that the grid extension will be cheaper than stand alone PV installation if the grid extension distance is less than 46 km.

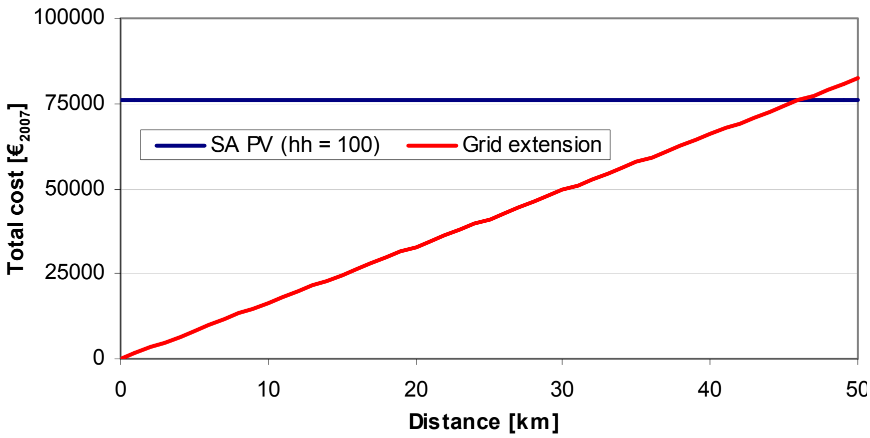


Figure 7.20: Stand alone PV vs. grid extension (with extension distance)

The grid extension cost in large settlements could be higher compared to the values shown in figure 7.20 due to high voltage transmission grids requirements and other factors; this has not been separately calculated in this small village.

The results shown above imply only for the base year, i.e. as of 2009. However, the coming years will see the decrease in stand alone solar PV system price and perhaps the increase in grid extension costs due to increase in material and manpower costs. The cost calculations for individual household based on the combination of different scenario of grid extension cost growth rate and solar PV system price decrease in the future are given in figure 7.21.

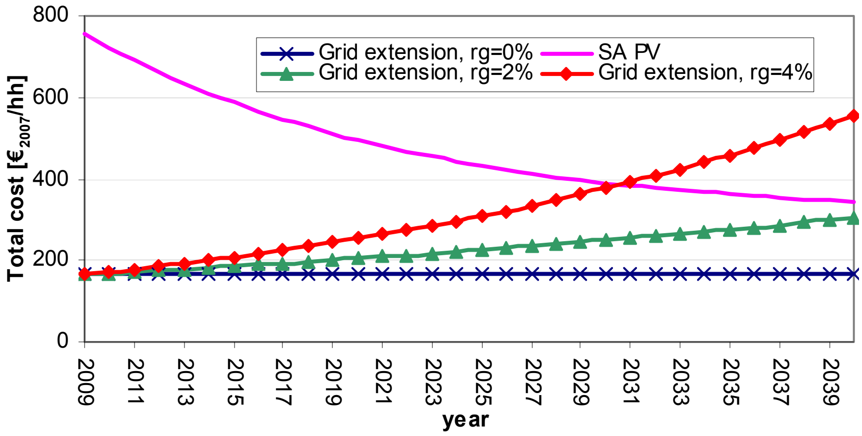


Figure 7.21: CBA results - stand alone PV system vs. grid extension, Nepal

Although both of the options will cause losses, the grid extension option is found to have less loss over the next decades in the reference village of 100 households.

7.6 Concluding Remarks

Electricity plays a vital role in socio economic development of a country. Economic growth and improvement of peoples' living standard are all directly or indirectly related to the increasing utilization of energy, of which electricity is the most important. Nepal has a large number of remote and small villages lacking electricity. The country essentially depends on traditional energy resources to meet its energy demand. National electricity grid has reached to about only 44 % of its population, mainly to those living in urban areas. Out of the total electricity generated so far, the major share of it has been consumed by residential customers, mainly for lighting purpose. There is increasing demand of electricity for lighting and it will go up dramatically in the years to come in the urban areas. This situation will further worsen the daily load shedding problems in grid connected communities.

Many mountainous villages will still suffer without grid electricity in foreseeable future. This has not only to do with poor economic condition of the country to construct new power plants and grid infrastructure, but also to do with remote topography and scattered population throughout the mountainous region. However, development and promotion of alternative energy sources in rural areas would help enhancing the quality of rural life by reducing the time spent in fuel wood collection, creating additional employment opportunities, health improvement, and increasing children's access to education. Additionally, the promotion of alternative energy sources contributes directly to reducing the green house gases emission. Among the various decentralized energy service technologies, solar PV is one of the proven and potential technologies for rural electrification. Solar photovoltaic technology is acclaimed in Nepal, especially in residential sector for lighting purpose. Because of successful PV promotional programmes from the government as well as from the private sector, PV expansion has been expected to increase in the future, at least until the government continue providing subsidy for PV systems.

Like in many other countries, solar PV systems have not yet been able to compete with free electricity market in Nepal. The break even year has been calculated to occur in 2036 for the PV systems with life time as of today, i.e. 25 years, but it will be as early as in 2026 if the PV systems with longer life time of up to 40 years are available by then. This break even year is much later because the grid electricity has almost solely been generated from hydropower, and a kWh grid electricity price is relatively low. This is why it is recommended that the urban households should not invest in solar PV systems as long as they have access to grid electricity. Instead, in order to secure the reliable electricity for grid connected customers, the government (i.e. utility) should invest in more power plants, mainly based on hydro resources.

In reviewing the CBA results, it is not worthwhile for the government to provide subsidy and encourage people to invest in solar PV systems in Nepalese urban areas. All the subsidies and the investment will simply flow into uneconomic and unproductive sector, simply for expensive household electrification. Instead, the focus should be paid in investing the subsidy money in productive sectors (which might also be in electricity generation sectors but using cheaper technologies, e.g. hydropower), which will eventually uplift the economic growth of people. The country can wait for urban area PV sector investment until the price for solar PV system becomes low enough to make its installation economic, caused by mass installations in many parts of the world, where solar PV is already or near to its break even condition.

In many remote and isolated villages, there is no convincing techno-economical alternative to solar PV for electricity generation due to modularity of PV systems. In such areas, due to dispersed settlements at one hand, and less electricity demand on the other hand, grid extension costs per kWh electricity transmission will be very high. It is recommended that, the rural households should be further provided with subsidized solar home systems, unlike in urban areas. Even if there will be price reduction of solar modules in future, it will not have big impact in absolute amount of price reduction for very small systems (for frequently used system size of 40 W_p). Providing these dwellers having electricity for lighting will have a big socio-cultural meaning that those people will not feel to have been marginalized and excluded from the mainstream of people enjoying the benefits of electricity.

Subsidy plans should not be, though, targeted with an open end time frame. Therefore, before deploying the solar subsidies, the government should first carry out the feasibility study on individual sites to assess whether the subsidy money can be distributed among villagers through any other productive projects. If subsidy money could be invested to increase the productivity of any sectors (e.g. agricultural sector, small enterprises, etc.), people will ultimately have access to the invested money, and they can invest it to buy solar home system. This will eventually help to achieve one of the government's goals for sustainable development. Another important point to be noted is a detail feasibility study is necessary to assess the possibility of micro hydro or other locally available resources based power generation and installation of micro grid. This will be promising only if the households are not dispersed very far from each other. If no water resource is available, the installation of community size solar PV system and its use as battery charging station could be another option. Each household could be provided a solar battery, and they might be given the possibility of exchanging their discharged battery with a fully charged one at PV operated charging station. This practice is widely popular in Nepal for natural gas cylinders that are used for cooking purpose in urban areas. Same model could be used for batteries in rural electrification as well. Based on the resources available, a hybrid system based on combination of different resources available at site (e.g. solar, hydro, wind, bio-fuel, etc) might be the other solution, though proper management is inevitable to supply the cheaper electricity in need.

Based on the assumptions made in this study, neither grid extension nor the installation of solar PV systems is an economic option in the reference village and alike until several coming decades. However, the need of electricity is inevitable, and hence the supply is a must. Therefore, depending upon the characteristics of the village, government might extend grid or promote stand alone PV systems. Government should keep on supporting rural electrification, either by continuing providing subsidy, or letting this money flow among the villagers by investing this subsidy money in any productive sector is the region so that people have money to buy solar home systems at their own. Depending upon the site, hybrid system could also be deployed using micro grids for electrification. Such attempts should be complementary for sustainable development of the region and maintaining social cohesion.

8 AUTONOMOUS WATER SUPPLY SYSTEM

The study discussed in the previous chapters dealt with the prospects of grid connected versus stand alone electricity supply. When targeting towards stand alone electricity supply, it might not make sense to keep the grid connection only for water supply. These investigations are done in this chapter. Moreover, autonomous water supply system will have a drawback that it will increase the household electricity demand and thus change the calculations done so far.

The freshwater scarcity in many countries in the world, the rapid population growth, the draught disasters and the climatic changes cause high demands of water and require farsightedness in water management. The WHO information explains that approximately 1.7 million deaths per year are directly attributed to unsafe water supply, sanitation and hygiene [WHO, 2009]. This global water crisis requires a solution which could provide both the improvement in quality and quantity of water. Many public and private utilities as well as communities have already practiced different water management approaches for a long time to ensure the water demand at reduced cost (e.g. through ground water extraction, rain water harvesting, awareness and dissemination of water saving appliances to households, etc.).

Quantitative and/or qualitative water shortage is still a big problem in many societies especially in the arid regions and in developing countries. Also, the costs for drinking water and wastewater disposal are increasing over the time, only its rate varies in different countries. A guarantee of adequate water supply and reduction of the associated costs is important for individual users. Similarly, reduction of the wastewater quantity and the associated costs is significant for municipalities, responsible bodies for wastewater disposal. Thus, sustainable use of valuable water resources is crucial for the society as a whole.

An autonomous water management concept at household could be a decisive step to ensure the sufficient quantity and quality of water at lower cost and to reduce pressure for the environment. This could be a sustainable approach, especially if the energy required for operating the autonomous water supply system is supplied through renewable energies, e.g. solar photovoltaic systems. These aspects have been analyzed in this study. The study aims to develop an autonomous water supply concept for a household located in Germany. With the help of the model discussed in chapter 6, the water network access distance required for economy of autonomous water supply system will be discussed. The study assumes that: (i) the freshwater demand of the household will be supplied through rainwater harvesting if the rainwater volume is sufficient; otherwise, the groundwater will also be used as freshwater complementary source (ii) the process water demand will be supplied with the recycled greywater, and (iii) the black wastewater will be treated on site before it is discharged into the ground. Although autonomous water supply practices are not common in German households, the greywater recycling is being promoted by different manufacturers. The household-scale greywater recycling technologies are well developed and are already available in the market, not only in Germany, but also in other countries, e.g. Australia, Canada, etc. Therefore, in addition to the analysis of the autonomous water supply household, a detail study of the 'greywater only' recycling systems has been carried out.

In the developing countries, the autonomous water supply concept could be useful in the tourism sector (e.g. hotels), where high quality and reliable water supply and sanitation systems are necessary. In other cases, where the water supply infrastructure is either poor or not existing at all, such concept could only be applicable for the water supply and sanitation in a whole village. However, the present study does not cover these aspects.

8.1 Greywater Recycling

Domestic wastewater consists of grey and black water and is usually treated using a shared sewerage system to limit pollution and health risks, before being returned to the environment at large. The majority of greywater ends up as effluent in rivers and oceans in this way. Numerous research projects with long term scientific investigations have led to industrial products of greywater recycling plants which are now available in the market. However, the use of these high technologies has been so far very limited.

