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Research Project

Low-cost energy technologies for universal access

Preliminary candidate list of appropriate technologies, business models and enabling environment for universal access to modern heat

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Reja AMATYA[1], Andres GONZALEZ[2], Robert STONER[1], Ignacio PEREZ-ARRIAGA[1, 2]

[1] Massachusetts Institute of Technology, USA
[2] IIT Comillas University, Spain

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Research project

Low-cost energy technologies for universal access

The UN Secretary General's Advisory Group on Energy and Climate Change defines Universal Access as "access to clean, reliable and affordable energy services for cooking and heating, lighting, communications and productive uses". The International Energy Agency (IEA) establishes that achieving a minimum basic Universal Access to electricity and providing clean cooking facilities for 2030 would require around $1 trillion cumulative investment. IEA also highlights electricity as the most critical energy carrier for development while the use of biomass in inefficient stoves remains one of the main causes of premature deaths.

It is clear that a problem of this magnitude cannot be seriously approached without private capital and, most likely, with the serious involvement of energy companies, although decentralized approaches – either transitory or not – cannot be ruled out and they are already taking place. Obviously this will happen only if an attractive business model can be defined. This model must include: the definition of the appropriate (low cost) technologies to be used; a regulatory framework that clearly defines the rights and obligations of all parties involved and, specifically, the rules of remuneration for the provision of the service; and the sources of finance for this activity. Such considerations are central to this research project and represent a considerable challenge for rural areas.

The purpose of this project is to contribute to the development of Universal Access strategies and tools for policymakers, global businesses and practitioners, supporting the publication of periodic technologies, strategies and business models country reports with roadmaps to universal access.

This Working Paper is one of the first reports of the Low cost energy technologies for Universal Access project by the Massachusetts Institute of Technology (MIT) acting through MIT's Energy Initiative (MITei) and in collaboration with Enel Foundation. The project is developed in collaboration with Comillas Pontifical University – Institute for Research in Technology (COMILLAS – IIT) under the scope of the Comillas University Massachusetts Institute of Technology Electricity Systems (COMITES) Program.

As the first phase of the project, we have researched various appropriate technologies, such as electricity in the first working paper (EF Working Paper 11/2014 "*Preliminary candidate list of appropriate technologies, business models and enabling environment for universal access to electricity*") and modern heat in this second working paper (EF Working Paper 12/2014 "*Preliminary candidate list of appropriate technologies, business models and enabling environment for universal access to modern heat*"). We have investigated business practices that have been adopted around the world for the dissemination of these technologies. We have also focused on the existing regulatory, governance and financing frameworks that enable the sustainability, replicability, scalability and upgradability of these technologies and business models in order to provide long-term, reliable and affordable access to modern energy services for all.

In the second phase we will apply our methodology – including data, logic processes and the potential use of software tools to specific countries and regions to develop a comprehensive assessment of the appropriate modes of electrification, heating and cooking for the entire population, as well as the technologies, the business models and the enabling environments that would provide universal access to modern forms of energy services, starting with the cases of Peru and Kenya to be issued in 2015. This phase will be described in the forthcoming third working paper.

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Abstract

Although the International Energy Agency (IEA) considers electricity as the most critical energy carrier for development, the sheer number of people relying on traditional biomass for cooking is nearly two times the people without electricity access. Under business-as-usual scenario, the number is projected to rise from 2.7 billion today to 2.8 billion in 2030. Lack of access to clean and affordable modern cooking fuels has a direct impact on health and social well being of a person. The IEA estimates that household air pollution from the use of biomass in inefficient stoves leads to over 1.9 million premature deaths per year.