Unlike in many other countries, water scarcity is not the case as of today in Germany. However, the measures have to be taken to reduce the freshwater consumption and to substitute the drinking water with recycled greywater, in areas which need water of acceptable quality (not necessarily drinking water quality) such as for toilet flushing, outdoor irrigation, washing clothes or others, e.g. car washing. As a result, the negative effects of the drinking water extraction and distribution processes (e.g. energy and chemical requirement, drop in the groundwater level, consumption peaks) could be reduced. Greywater recycling plants reduce the amount of wastewater produced and consequently, the water pollution too [fbr, 2005].

8.1.1 Greywater at Household

Greywater is defined as the urban wastewater that includes water from baths, showers, hand basins, washing machines, dishwashers and kitchen sinks, but excludes streams from toilets [Jefferson et al, 1999; Otterpohl et al, 1999]. fbr [2005] defined greywater as a part of the household wastewater, which is the drain from bath tubs and shower trays, washbasins and washing machines and may also contain high strength kitchen wastewater, excluding blackwater[4]. Some authors exclude kitchen wastewater from the other greywater streams [Little, 2002; Wilderer, 2004].

Morel and Diener [2006] reported that, in the developed countries, the typical daily per capita greywater generation volume varies about 90-120 liters, which depends on lifestyles, living standards, population structures (age, gender), customs and habits, water installations and the degree of water abundance. However, the volume of greywater in low income countries with water shortage and simple forms of water supplies can be as low as 20-30 liters per person-day. Eriksson et al [2003] mentioned that greywater generally constitutes 50-80 % of the total

[4] Blackwater is part of the household wastewater, the drain from toilets and therefore, contains urine and faeces.

household wastewater. Due to the low levels of contaminating pathogens and nitrogen, reuse and recycle of greywater is receiving more and more attention [Li et al, 2009]. The least concentrated flows of the available household greywater are especially appropriate for recycling. For residential buildings, these are the drains from bath tubs and shower trays as well as washbasins. Under certain conditions, the use of the washing machine drain or even kitchen wastewater may be of significance [fbr, 2005].

Average daily per capita water consumption by household consumer in Germany is about 125 liters [WVGW, 2008]. The average water consumption by sector (% consumption per inhabitant and day) for private households is given in figure 8.1 (modified from [fbr, 2005; Mehlhart, 2001]). It can be seen that the greywater generation reaches up to 70 % of the total water consumption. Moreover, about 48 % of the household water demand could be substituted with the process water (for cleaning, washing machine, toilet flushing and irrigation). This means that the recycling of the partial volume of the greywater generated at home could save up to 48 % of the total water consumption.

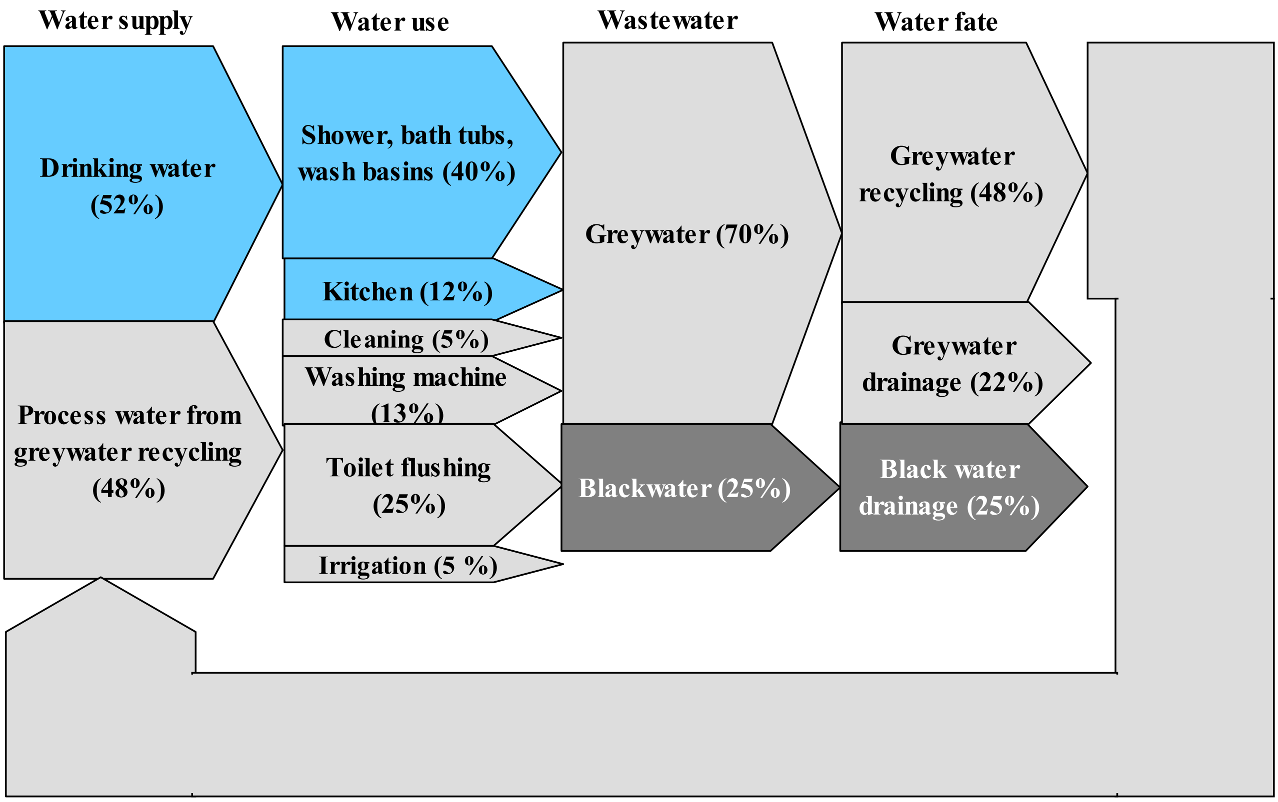


Figure 8.1: Grey-and black-water generation in a German household

8.1.2 Greywater Characteristics

EA [2008] defines water quality as a whole in a wide term covering physical, chemical and biological quality.

Physical quality includes how clear the water is (i.e. turbidity), total suspended solids in the water and its temperature.

Chemical quality includes how acid or alkaline the water is (i.e. pH), how much disinfectant is present (residual chlorine or bromine), the amount of dissolved oxygen in the water and biochemical oxygen demand – a measure of the amount of organic material in the water.

Biological quality mainly relates to the presence of bacteria and viruses.

Greywater from showers, baths and washbasins will often be contaminated with human intestinal bacteria and viruses as well as organic debris such as skin particles and hair. It will also contain residues of soaps, detergents and other cosmetic products; these often contain nutrients that help bacteria develop. This is exacerbated by the relatively high temperature of greywater, which can encourage the growth of bacteria further. This is why the untreated greywater should never be stored for more than a few hours to avoid unpleasant odor development. The most significant risk from greywater is exposure to pathogenic micro-organisms derived from faecal contamination. However, the physical and chemical characteristics of greywater are also important as these can encourage the growth of bacteria, interfere with treatment or disrupt the operation of fittings that use water. For these reasons, the physical, chemical and biological water quality of greywater must be suitable for its intended use [EA, 2008].

The organic substances in greywater are measured by means of the biological oxygen demand (BOD) or chemical oxygen demand (COD) parameter. The content of the organic substances depends on the origin of the collected greywater. Table 8.1 gives an overview on the expected concentrations of untreated greywater from different sources. It can be seen that the greywater from showers and bathtubs are polluted. When greywater from washing machines is added, a considerably higher concentration of substances in the greywater is expected and as a consequence, a higher treatment expenditure. The additional use of kitchen wastewater (sink, dishwasher) will further increase the pollutants [fbr, 2005]. The values listed in table 8.1 may vary from region to region, based on the fresh water quality and its intended use.

Table 8.1: Composition of untreated greywater of different origins [fbr, 2005]

	Unit	**From bath tubs, showers & hand washbasins** [a]	**From bath tubs, showers hand washbasins & washing machines** [a]	**From bath tubs, showers hand washbasins, washing machines, & kitchens** [a]
COD	mg/l	150-400 (Φ 225)	250-430	400-700 (Φ 535)
BOD_5	mg/l	85-200 (Φ 111)	125-250	250-550 (Φ 360)
P_{total} [b]	mg/l	0.5-4 (Φ 1.5)	n/a	3-8 (Φ 5.4)
N_{total} [b]	mg/l	4-16 (Φ 10)	n/a	10-17 (Φ 13)
pH	-	7.5-8.2	n/a	6.9-8
Faecal coliform (*E. coli*)	1/ml	10^1-10^5	10^1-10^5	10^2-10^6
Total coliform	1/ml	10^1-10^5	10^2-10^6	10^2-10^6

[a] The values are based on experience from measurements from Nolde [1995] and Bullermann et al [2001]

8.1.3 Importance of Greywater Recycling

The main purpose of greywater recycling is to substitute the drinking water in applications which do not require drinking water quality. Non potable reuse applications include certain industrial, irrigation, toilet flushing and laundry washing. With greywater recycling, it is possible to reduce the amounts of freshwater consumption as well as wastewater production, in addition to reducing the water bills. Greywater has a relatively low nutrient and pathogenic content and therefore, it can be easily treated to high quality water using simple technologies. If greywater is regarded as an additional water source, an increased supply for irrigation water can be ensured which will in turn lead to an increase in agricultural productivity [fbr, 2009]. Unlike rainwater harvesting, greywater recycling is not dependent on season or variability of rainfall and as such is a continuous and a reliable water resource. This results in smaller storage facilities than those needed for rainwater harvesting.

Recycling greywater not only reduces the consumption of freshwater, it also reduces the volume of water discharged into the sewerage system. Consumers with water meters could therefore save money on both their water supply and wastewater bills. fbr [2009] summarizes the benefits of greywater recycling as below:

- Greywater recycling saves water and reduces the amounts of fresh, high quality drinking water by substituting the water demand not intended for drinking
- On site greywater treatment reduces the volume of wastewater that must be diverted to more costly sewage and septic treatments
- Greywater is a valuable resource for landscaping and plant growth especially in arid climates
- Greywater is rich in phosphorous, potassium and nitrogen, making it a good nutrient or fertilizer source for irrigation
- The use of greywater for irrigation reincorporates nutrients from the waste stream into the food chain, rather than contributing to surface and ground water pollution via sewers and septic systems
- Greywater diversion is particularly well suited for small scale and decentralized wastewater systems and can be implemented in either a rural or urban setting

However, there are also some drawbacks of greywater reuse as:

- The cost of installing and maintaining the greywater system
- Operation of greywater recycling systems require energy (e.g. for pumping, filtration, etc.). This will need an additional PV capacity to supply this energy.
- There exists the potential for pollution and adverse health effects as the greywater contains impurities and micro-organisms derived from personal cleaning activities

8.1.4 Greywater Recycling Technologies

The greywater treatment approaches range from simple, low cost devices that route greywater directly to applications such as toilet flushing and garden irrigation, to highly complex and costly advanced treatment processes incorporating sedimentation tanks, bioreactors, filters, pumps and disinfections units [CRD, 2004]. The choice of technology for greywater recycling depends on several factors, e.g. planned site, available space, user needs, investment and maintenance costs, etc. According to fbr [2009], an efficient and functional treatment scheme for greywater recycling comprises: primary treatment / buffering tank, secondary biological treatment, UV-disinfection, storage tank and booster pump. In the context of Germany, the greywater recycling methods, either proposed or in use, are summarized in figure 8.2. It was mentioned that the most efficient greywater treatment systems are biological in combination with physical treatment processes. Such systems have been successfully employed in the past more than two decades for greywater treatment and several such examples exist in Germany installed in one family households, hotels or multi-storey residential buildings [Nolde, 2005].