Among 2.7 billion people using biomass for cooking, many of them still use traditional three-stone fire, which is highly inefficient and polluting. Moving the entire population to adopt clean Biogas-LPG-Electricity-Natural gas (BLEN) cookstove would be economically as well as logistically impractical. Therefore there are various intermediary technologies that will have to be considered for universal access. Advanced cookstove and solar cooker are among the few options. Modern cooking fuels such as liquefied petroleum gas (LPG), biofuels, and Dimethyl Ether (DME) are the ultimate clean solution for household cooking. Adoption of such modern fuels and stoves will depend highly on income level, regulatory pricing policy (subsidy), physical access to fuel (supply chain) and cultural preference. Water heating is another one of the major applications under the modern heat within residential energy consumption. Due to high equipment and maintenance cost, and unavailability of electricity/natural gas, electric and gas water-heating options are not widely used in developing countries.

In most rural parts, biomass burning is the easiest way of heating water. Solar water heater is potentially a low-cost option for residential as well as commercial use that can provide modern energy access with no added fuel cost. Privately funded business models are hard to find in ventures involving universal access, primarily due to low return margins and high default risk. Most technology dissemination has been through government, non-profit, non-governmental organization (NGO), or cooperative models. However, operational challenges and bureaucracies hinder progress, scalability and quality of products. Public private partnerships are increasingly becoming a common choice where just one entity cannot handle all the issues, and also it is the means of addressing salient issues and sharing risks. Apart from the financial viability, enabling regulations and energy policy can accelerate dissemination of a technology for universal access.

Keywords: Universal Access, solar water heater, modern cooking technologies

JEL Codes: Q4, Q41, Q42, Q43, Q47, Q48, N70, O13, O18, O19, O33, O38, O44, Q56

Corresponding Author

Reja Amatya
Massachusetts Institute of Technology,
77 Massachusetts Avenue, Building E19-432
Cambridge, MA, 02139-4307
Email: ramatya@mit.edu

1 Water heating: solar water heater

1.1 Introduction

Water heating is one of the major applications within residential energy consumption. In 2009, nearly 18% of the total energy consumption in homes by end users in the United States was water heating[1]. Similarly, 15% of households' energy use is for water heating in Europe, and 30% in Japan[2]. Electric and natural gas water heaters are the most common types used in developed countries. Due to high equipment & maintenance cost, and unavailability of electricity or natural gas in most developing countries, these water-heating options are not widely in use.

Those who can afford in urban areas do have electric heaters, also known as geysers. Due to unreliable electricity, often these are non-functional. In rural areas, either people do not use hot water for household purposes or if needed, use biomass stoves to heat water. Solar water heaters are a potential low cost option for residential as well as commercial use that can provide modern energy access in many developing countries with no added fuel cost.

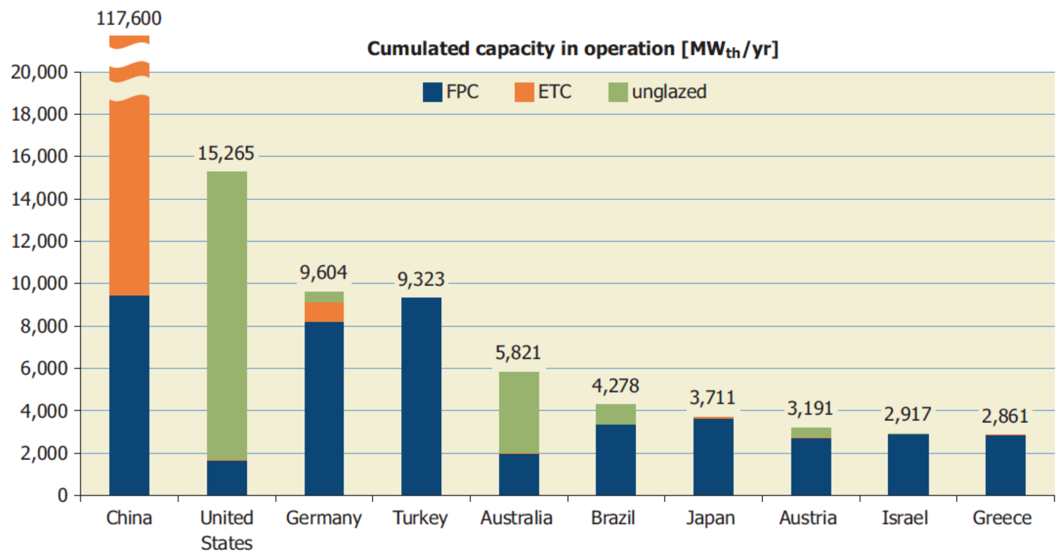
Solar water heating is a technology that utilizes the sun's energy to heat water. Solar water heaters (SWH) are the most cost-effective among all the solar thermal technologies currently available. Reported levelized energy cost ranges from 5-15 cents/kWh depending on location and exact technology. Since 1980, utilization of SWH has increased tremendously with new installation annual growth rate of 13.9% between 2009-2010[3]. The Renewable Energy Policy Network reported 70 million houses using SWH at the end of 2010, with the installed global capacity of 195.8 GW_{th}[3].

China alone has installed 1.08×10^8 m^2 of SWH, which is nearly 60% of the total installed system worldwide[4]. 90% of the current operational systems in China are for single-family domestic applications, with relatively slower growth in other markets such as tourism sector (hotels) and public sector (hospitals). The second largest market for SWH is Europe with installed capacity of 32.5 GW_{th}. Asia excluding China has less than 10 GW_{th} installed systems, with South America having only 5.5 GW thermal capacity[3].

Figure 1 shows the cumulative capacity in operation in various countries with China leading in total installations. Distribution is shown for different types of solar collectors: flat-plate collector (FPC), evacuated-tube collector (ETC) and unglazed collector. Detail technical descriptions are provided below.

[1] U.S. Energy Information Administration, n.d.
[2] Duffour, 2012
[3] Weiss & Mauthner, 2012a
[4] Han, Mol, & Lu, 2010

FIGURE 1 - Total installed capacity in operation in the 10 leading countries by the end of 2010

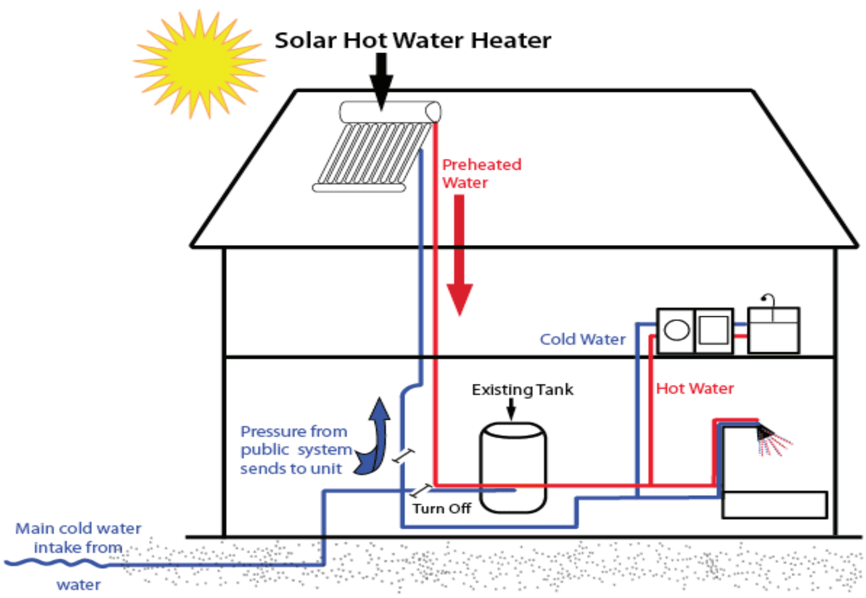


Source: Weiss & Mauthner, 2012b

1.2 Technology

Domestic solar hot water systems consist of solar collectors, that absorb sunlight, heat exchangers/transfer medium to transport the collected heat, and solar tanks to store the hot water in an insulated environment (Fig. 2). Broadly, the system can be divided into two categories: active, which have circulating pumps and controls, and passive, which relies on the principle of thermosyphon.