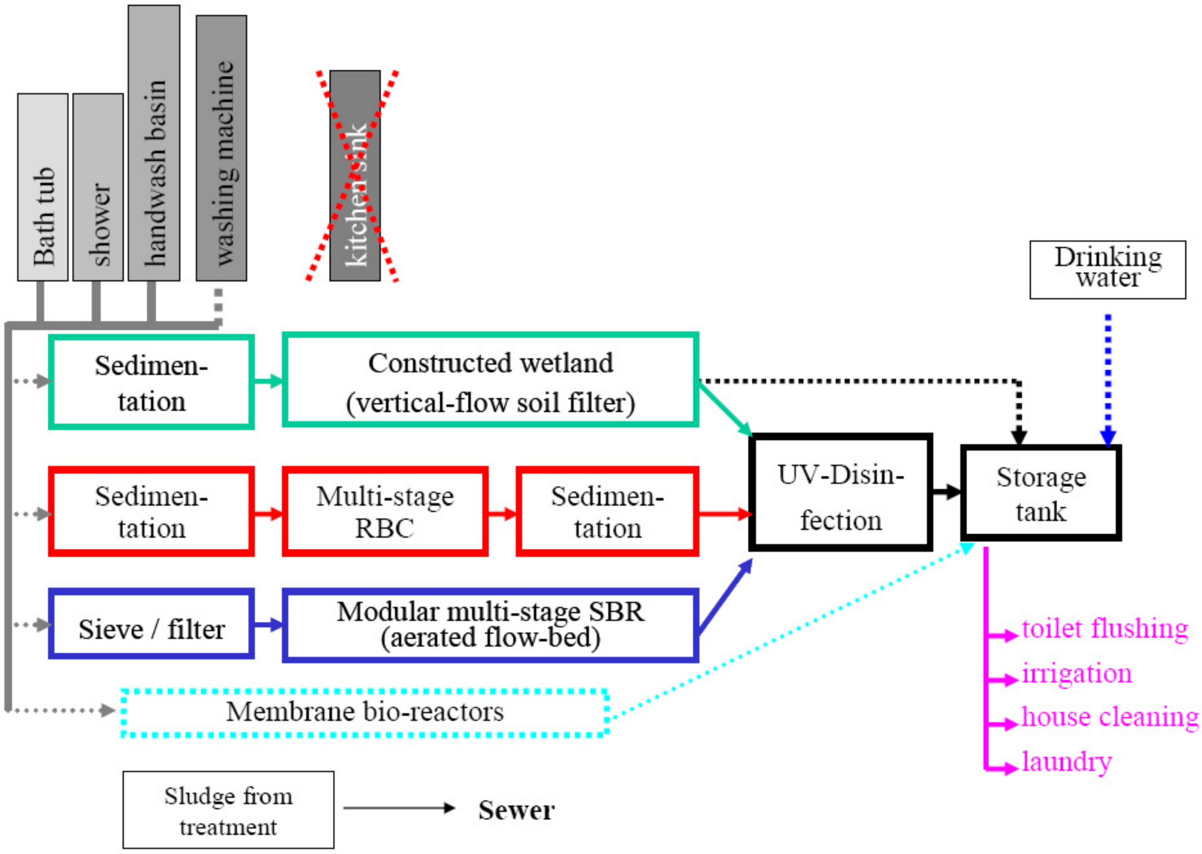


Figure 8.2: Greywater recycling alternatives in Germany [Nolde, 2005]

Basically, there are a number of greywater treatment systems commercially available in Germany and in other countries. Some of the treatment procedures are described below. Similar methods are also used for the wastewater treatment (except the diversion system).

i. Diversions Systems

The diversion system is probably the simplest method of greywater reuse. Diversion devices direct untreated greywater typically from bathroom sinks or laundry to a sub surface garden irrigation system. Sub surface drip irrigation systems minimize human contact with the greywater. When kitchen sinks are included in a diversion greywater system, a kitchen waste separating filter is needed to avoid clog in piping. The method is simple to use and it needs low investment and operation-maintenance costs. However, the reuse of the water is limited to sub surface irrigation because no treatment or disinfection is provided [CRD, 2004].

ii. Constructed Wetlands

Constructed wetlands have been used successfully for the treatment of wastewaters. Physical, chemical and biological processes combine in wetlands to remove contaminants from wastewater. Greywater treatment is achieved by soil filtration in reed-bed systems which reduce the organic load of the greywater considerably. Additionally, it decreases the concentrations of fecal bacteria. If properly designed, these systems would produce a clear and odorless effluent, which can be stored for several days without the need for disinfection. One disadvantage of such systems is the high evaporation rate from the reed-beds, especially in warm climates and the large area requirement. Compared to conventional treatment methods, constructed wetlands are simple to construct, inexpensive and environment friendly. They also provide food and habitat for wildlife and create pleasant landscapes [fbr, 2009].

iii. Rotating Biological Contactors (RBC)

Multi stage rotating biological contactors have been successfully employed for wastewater treatment. These are usually preceded by a primary sedimentation stage with a final clarification stage for organic load removal. The treated water has to be subjected for disinfection, e.g. UV disinfection that yields high quality water for non potable uses. RBC systems can be placed in the cellar as they have a low space requirement [fbr, 2009].

iv. Sequencing Batch Reactors (SBR)

The sequencing batch reactor is a variant of the activated sludge process except that it is operated (filled and emptied) discontinuously. There are four stages to treatment: filling, aeration, settling and decanting. It consists of a primary sedimentation tank, an aerated flow-bed reactor in which the bacterial biomass is mainly fixed on foam cubes or other carrier material, and a storage tank. Sequencing batch reactors for greywater treatment are available on the market in the modular design such that, single modules can be added variably dependent on the amounts of generated greywater to be treated [fbr, 2009].

v. Membrane Bioreactors (MBR)

The membrane bioreactor is a suspended growth activated sludge system that utilizes micro-porous membranes for solid/liquid separation. The system consists of a pre-treatment settling tank, an aerated settling tank which also stores the intermittently produced greywater and the aerated activated sludge tank. The generated sludge is held back by the submerged membrane filter module installed in the aeration tank. The purified greywater passes through the membrane under a pressure of 0.1-0.3 bars yielding a bacteria-free effluent. MBRs require less space than traditional activated sludge systems. There are four kinds of membrane systems in use ranging from lower to higher quality filtration: micro-filtration, ultra-filtration, nano-filtration and reverse osmosis [fbr, 2009]. The major disadvantages of these systems are high initial cost and high energy demand for their operation.

vi. Disinfection

Disinfection may be achieved using chlorine, ozone or ultraviolet light. The most common and simplest method of disinfection is chlorination, using sodium hypochlorite. Ozone is another means of chemical disinfection, typically generated onsite using a device that applies a high voltage potential to air, bubbling the ozonated air through the water. The disinfection using UV light is becoming popular as it requires no chemicals [CRD, 2004].

8.1.5 Greywater Reuse and Regulations

The properties of greywater reveal that it should be treated at a higher standard before reuse so as to avoid health risk and negative aesthetic and environmental effects. The major target of greywater reclamation and reuses is to reduce the suspended solids, the organic strength and the micro-organisms due to its relationship with the aesthetic and health characteristics of the product water and directly through legislative requirements [Li et al, 2009].

Hygiene requirements: In Germany, the treated greywater for use as a non potable water source should meet the requirements of the EU Guidelines for Bathing Water (76/160/EEC). These include total coliforms: < 100/ml and E. coli: < 10/ml among others. Physical and chemical parameters of significance include BOD_7: < 5 mg/l and O_2 Saturation: > 50%. UV disinfection is usually employed as the final treatment stage as a precautionary measure to protect human health.

Technical requirements: Treated greywater should not be a source of odor and nuisance to the user and it should be nearly free from color and suspended solids. It should be further guaranteed that no cross connections exist between the drinking water and treated greywater networks. A proper and clear designation of the network pipes with different colors and labels protects against unauthorized use.

Greywater from baths, showers, washbasins and washing machines has to be collected separately from blackwater, treated and eventually disinfected for reuse as a non potable water source. Garden irrigation is most commonly applied, whereby greywater can be diverted to the garden for immediate use. Treated greywater can be used for indoor purpose such as toilet flushing, laundry washing, car washing, industrial use and other purposes. The direct discharge of treated greywater into surface waters is also possible and it requires appropriate authorization. Generally, the regional regulations concerning the discharge of wastewater have to be followed. Process water from greywater recycling plants should be hygienically / microbiologically safe, colourless and almost free from suspended matter. According to Nolde [1999], greywater from recycling systems should fulfill four criteria: hygienic safety, aesthetics, environmental tolerance and technical and economical feasibility. However, there has been no uniformly enforceable international water reuse guideline to control the quality of the reclaimed wastewater. In many cases, the national water reuse guidelines vary from state to state [Li et al, 2009]. Different studies [Maeda et al, 1996; Nolde, 1999; Ernst et al, 2006; Asano, 2007] have proposed the following non potable greywater reuse guidelines (table 8.2). Such guidelines include parameters like fecal coliform, total coliforms, total suspended solids (TSS), turbidity, BOD_5, detergent, total nitrogen (TN) and total phosphorus (TP).

Table 8.2: The standards for non potable greywater reuses and applications

Categories	Treatments goals	Applications
Recreational impoundments, lakes	BOD_5: ≤10 mg/l TN: ≤1 mg/l TP: ≤0.05 mg/l Turbidity: ≤2 NTU pH: 6–9 Faecal coliform: ≤10/ml Total coliforms ≤100/ml	Ornamental fountains; recreational impoundments, lakes and ponds for swimming
	BOD5: ≤30 mg/l TN: ≤1 mg/l TP: ≤0.05 mg/l TSS: ≤30 mg/l pH: 6–9 Faecal coliforms ≤10/ml Total coliforms ≤100/ ml	Lakes and ponds for recreational without body contact
Urban reuses and agricultural irrigation	BOD5: ≤10 mg/l Turbidity: ≤2 NTU pH: 6–9 Faecal coliform: ≤10 / ml Total coliform ≤100/ ml Residual chlorine: ≤1 mg/l	Toilet flushing; laundry; air conditioning, process water; landscape irrigation; fire protection; construction; surface irrigation of food crops and vegetables (consumed uncooked) and street washing
	BOD5: ≤30 mg/l Detergent (anionic): ≤1 mg/l TSS: ≤30 mg/l pH: 6–9 Faecal coliforms ≤10/ml Total coliforms ≤100/ml Residual chlorine: ≤1 mg/l	Landscape irrigation, where public access is infrequent and controlled; subsurface irrigation of non-food crops and food crops and vegetables (consumed after processing)

8.1.6 Economics of Greywater Recycling

For conventional water supply and wastewater disposal, a large variety of technical facilities are required for water abstraction, treatment, storage and distribution as well as for wastewater collection, treatment and disposal. Consequently, there is a high share of investments (new construction, extension and renewal) in the total costs of utilities. Therefore, the share of fixed costs amounts approximately to 70-80 % [WVGW, 2008]. The volume dependent costs only exist to a small extent. They comprise electricity costs for pumping, costs of equipment for water treatment, etc.

Use of the greywater recycling plant at household can not replace the infrastructure of the utilities for water supply and wastewater disposal. It will only help to reduce the user's 'volume dependent' water costs by lowering the freshwater consumption and the wastewater generation. Such recycling plant needs an investment cost as well as some operating costs, e.g. for energy, etc., depending upon the type of the technology used for greywater recycling. If the greywater recycling plant is to be retrofitted in an existing house, there will be some extra piping costs. These costs could be avoided if the greywater recycling plant installation is considered in the planning phase before a house is built.