FIGURE 2 - SWH installation in a house



Source: http://www.solar-energy-for-homes.com

Within an active heating system, it can be either a direct circulation system, which circulates water through the collectors into the home, or an indirect circulation system that circulates a non-freezing, heat-transfer fluid (such as propylene glycol) through the collectors and a heat exchanger.

This heats the water and then flows into the home. Such systems are useful for colder climates where water freezing may be a problem for circulation. Due to additional cost of pumps and controls for active systems, they are less popular than passive systems, and accounts for 11% of the total SWH.

Passive solar water heaters are typically less expensive than active systems, but usually not as efficient. However, due to no moving parts, they are more reliable and typically last longer. With minimal maintenance, such systems can last as long as 30 years. Most passive heaters are based on thermosyphon, where warm water rises as cooler water sinks to provide the flow due to natural convection.

Most SWH require well-insulated storage tanks. Heat loss from the tank can significantly decrease the overall system efficiency. Solar storage tanks have additional outlet and inlet connections to and from the collector.

The collector is typically coated with dark paint or spray that allows absorbance of maximum solar spectrum. Expensive selective absorber can have absorption coefficient up to 0.96. For comparison, ordinary black paint’s coefficient values ranges from 0.6-0.8.

1.2.1 Types of solar collectors

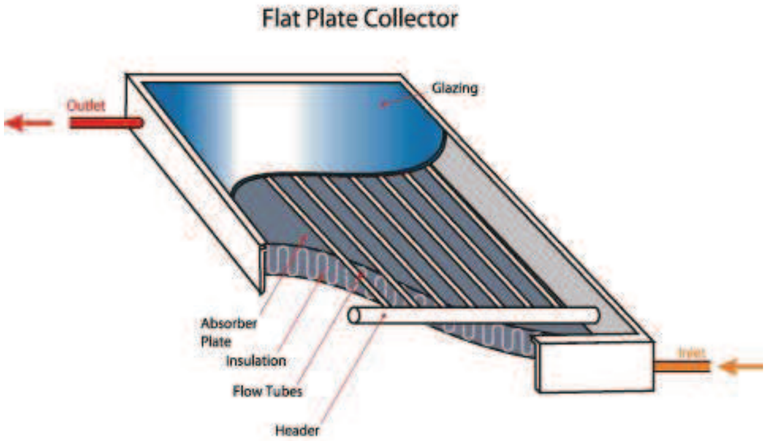
Flat plate collector

Glazed flat-plate collectors are insulated within weatherproof boxes that contain a dark absorber plate under one or more glass/plastic covers (Fig. 3). Collector temperatures up to 200°C can be reached under good solar irradiances. These types of collectors are common for domestic water heating applications in most countries that deploy SWH (31.7% of all installed SWH)[5].

Unglazed collectors – typically used for solar pool heating – have a dark absorber plate made of metal or polymer without enclosure. These are the simplest and least expensive type of collector. Convection losses around the absorber plate significantly reduces the thermal efficiency, thus they have limited household applications.