The ecological aspects of greywater use are not yet accounted for in conventional economical considerations. The effects of high drinking water consumption on water resources and wetlands, in addition to the effects of high amounts of discharged wastewater on water body load, have not been monetarily measured. For holistic assessment, these aspects must be taken into account. Currently, sufficient data is not available to carry out this overall consideration. Moreover, when comparing the costs of the conventional water supply and disposal systems with those of other water systems such as the use of greywater, subsidies delivered for the infrastructure of the conventional water supply and wastewater treatment systems are generally not taken into consideration [fbr, 2005]. However, the assessment of these indirect benefits is also out of scope of this study due to the unavailability of quantitative data. In the following section, a thorough economic feasibility of greywater recycling plants in Germany is carried out.

8.1.7 Cost Benefit Analysis

The model to calculate the present value of the total cost and the total imputed revenue of the 'greywater only' recycling plants is described here. This is similar to the one described in chapter 5-7 and it is also used for the calculations of autonomous household in section 8.6.2.

Total Costs

The investment and operating cost will be associated with the installation and operation of the greywater recycling plant at house. Investment cost includes the cost needed to buy and install the plant at home. These costs are dependent on the size of the plant and type of technology. For simplicity, this cost will be covered by a bank loan, thus the interest on loan has to be paid back. The additional costs for separate greywater and process water piping works have to be calculated according to the local conditions. The market price for a household size greywater recycling plant (MBR type) in Germany varies between 3000-4000 € [Sturm, 2009]. The operating costs include the costs for repair and maintenance, electricity, etc. These costs highly depend on the selected technology (e.g. for simply constructed plants, annually 1 % of the investment costs is sufficient and for high technology facilities, annually up to 4 % of the investment cost is required [fbr, 2005]). The equation to calculate the present value of total cost is given by:

$$C_t = C_i\left[\left\{\sum_{n=1}^{n=N}\frac{1+i(N-n+1)}{N(1+d)^n}\right\}+\left\{k_v\sum_{n=1}^{n=N}\frac{1}{(1+d)^n}\right\}\right] \qquad [8.1]$$

where,

C_t	is the present value of total cost [€$_{2007}$]
C_i	is the initial investment cost for greywater recycling plant [€$_{2007}$]
N	is the recycling plant life time [year]
d	is the discounting rate [%]
i	is the interest rate [%]
k_v	is the variable cost factor (% of initial investment)

Total Revenue

There is no direct revenue from the recycled greywater at home, but its use will minimize the freshwater and wastewater bills that would have to be paid to the utilities. This avoided amount of the bill has been considered as revenue in this study. It depends on the quantity of freshwater saving, the utility charge for freshwater use and wastewater disposal, etc. In the cases where the water saving as well as freshwater and wastewater charges are high, the installation of greywater plant might be economically feasible. The equation to calculate the present value of total revenue is given by:

$$R_t = V_w\left(P_w + P_{ww}\right)\sum_{n=1}^{n=N}\frac{\left(1+\left(r_{fw}+r_{ww}\right)\right)^{n-1}}{\left(1+d\right)^n} \qquad [8.2]$$

where,

R_t	is the present value of total revenue [€$_{2007}$]
V_w	is the volume of recycled greywater [m^3/yr]
P_w	is the freshwater price [€$_{2007}$/m^3]
P_{ww}	is the wastewater disposal charge [€$_{2007}$/m^3]
r_{fw}	is the annual freshwater price growth rate [%]
r_{ww}	is the annual wastewater charge growth rate [%]

The average per capita water consumption in Germany has declined by approximately 15 % since the early 1990s, and currently it amounts to about 125 liters per day. In 2007, the average price for drinking water was 1.85 €$_{2007}$/m^3. However, those values differ between different states and regions within Germany. In 2007, drinking water prices have remained almost stable; they increased only about by 0.5 % on an average. Since 1995, the per capita burden for the drinking water price had increased only by 7.7 %. The World Bank considers it problematic if citizens have to spend more than 4 % of their available income for water services. In Germany, this value is considerably lower. In 2007, the wastewater charges increased by 1.4 % as compared to the preceding year [WVGW, 2008].

Using the equations 8.1 and 8.2, the total cost and the total revenue of the greywater recycling plant has been calculated and the results are discussed in section 8.1.8.

8.1.8 Results

Two different cases are considered: (i) only the light greywater (40 %) from shower and washbasins will be recycled (excluding from kitchen, cleaning and washing machine); and (ii) all the process water demand at house (48 %) will be supplied with recycled greywater.

Case 1

Under this case, a four member household will save the annual water consumption of about 73 m^3 (40 % of per capita daily water consumption of 125 liters). Rest 60 % of the household water demand will be covered by freshwater. The default values for different parameters used in the calculation of cost benefit analysis are given in table 8.3.

Table 8.3: Default value – case 1

Description	Value
Price for greywater recycling plant (including installation), C_i (€$_{2007}$)	4000
Plant life time, N (years)	25
Operating costs, k_v (%)	4
Interest rate, i (%)	6
Discounting rate, d (%)	4
Base year freshwater price, P_w (€$_{2007}$/m^3)	1.8
Base year wastewater disposal charge, P_{ww} (€$_{2007}$/m^3)	2.2
Annual growth rate for freshwater price, r_{fw} (%)	1
Annual growth rate for wastewater charge, r_{ww} (%)	1

Benefit of the system has been calculated by subtracting net present value of total cost from net present value of total revenue, and the calculated values are given in table 8.4.

Table 8.4: CBA results – case 1

Description	Value
Total cost, C_t (€$_{2007}$)	7250
Total revenue, R_t (€$_{2007}$)	5615
Benefit (loss), B (€$_{2007}$)	-1635

The result of the cost benefit analysis implies that the system is not economically feasible under the aforementioned circumstances. The breakeven values for different parameters, which would have been necessary to make the recycling plant at breakeven, have been calculated ($B = R_t\text{-}C_t = 0$) and they are presented in the figure 8.3.

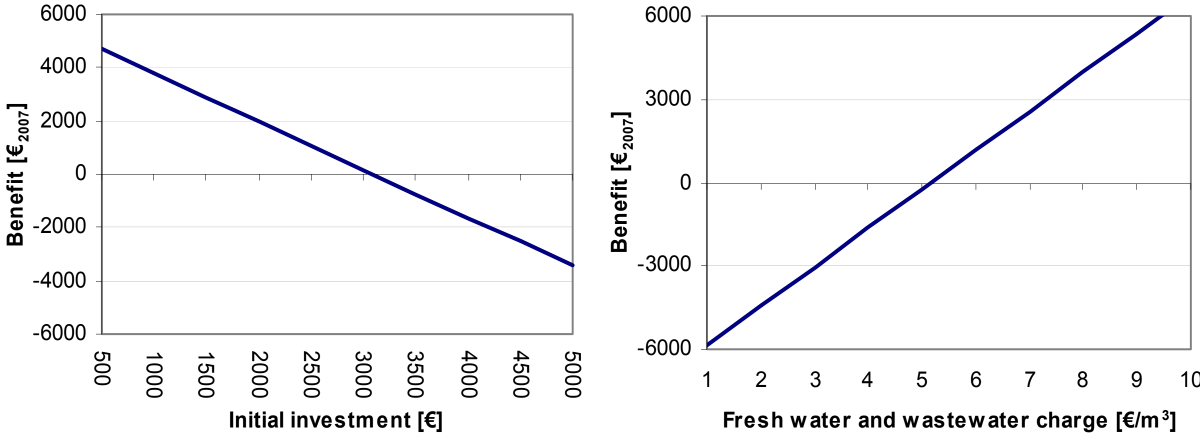


Figure 8.3: Breakeven values of different parameters – case 1

As shown in figure 8.3, the greywater recycling system would have been at breakeven, if the system cost was as low as around 3000 € or the combined freshwater and wastewater charges were as high as about 5 €/m^3.

Case 2

Under this case, a four member household will save the annual water consumption of about 87 m^3 (48 % of per capita daily water consumption of 125 liters). All the process water need at house will be covered by greywater and the rest 52 % of the household water demand will be covered by freshwater. The default values for different parameters used in the calculation of cost benefit analysis are used as given in table 8.3, except for the operating expenses. The operating expense depends on the amount of recycled greywater and this is why it has been increased proportionally (19.2 %) with the amount of increased volume of greywater compared to in case 1. The investment cost has been assumed the same, because the systems available in market for one family house are generally with the storage capacity of 300 liters.

The result of cost benefit analysis shows that the project will still cause losses of 558 € (corresponding net present values of cost and revenue to be 7250 € and 6692 €, respectively). Compared to case 1, the loss from the system is less because of the relatively higher revenue due to the bigger volume of water saving. The breakeven analysis has also been carried out to identify the necessary greywater recycling investment cost or the combined freshwater and wastewater prices. The results are shown in figure 8.4.

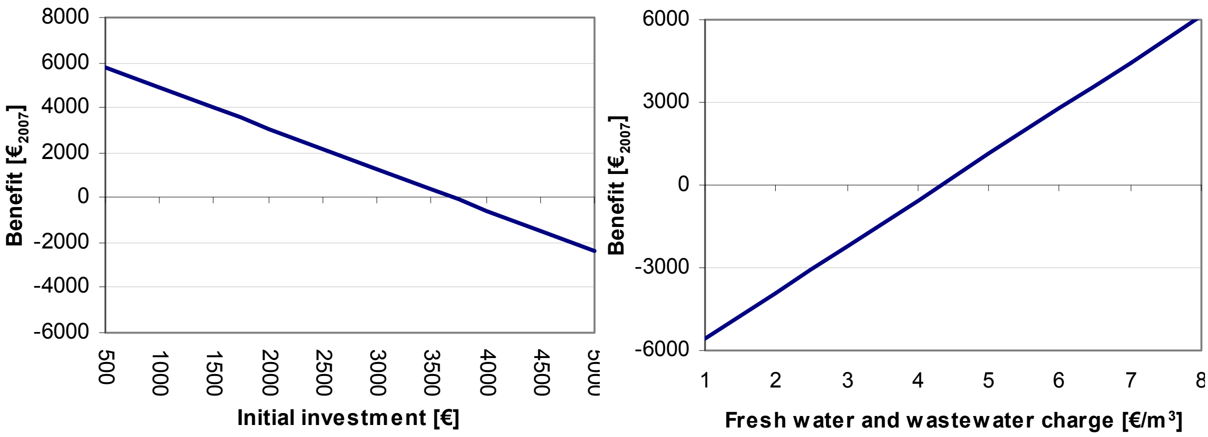


Figure 8.4: Breakeven values of different parameters – case 2

The results confirm that using the greywater recycling plant at a single family house is not economic. In equation 8.2, the revenue is directly proportional to the volume of recycled water. This is why, more the people connected in the system, the more water will be recycled and thereby more revenue will be generated. The fixed costs will remain the same, only the operating costs will vary, but the share of operating costs in total cost is very less. Therefore, it might be economic if the bigger scale recycling plant is installed e.g. at hotels or multi-storey buildings. In this case, the volume of water will be big and thereby the savings related to the avoided bills of water and wastewater would be of large amount, but the system size and its cost would not increase proportionally. One of the reasons for the smaller system size is that there will be more cycles of greywater generation and its reuse when many people are involved in the systems. In contrast, in a single family house, the greywater generation will be in the morning and evening, and the water process water demand will also be in these hours. The plant will be idle for whole day.

8.1.9 Energy Use by Greywater Recycling Plants

The energy consumption in the greywater recycling depends mainly on two factors – the type of technology used for recycling and the intended use of recycled water (quality standard required). However, it will be very much techno-dependent. For example, the membrane filtration and reverse osmosis processes will need much more energy than simple chlorine disinfection. In general, the higher the standard of water quality requirement, the more energy intensive the process is. By looking only from the energy consumption perspective, EA [2008] mentioned that using bath-water (cooled) to irrigate the garden in place of freshwater will save more energy. But using a biomechanical system to treat greywater will generally use more energy than if freshwater was used instead. The literatures discuss about the energy consumption in greywater treatment systems with a high degree of difference.

Bullermann et al [2001] mentioned that the energy need in mechanical membrane filtration process is around 1.5-2.5 kWh/m^3 and in biological aeration process is around 2.5-5.0 kWh/m^3. Nolde [2007] stated the energy consumption value for rotating biological contactors method to be less than 2 kWh/m^3 and for closed sequencing batch reactors to be around 1.5 kWh/m^3. EA [2008] estimated the value for biological pre treatment through aeration and then membrane filtration process to be around 3.5 kWh/m^3. Sellner [2009] mentioned the value for membrane bioreactor process is around 2.6-3.67 kWh/m^3, depending upon the plant size. Friedler and Hadiri [2006] mentioned it for membrane bioreactor process to be around 1-1.5 kWh/m^3. Berlin Senate Department for Urban Development [2007] stated that the energy requirement for greywater treatment including service water distribution should not exceed 2 kWh/m^3 and for rainwater harvesting systems undergoing no treatment, the energy demand should lie below 1 kWh/m^3.

It is difficult to come with a single and exact value after reviewing these different values. However, an average value of 3 kWh/m^3 has been chosen for membrane bioreactor treatment process and it is used in the further calculations. A calculation has been made to determine the PV system size needed at household in order to supply the electricity demand of such plants. The methodology used in the calculation is the same as used in chapter 5 (for grid connected systems) and chapter 6 (for stand alone systems). The results obtained are given in table 8.6.

Table 8.5: PV system size for energy supply to greywater recycling plant

		Case 1 (219 kWh/yr)	**Case 2 (261 kWh/yr)**
Grid connected PV system	kW_p	0.24	0.28
Stand alone PV system	kW_p	1.15	1.37
Battery for stand alone system	kWh	3.67	4.38

For the systems installed in 2009 in Germany, the PV electricity generation costs were calculated to be about 0.29 €/kWh and 1.71 €/kWh for grid connected and stand alone systems, respectively (chapters 5-6). The solar PV systems are not yet market competitive, and it would also not be economical to supply the electricity demand for the operation of greywater recycling plant from solar PV. It will further increase the overall losses.

8.2 Water Network Access Costs

By using the greywater recycling plant, the costs related with the water network connection to the house are not avoided because the use of greywater recycling plant is supposed to be at the existing house in urban areas. In this case, the house still needs the network access for freshwater supply and wastewater disposal. These costs could be very high if the house is far from the existing municipal water network. If the household switches to an autonomous water supply and treatment system, the initial water network access costs could be avoided. Such expense could be considered as revenue (at a distance of up to10 meters, the initial water network access cost in Cologne, Germany is 2280 € and there is an extra cost of 95 €/m for an additional distance [Rheinenergie, 2008]). Similar to the case of electricity grids mentioned in chapter 6, the costs for the water network infrastructure connection to the house have to be paid by the house owner after a house is newly built. For the city of Cologne, the water network access costs are shown in figure 8.5.

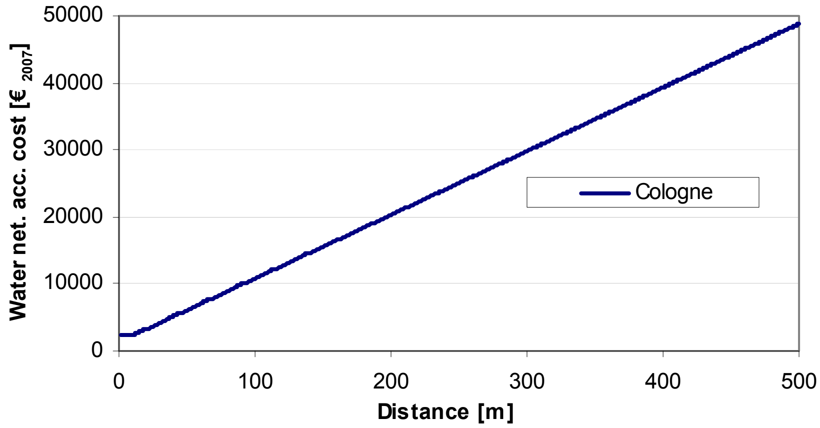


Figure 8.5: Costs for water network access to the new house in Cologne

As shown in figure 8.5, such costs might reach up to 48830 €, if a house is at a distance of 500 meters. In the following section of this study, water network costs avoidance option has been analyzed by introducing the concept of rainwater harvesting for drinking water supply, greywater recycling for process water supply, and the wastewater treatment at house using a wastewater recycling plant. If many of the households plan to go for autonomous supply, probably the unit water use and wastewater disposal costs of the utilities might grow very high, because the infrastructure is still needed and it should be financed further. Therefore, it might need some legal arrangements to support the concept of aforementioned water autonomous households. However, these drawbacks have not been considered in this study.

8.3 Rainwater Harvesting

Rainwater harvesting is an ancient technique. This has gained significant space in the modern water saving sanitary techniques so as to reduce the consumption of drinking water. It can be also applied for private and public buildings as well as for industrial areas. Such system collects water from a roof piped to a storage tank where it is then used either inside or outside the building. Designs range from a simple rain barrel at the bottom of a downspout for watering a garden to extensive cistern systems that can provide a substantial amount of the water for household use. New filtration and treatment technologies facilitate the application of rainwater harvesting. Rainwater harvesting systems can be installed in existing buildings or incorporated into new constructions.

A basic rainwater collection system includes a roof, gutters or roof drains, and a piping system to convey the water to and from a storage tank or cistern. Basements can be good locations for storage tanks as the water will be gravity fed and protected from freezing. In some instances a separate structure could be used to enclose the tank and equipment, which will increase the roof surface catchments area. Many rainwater collection systems as well as individual components are commercially available [DCBS, 2009].

8.3.1 Rainfall in Cologne and Rainwater Storage Tank

The basic rule for sizing any rainwater harvesting system is that the volume of water that can be captured and stored (the supply) must equal or exceed the volume of water used (the demand). One method of determining the feasibility of a proposed system is the monthly water balance method. The monthly anticipated rainfall is converted into a monthly rainwater harvest volume, and the monthly household demand is subtracted from it. If the rainwater harvesting system is intended to be the sole water supply source for a household, the catchments area and storage capacity must be sized so as to meet the water demand through the longest expected interval without rain in order to ensure a year-round water supply. Otherwise, an alternative water supply system has to be planned.

In Germany, the average annual precipitation varies from place to place e.g. from 521 mm/yr in Magdeburg to 1275 mm/yr in Kempten, being about 708 mm/yr in Cologne [WWCG, 2009]. The monthly average rainfall in Cologne has been shown in figure 8.6.

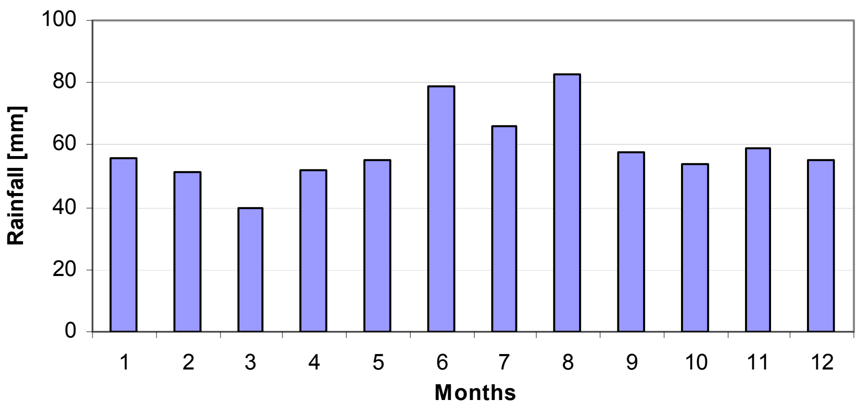


Figure 8.6: Rainfall in Cologne

Using the average monthly rainfall data, the potential volume of the average monthly rainwater collection, V_r (in m^3/month), is given by:

$$V_r = A_c \; M \; \eta_c \; \eta_r \qquad [8.3]$$

where,

A_c is catchment area [m^2]

M is average rainfall [m]

η_c is collection efficiency [%]

η_r is efficiency of rainwater treatment systems [%]

For a single family house, the catchments area (of the roof) has been assumed to be 100 m^2. The collection efficiency is dependent on the type of roof. For common brick-tile roof, it is taken as 80 %. The rainwater treatment system efficiency is considered as about 95 %.

Monthly water demand in a four person household and the potential rainwater harvest is given in the figure 8.7. Likewise, monthly average volume of water demand has been calculated by dividing the annual average by 12 (the different number of days in different months has not been taken into account). Monthly rainwater harvest is calculated using the equation 8.3. It can be seen in figure 8.7 that the rainwater is not enough to supply the water demand in all the months. This means that there is a need for a complementary water supply source.

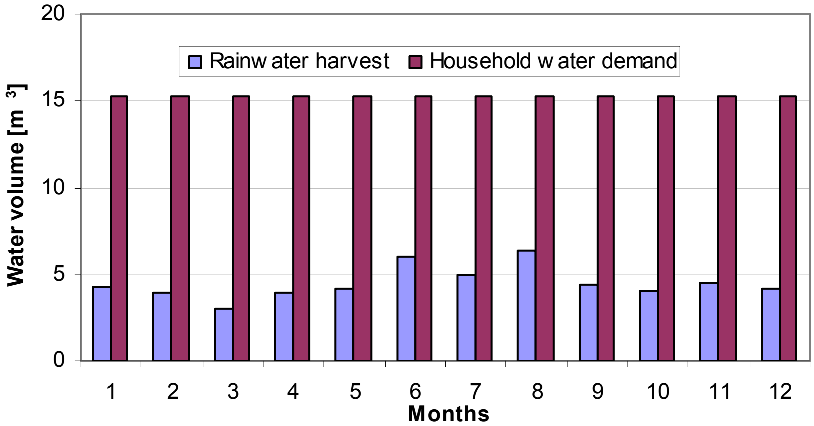


Figure 8.7: Monthly water demand and rainwater harvesting

A rainwater storage system is needed at the household because the rainfall will not be evenly distributed every day in the year. In this study, the rainwater storage tank size has been calculated in such a way that the half of the potential monthly harvest volume in the rainiest month (i.e. August) could be stored in the tank. The storage tank size (T_s) in m^3 is given by:

$$T_s = 0.5\, V_r \qquad [8.3]$$

Thus calculated storage tank size is around 3.2 m^3. The harvested rainwater will be treated before it is supplied as drinking water using the treatment and disinfection processes already discussed in section 8.1.4.

As shown in the figure 8.1, freshwater demand of a house is around 52 % of total water demand, but the harvested rainwater can cover only around 29 % of the demand (figure 8.7). Therefore, the rest of the freshwater demand (around 23 %) of the water should be supplied by other alternative means. For this purpose, a groundwater extraction system has been chosen in this study and it is discussed in section 8.4.

Economics of Rainwater Harvesting

The costs associated with the rainwater harvesting system include the investment costs (e.g. for storage tank and its installation, piping system, pumping system, a treatment and/or disinfection system, etc.), the repair maintenance costs (e.g. replacement of filters, etc.) and the variable costs (e.g. chemicals for disinfection, energy for pumps operation, etc.). There is no direct revenue from the rainwater harvesting systems, but the avoided water bill is considered as the revenue. Detail of the calculations is given in section 8.6.2.

8.4 Groundwater Extraction

Groundwater is derived principally from surface water (sources include rainfall, waterways, irrigation and water storages) that infiltrates through the soil until it reaches the water table. The water table is the level below which all the spaces between soil/rock materials are saturated with water. Groundwater is also found in layers of porous rock called aquifers. Groundwater is an important part of the water cycle and is fundamentally linked to surface water. When groundwater is discharged into springs, wetlands, rivers and other waterways it is once again considered surface water. The physical properties of groundwater can vary greatly, particularly the dissolved mineral concentrations. Groundwater is usually extracted via bores either by pumping or under natural pressure.

In general, it is not necessary to have an extracted water storage system because the water can be pumped from the ground at the time of its use. The fixed costs will include the boring of the ground and installment of the water extraction pipelines and the pumps. Operating costs will include the energy costs for the operation of extraction pump and pressurizing pump (if applicable), the repair maintenance costs and water treatment costs, if necessary. The avoided utility bill is considered as the revenue. Detail of the calculations is given in section 8.6.2.

8.5 Wastewater Treatment

When a house is water autonomous, the wastewater generated should be treated at home. For this purpose, a wastewater treatment system is supposed to be installed. There are different types of wastewater treatment systems available in the market. In principle, they are similar to the greywater recycling systems (section 8.1.4). Under the assumptions of this study, a sequencing batch reactor or the rotating biological contactors type will be used for the wastewater treatment. Since the blackwater will not be reused, disinfection is not necessary. The treated wastewater can be disposed in two ways. If there is a nearby river, it can be directly drained to the river. If it is not the case, the water should be sent into the ground through ground infiltration process. Depending upon the geology of the soil, simple shallow type or more complex well type ground infiltration systems can be used. The former is obviously the cheaper option. This study considers the ground infiltration option of the treated wastewater. Amount of water to be treated will be the total amount of water consumed at home minus the recycled greywater (i.e. 100 - 48 = 52 %). The amount of recycled greywater used for the irrigation (5 %) could also be decreased and the final amount of water to be treated will be about 47 % of household water consumption, i.e. equal to a daily amount of 235 liters in a four person household.

The costs incurred in these systems are the initial wastewater treatment system installation costs and its operating costs, which include energy costs, repair maintenance costs, etc. Additionally, the sludge from the wastewater treatment plant should be removed periodically (twice per year in average), depending upon the size of the plant, type of the treatment technology, etc. Detail of the cost and revenue calculations is given in section 8.6.2.

8.6 Results

8.6.1 Water Balance in a Water Autonomous House

The overall water balance of a four member household with an average annual water consumption of 182.5 m^3 will be as shown in the figure 8.8.

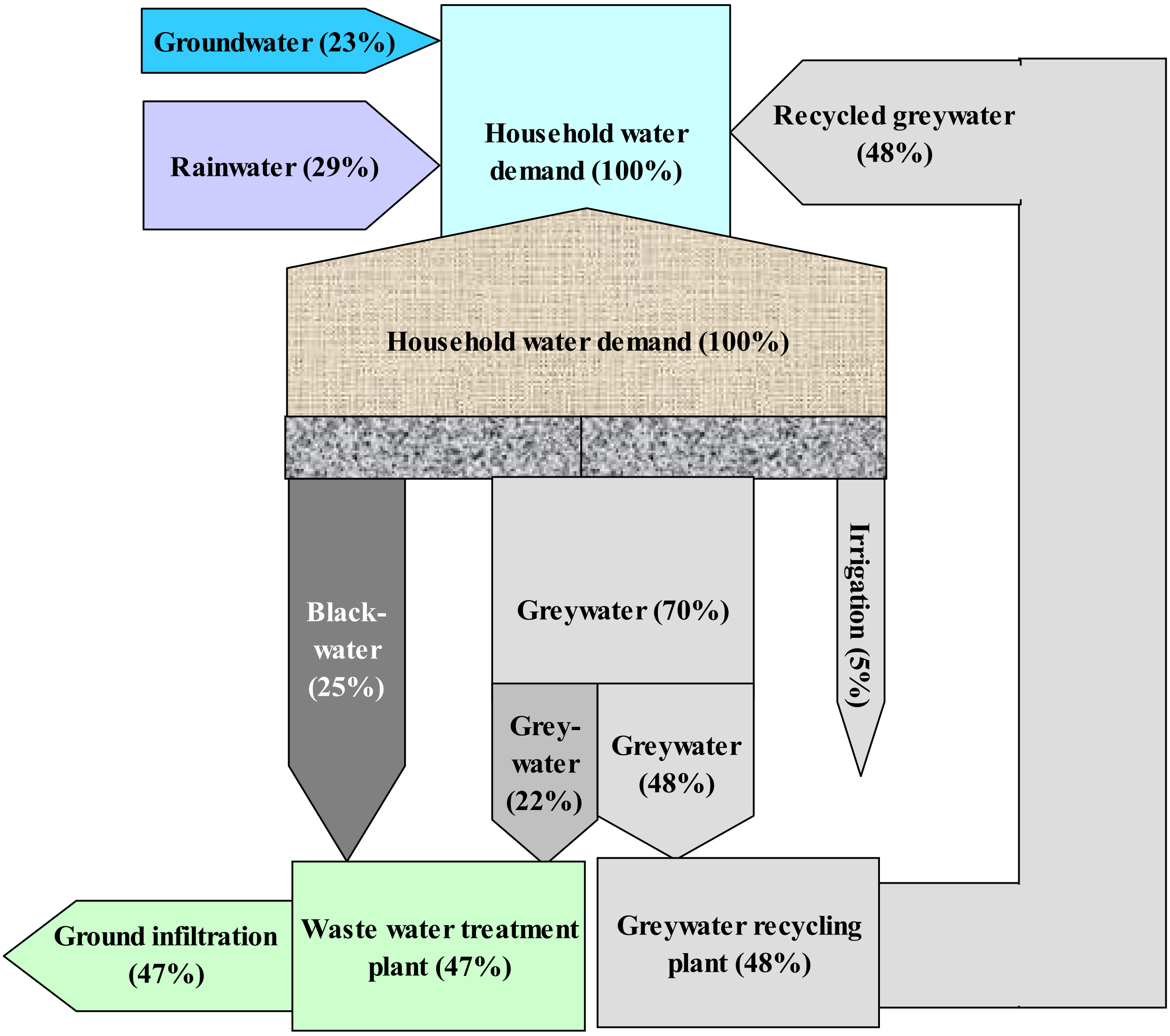


Figure 8.8: Autonomous household water flow

8.6.2 Economics of Water Autonomous House

Cost Calculation

The total costs of the water systems in a water autonomous house will be the sum of the costs of greywater recycling, rainwater harvesting, groundwater extraction and wastewater treatment and disposal. All these four components will require some investment costs for the installation of respective plants at house and some operating costs. The initial investment cost would be covered with a bank loan and the variable costs would be covered with the savings from avoided water use and disposal bills. The total costs associated have been calculated using the equation 8.1. The individual system costs and economic parameters used in the calculation have been shown in table 8.6.

Table 8.6: Individual water handling system in detail and their costs

Description	**Greywater**	**Rainwater**	**Groundwater**	**Wastewater**
System capacity	240 l/day treatment (88 m^3/yr)	3200 l - tank 145 l/day treatment (54 m^3/yr)	115 l/day extraction/ treatment (41 m^3/yr)	235 l/day treatment/ disposal (86 m^3/yr)
Water treatment system	MBR	Filtration, chlorine/ UV disinfection	Chlorine / UV disinfection	SBR or RBC, ground infiltration
Initial investment cost (including installation [a])	4000 €	5000 €	6000 €	12000 €
System life time [b]	25 years	25 years	25 years	25 years
Annual operation costs (% of initial investment cost)	4 %	3 %	2 %	3 %
Energy demand (kWh/m^3)	3	1	1	1
Present value [c] of individual system cost (€/hh)	7250	8281	9000	19875
Cost for individual system water processing (€/m^3)	3.31	6.26	8.58	9.27

[a] based on personal communication with Sturm [2009]

[b] Some components need to be replaced in the certain intervals (as per manufacturer's guide). The replacement cost is supposed to be covered by the annual operation costs.

[c] The present value of the cost is calculated by considering initial investment as well as operating costs throughout the system life time using equation 8.1. System life time of 25 years does not apply to all system components, e.g. pumps, membrane, etc.

SBR: Sequencing Batch Reactor, MBR: Membrane Bio-reactor, RBC: Rotating Biological Contactor, UV: Ultraviolet

Thus the present value of the water associated costs in an autonomous water household has been calculated to be around 44406 € (i.e. 9.73 €/$m^3$of water usage). The share of different water system cost is shown graphically in the figure 8.9.

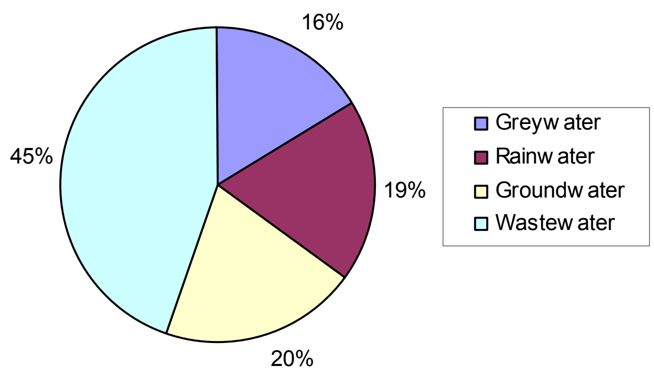


Figure 8.9: Shares of different water handling system cost

The cubic meter water handling costs for individual systems would have been less, if the systems were operated in their full scale. For example, in the case of ground water extraction, most of the costs are fixed costs, and operating costs will be basically only the energy costs. Therefore, if the system is operated whole day, the unit water handling costs would have been significantly less.

Revenue Calculation

The revenue from the system will include avoided water bill as well as water network access costs. The present value of the avoided water bill (in €) has been calculated using the equation 8.2. Likewise, equation 6.14 has been used to calculate present value of avoided water network costs. The avoided water network cost has been considered only for 25 years, equal to the water system life time. For an annual water consumption of 182.5 m^3, combined water and wastewater charge of 4 $€_{2007}/m^3$ (with a combined annual growth rate of 2 %), discounting rate of 4 % and the initial water network access costs of 2280 $€_{2007}$/hh, the present value (for base year 2009) of the total revenue has been calculated to be 16460 $€_{2007}$/hh.

Cost Benefit Analysis

The benefit of the water supply system has been calculated by subtracting the total cost from the total revenue. As shown in figure 8.10, the system will cause losses if it is implemented.

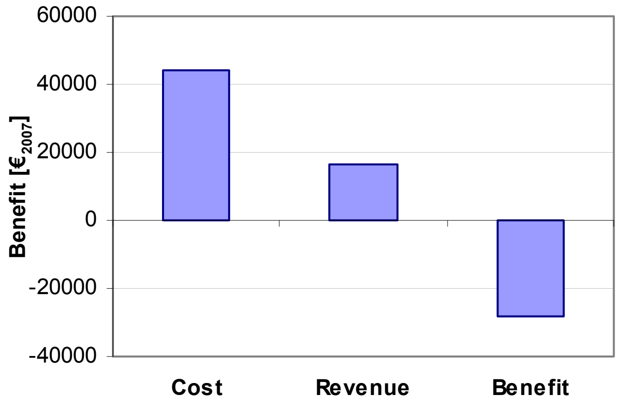


Figure 8.10: Cost benefit analysis – autonomous water house

If the house is far from the available water network, the total revenue will swell (due to additional avoided expenses for water network access). The cost benefit analysis for the grid access costs more than 10 m has been calculated and the breakeven distance has been found to be around 287 m as shown in figure 8.11. In the calculation, water only grid access cost has been considered.

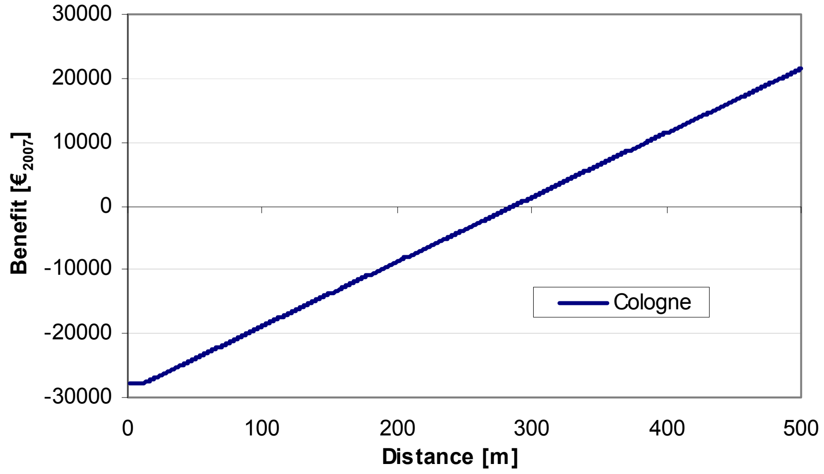


Figure 8.11: Benefit with increased grid access distance

When the avoided grid access cost is considered for a house, it should be analysed carefully to avoid duplication while calculating costs in energy autonomous section and water autonomous section. For example for the city of Cologne, the energy only costs is 1180 € (additional costs for a distance more than 10 m is 65 €/m), water only cost is 2280 € (additional costs for a distance more than 10 m is 95 €/m), but if the both of the installations are made at once, the total cost will be only 2760 € (additional costs for a distance more than 10 m is 105 €/m).

In principle, with the assumption that the freshwater and wastewater disposal prices charged by the utilities will increase in the coming years, and a water network parity point might occur in the future. This is shown in figure 8.12.

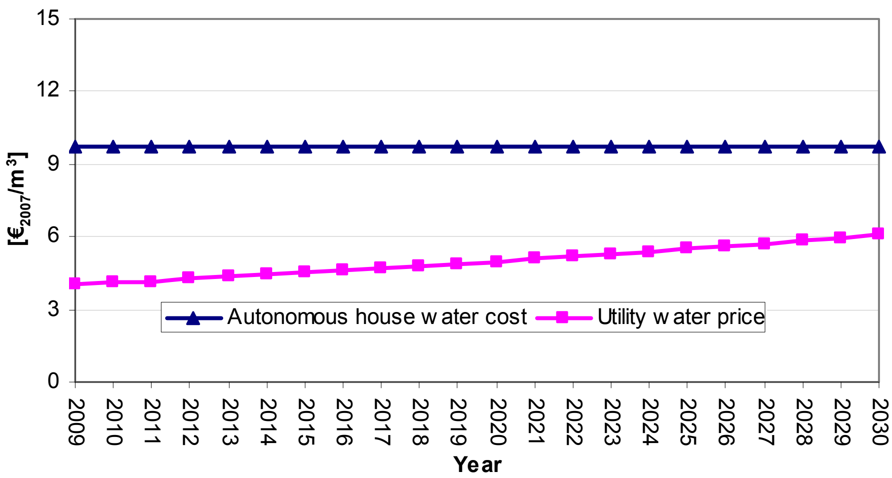


Figure 8.12: Water network parity

As shown in figure 8.12, an autonomous water household in the cities like Cologne can not be expected to be competitive with the utility water supply and disposal systems in the coming decades (before 2055).

The total costs for autonomous water household might also decrease caused by the maturity in the technology. However, in this study, the decrease in total costs for water autonomous house has not been calculated because there are no extensive literatures available in the experience curve analysis for the autonomous water household technologies. Also, water treatment and the pumping technologies have been well developed and it is unlikely that there will be significant price reduction with increase in the production volume. This is why the total costs for autonomous water house looks like a straight line in the figure 8.12.

8.6.3 Economics of Electricity and Water Autonomous House

In view of energy and the water autonomous household (combination of chapters 6 and 8), the economic analysis has also been carried out. The electricity demand will be supplied with solar PV system and the total system costs calculated in chapter 6 was around 149584 $€_{2007}$/hh. If the grid electricity is avoided, then the water supply and treatment system energy demand has also to be supplied by solar PV, and in this case, an additional electricity demand of around 443 kWh/yr has to be added (leading to an average annual energy consumption of 3943 kWh/yr). This corresponds to an additional stand alone PV system's module size of 2.3 kW_p and battery size of 7.4 kWh. And, the present value of total costs for PV system will be around 18933 $€_{2007}$/hh. The total water related costs are calculated in section 8.6.2 to be around 44406 $€_{2007}$/hh. The total revenue in this case will be the avoided electricity-water bill and the combined avoided grid infrastructure access costs. The calculated cost benefit analysis results are shown in figure 8.13.

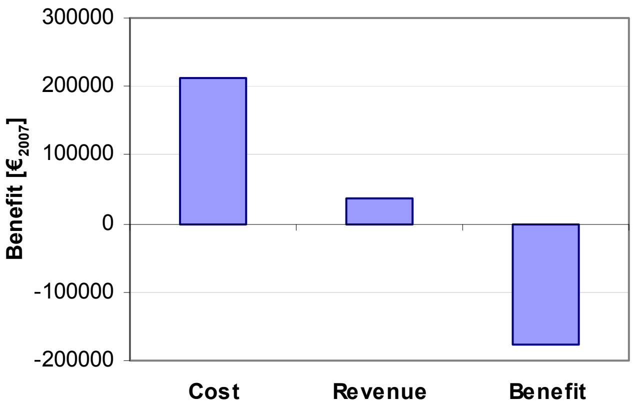


Figure 8.13: Combined water and energy autonomous house

While talking about water autonomous household, it is also important to consult the legal requirements. In some cases, the authorities might not give the permission to build a house in a site which is far from existing infrastructures. In other cases, households might not be allowed to treat their wastewater at home premises or they might not be allowed to use rainwater as drinking water. Such legal aspects might differ from site to site and country to country, being tougher rules in developed countries. Survey of legal requirements and its consideration in the analysis was out of scope of this study.

The total imputed revenue will soar with an increment in electricity grid and water network access distance. The benefit results with the increasing distance are shown in figure 8.14. The calculation implies that the autonomous household would have been economically feasible if the infrastructure access distance was more than around 1.58 km.

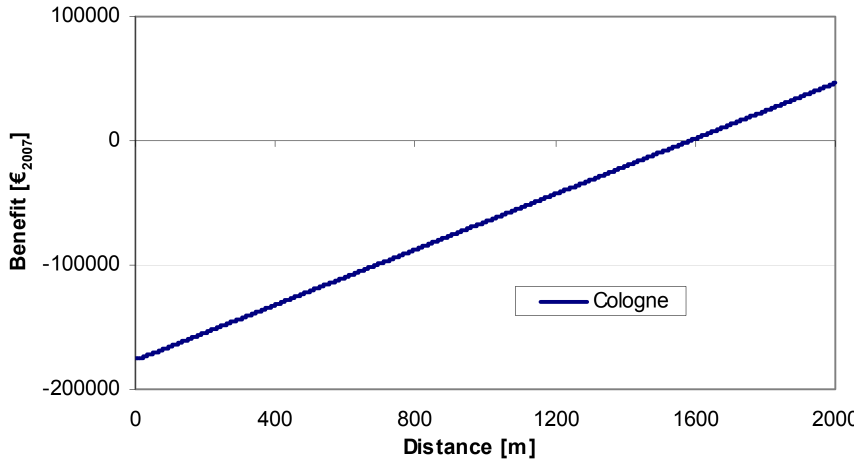


Figure 8.14: Benefit of autonomous water and energy house

The breakeven values over the coming years for combined electricity grid and water network access distance have been shown in figure 8.15.

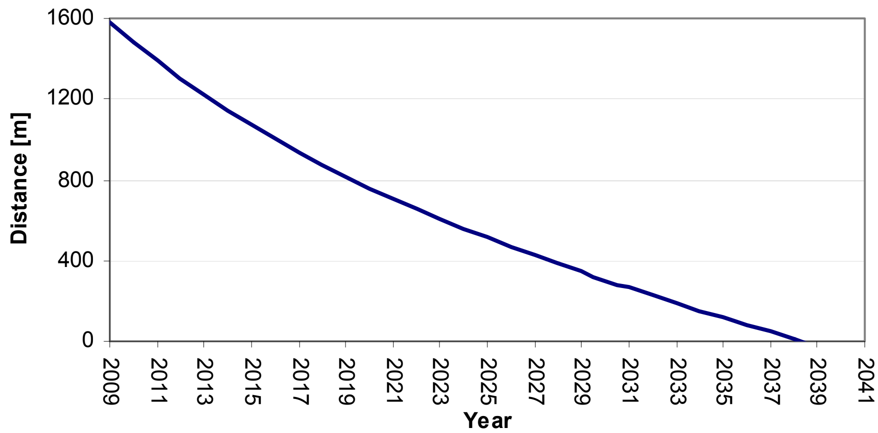


Figure 8.15: Breakeven grid access distance for combined case

The combined electricity grid and water network parity year has been shown in the figure 8.16. In the coming years, the total cost will decrease caused by the learning effect in solar PV systems. On the other hand, the combined water and energy charge are supposed to increase at the annual growth rate of 2 % and 4 %, respectively.

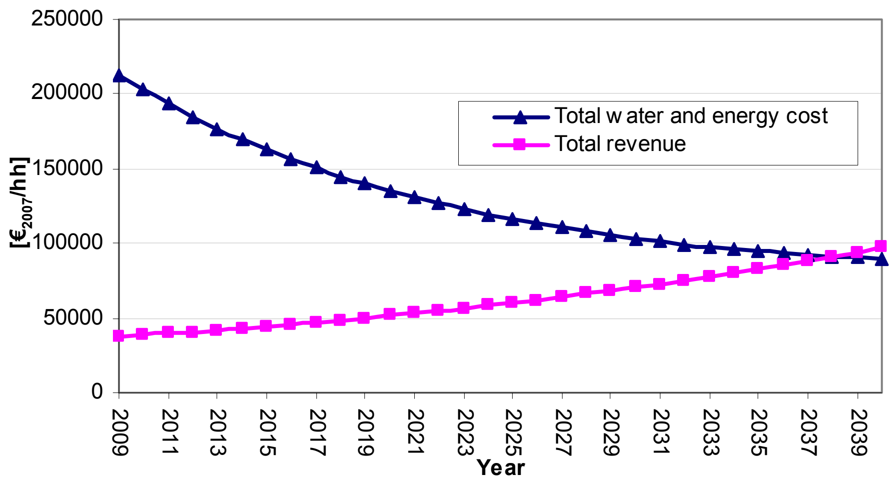


Figure 8.16: Electricity and water parity

The electricity grid cum water network parity year has been found to occur in around 2038. The parity year for the solar PV calculated in section 6.8.3 had been in around 2034. The later shifting of the parity year has been caused by the later occurrence of water network parity.

8.7 Concluding Remarks

An autonomous water management concept at household could ensure the sufficient quantity and quality of water and reduce pressure for the environment. This could be a sustainable approach, especially if the energy required for operating the autonomous water supply system is supplied through renewable energies, e.g. solar photovoltaic systems.

Average daily per capita water consumption by household consumer in Germany is about 125 liters. The greywater generation reaches up to 70 % of the total water consumption. Moreover, about 48 % of the household water demand could be substituted with the process water, i.e. the recycling of the partial volume of the greywater generated at home could save up to 48 % of the total water consumption. Recycling greywater not only reduces the consumption of freshwater, it also reduces the volume of water discharged into the sewerage system. Therefore, consumers could save money on both water supply and wastewater bills. Unlike rainwater harvesting, greywater recycling is not dependent on season or variability of rainfall and as such is a continuous and a reliable water resource. This results in smaller storage facilities than those needed for rainwater harvesting.

The greywater treatment approaches range from simple, low cost devices that route greywater directly to applications such as toilet flushing and garden irrigation, to highly complex and costly advanced treatment processes incorporating sedimentation tanks, bioreactors, filters, pumps and disinfections units. The cost benefit analysis shows that the household size greywater recycling systems are not economically feasible in Germany. A solar PV system size of about 1.15-1.37 kW_p (220-260 kWh/yr) would need in order to supply the energy needed to operate the greywater recycling plant.

The use of the greywater recycling plant at household can not replace the infrastructure of the utilities for water supply and wastewater disposal. However, use of autonomous water supply concept will make it possible to avoid the water network connection work and associated costs. The water balance in a four member autonomous house in Cologne has been calculated as follows: recycled greywater supply: 48 %, rainwater harvest and supply: 29 %, groundwater extraction and supply: 23 %, wastewater generation and treatment: 47 % (with an additional 5 % of the treated greywater being used for garden irrigation).

The cost benefit analysis shows that the autonomous water supply system is not economically feasible. Water handling charge would be as expensive as about 9.7 €/m^3 compared to the utility's charge for the same service only at about 4 €/m^3. However, if the house was located at a distance of over 287 m from the water network, such systems would have been economic.

Electricity demand for the operation of water supply and treatment system has been estimated to be around 443 kWh/yr. If a stand alone solar PV system is installed to supply the electricity requirements, the calculated system size will be as the module of 2.3 kW_p and the battery of 7.4 kWh.

Analysis for the electricity (from PV) and water autonomous case has also been made. Since neither of these systems is at breakeven so far, the combination of both will cause further losses. However, if the house is to be built at a distance of about 1.6 km from the existing electricity and water infrastructure, the house could choose autonomous electricity and water supply systems. Combined electricity and water parity year has been calculated to be in around 2038.

9 CONCLUSIONS AND FURTHER RESEARCH

9.1 Conclusions

The following conclusions have been drawn from the overall study:

1. Solar PV systems are the promising technologies as the electricity supplier in grid connected communities as well as in rural areas in the future, both in developed and in developing countries.
2. The price of solar PV systems has been decreasing at a learning rate of 20 % since its commercial application had started. This trend is expected to continue in the coming decades as well.
3. Solar PV installations worldwide will see a relatively higher growth rate in the coming years. The cumulative installations are expected to reach about 98 GW in Germany and about 4400 GW worldwide by 2060 (refers to a worldwide PV electricity generation of 3.3-6.6 PWh)
4. Thin film solar cells are recently introduced in the market and they are relatively cheaper than c-Si solar cells. Therefore, thin film solar cells are expected to lead the future market.
5. Different battery technologies are available in the market as an electricity storage device. However, only the lead acid battery type is widely used in solar PV applications, especially due to its lower price and readily availability.
6. An average household with four family members in Germany consumes about 3500 kWh electricity throughout the year. A PV system size of about 3.9 kW_p will be needed in order to make this house (in the city of Cologne) as zero electricity household.
7. Cost benefit analysis of grid connected PV system in Germany shows that the PV systems are not market competitive so far. A grid parity year has been expected to be in around 2021 with the wholesale electricity price and it will be in around 2012 with the end use electricity price. Grid parity will be affected by the price decrease for solar PV systems and the price increase for grid electricity from conventional sources.
8. However, with the introduction of cheaper thin film modules in the future, the grid parity year could occur within next few years. Information on learning rate, system life time and overall performance ratio of the thin film PV systems has yet to be awaited because such systems are very recently commercialized and the market has little experience with them.
9. Grid parity year will be earlier than 2021, if the PV systems of longer system life time (>25 years) are developed in the future. Similarly, these systems will reach grid parity earlier in the locations where average annual global radiation is higher than in Germany (For inclined surface the value is taken about 1205 $kWh/m^2.yr$ for Germany).
10. Increase of learning rate on solar PV systems from 10 % to 25 % will bring the grid parity year forward from 2028 to 2019 in German market.
11. In a zero electricity household, the analysis for the possible electricity consumption at the time of its generation using solar PV shows that about 42 % of the electricity generated

could be directly used without the use of any storage systems. This will bring the PV system's real grid parity year in around 2013, 2015 and 2017 for the PV systems with life time of 40, 30 and 25 years, respectively.

12. For the city of Cologne, the stand alone PV system size required in order to supply the household electricity demand throughout the year has been calculated as the module size of 22.1 kW_p and the battery size of 71.8 kWh. Such an enormous system size leads to production to load ratio of higher value, i.e. 2.83. One of the main reasons for this bigger system size is variations in the seasons leading to lower value of global radiation in winter, when the demand is high. While omitting the effect of seasonal variations in Cologne, though hypothetical case, the system size would have been decreased as to the module of 7.8 kW_p and the battery of 59.9 kWh. Such a battery bank can supply the electricity demand at household up to four days even if there is no sunshine at all.
13. Not surprisingly, the stand alone solar PV systems in Cologne, Germany are not economic. A breakeven year has been calculated to be in around 2034. This will, however, occur earlier if the PV system's life time is increased or if there is very high growth of conventional grid electricity price. The calculated grid parity year for no seasonal variation case was as early as around 2024.
14. Such a late occurrence of breakeven year makes room for the uncertainty that stand alone solar PV systems might never be preferred by German households, because there might be other cheaper development in other electricity generation and supply technologies by that time.
15. If a house is to be newly built at a distance of more than 2.1 km from the existing electricity grid operated by a utility, installation of stand alone solar PV system would be economic compared to the grid connection to the house. This distance would as shorter as only about 690 m, if the seasonal variations are omitted.
16. About 90 % of Nepal's energy demand is supplied with conventional biomass resources. Almost all the electricity but about 700 MW is generated from hydro resources. Just over 40 % of the country's population has access to electricity grids. Power supply is unreliable and daily load shedding hours of up to 12 hours in winter and dry seasons are not uncommon.
17. Because of higher values of average annual solar radiation (about 2014 $kWh/m^2.yr$) and sunshine hours, solar PV has a big prospect in Nepal. Such systems have already become popular and over 100,000 solar home systems have already been installed in different parts of the country.
18. Again, not surprisingly, solar PV systems have not yet been able to compete with the grid electricity in Nepal, if the analysis is to be made in terms of mere monetary benefit. The calculated grid parity year will have been as late as in 2036.
19. In the rural areas of Nepal, where the electricity demand is low, basically only for lighting purpose (e.g. 100 kWh/yr.hh in a village with 100 households and the grid extension distance of about 10 km), extending the grids until the village is not economically feasible

from the grid operator's perspective. Therefore, the government support and subsidies are necessary for the electrification of such locations.

20. However, the grid extension could still be cheaper than the stand alone solar PV systems installation in each of these 100 households. Moreover, there might be no promising and cheaper alternatives to stand alone solar PV systems in order to supply the electricity demand in a remote village with fewer people living there. Therefore, while planning the rural electrification, the analysis of grid extension or stand alone PV systems installations should be carefully examined.

21. Household could be autonomous not only for electricity supply, but also for water supply and its treatment/disposal. If a household in Cologne with an average annual water consumption of about 183 m^3 wishes to switch to autonomous supply, it has to supply its freshwater needs of about 53 m^3 from rainwater and about 42 m^3 from groundwater extraction. Rest 88 m^3 of the process water demand could be supplied with recycled greywater, out of which about 9 m^3 of the water will be used for garden irrigation. Additionally, a wastewater treatment and disposal system has to be installed at house premises in order to handle the 86 m^3 of the wastewater generated.

22. Autonomous water supply systems are not common in Germany, but the greywater recycling systems are already commercialized and there are manufacturers producing such units. An economic analysis of 'greywater only' recycling systems has been carried out and the cost benefit results confirmed that such systems are not economic so far.

23. The cost benefit of the autonomous water supply system shows that such systems are also not economically feasible under the current market conditions in Cologne. The water handling charges would be as high as 9.7 €/m^3. The yearly energy demand to operate such plant would be around 443 kWh. This corresponds to a stand alone PV module size of 2.3 kW_p and battery size of 7.4 kWh.

24. A breakeven water network connection distance for an autonomous water supply household has been calculated to be around 287 m.

25. The stand alone solar PV systems and on site water supply (and wastewater disposal) systems have been combined to make an electricity and water autonomous household. Not surprisingly, such system will not be economically feasible in the cities like Cologne. A combined breakeven distance (for connecting the house to water network and electricity grid) has been found to be around 1.6 km for a house in Cologne. The combined 'water network and electricity grid' parity year has been found to be in around 2038.

As a final conclusion of this study, it can be said that households should not shift from utility grid use towards stand alone systems in order to supply their electricity and water needs in densely populated areas with well developed grid infrastructure. This applies to both, German and Nepali case. However, in rural areas where the utility's infrastructure is not yet developed, the stand alone PV systems have no better alternatives. And with the decreasing cost for photovoltaics in the coming years, the evolution of grid infrastructure to rural areas *becomes less interesting as the breakeven distance for stand alone supply results in favor of autonomous supply.*

Furthermore, there will be a need for more grids in order to incorporate electricity generated from other renewable energy sources, and therefore, further investments to develop and operate stable grids are necessary. The role of grid infrastructure will not decrease in the future, rather is will increase.

9.2 Further Research

The following recommendations have been made for the further research:

1. The experience curves are extrapolated only for c-Si solar modules. An experience curve analysis for the thin film solar cells is necessary in order to assess the future market of solar PV more accurately. Similarly such analysis for battery technologies is also important for exact calculations.
2. This study dealt only solar PV systems and its grid parity. However, in the future the conventional grids will have higher mix of other renewable energy systems, e.g. wind energy. Therefore, separate grid parity for PV vs. renewable electricity and PV vs. conventional (nuclear and fossil fuels) electricity is important for better understanding of the future market development of PV and other renewable energy technologies.
3. While designing stand alone solar PV systems for Germany, an enormous system size has been calculated. This could be, however, reduced with the combined use of different RETs (in hybrid form). Such analysis is necessary to choose the best method of electrification.

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Conventionally, the utilities are supplying electricity and water to households through electricity grid and water networks. In this study, the future role of distribution infrastructures has been analysed.

Solar photovoltaic technology is chosen for supplying the household electricity demand. Economics of grid connected PV systems has been analysed with the help of experience curves. Grid parity years for Germany have been calculated as 2012 and 2021 in retail and wholesale electricity market, respectively. Using PV electricity at the time of its generation, real grid parity year would be between 2017 and 2013.

Breakeven year for stand alone PV systems in Cologne is calculated between 2026 and 2034. The breakeven grid access distance has been found around 2.1 km. Without seasonal variations, module size would decrease from 22.1 to 7.8 kW_p.

In Nepal, breakeven year for stand alone PV systems is calculated between 2036 and 2026. The rural electrification option from utility's and consumer's perspective has also been analysed.

The calculations for an autonomous electricity and water supply household in Germany show that the combined breakeven grid access distance would be about 1.6 km.

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