[5] Weiss & Mauthner, 2012b

FIGURE 3 - A glazed flat-plate SWH

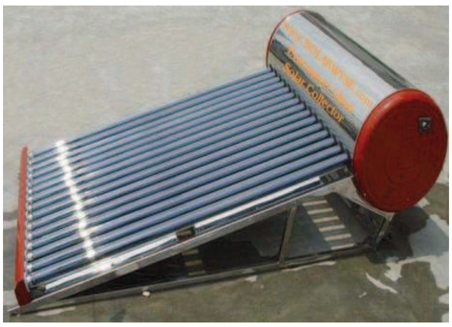


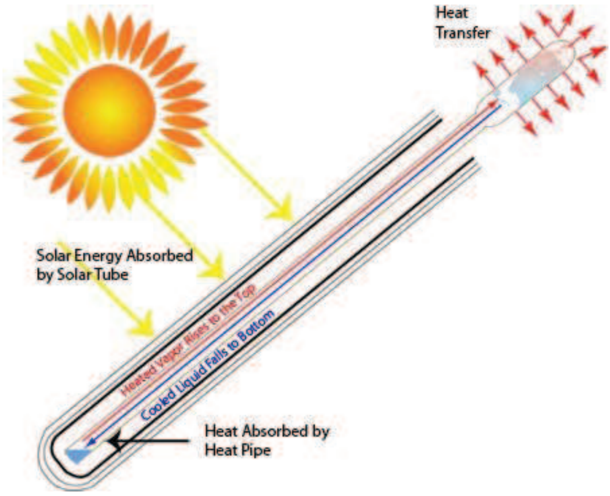
Source: http://www.southface.org

Evacuated-tube solar collector

Slightly expensive than glazed flat-plate collector, these evacuated systems feature parallel rows of transparent glass tubes (Fig. 4). Each tube contains concentric glass outer tube and a metal absorber tube attached to a fin. The glass is evacuated to pressures below 1kPa. Overall higher thermal efficiency is achieved for such evacuated tubes as convection losses are completely suppressed in comparison to flat-plate collectors. Even though expensive, they are the dominant type of collectors (56.6% of all installed SWH) used for SWH as they are used in nearly 90% of the installed systems in China[5].

FIGURE 4 - An evacuated-tube SWH





Source: http://www.bandrservice.com

Unglazed collectors are most suitable for applications where water temperature has to be only 10-20°C above ambient. Glazed flat-plate collector can provide water temperatures up to 50°C above ambient. For higher temperature needs, evacuated-tubes have to be considered. When selecting a solar water heater, following are the key steps:

- estimate the cost and energy efficiency of a solar water heating system at a given location;
- evaluate site's solar resources;
- determine correct system size;
- investigate local codes, covenants, and regulations.

1.2.2 Advanced technologies

Along with hot water heating, SWH can be combined to provide other useful energy resources such as hybrid water/space heating, hybrid SWH/Photovoltaic system, and hybrid SWH/Thermoelectric system. For the water/space heating system a larger fluid volume is required where additional fluid flow can be used in radiators for internal space heating. In countries like Sweden, such hybrid systems are more popular than stand-alone SWH[6].

SWH along with photovoltaic (PV) can provide hot water as well as electricity for domestic use. PV panel as a front collector utilizes most of the sun's visible light to produce electric power. Waste heat generated at the backside can be utilized as input for SWH. Even though thermal efficiency maybe slightly lower for such hybrid systems compared to stand-alone SWH, dual functionality of hot water and electricity generation can be attractive in certain applications such as providing energy in remote residences. Also, removal of excess heat from the PV panel can increase the overall electric efficiency for the system. Currently, the market for such systems is limited to the USA and Europe primarily due to high overall capital cost.

Another hybrid system with the potential of dual outcome is generation of electricity using thermoelectrics within SWH. Recently, scientists have shown work where a solar thermoelectric generator embedded in an evacuated-tube type collector can have thermal-to-electrical efficiency in the range of 4-5%, with water temperature at 50°C, which can be used for multiple household applications[7]. Similarly, theoretical modeling for large-scale solar thermal systems using thermoelectrics have shown optimized thermal system efficiency as high as 52.6%. Passive mechanism of thermosyphon can be used in the case of water heating at the cold side of the thermoelectric generator module[8]. A slightly complex system with concentrated solar water heater using thermoelectric and micro-channel cooling exchanger has been studied

[6] Weiss, 2003
[7] Kraemer et al., 2011
[8] Milijkovic & Wang, 2011

by A. Shakouri et al.[9], where the modeling shows predicted electrical efficiency in the order of 10%, making it comparable to PV modules' efficiency for such hybrid systems.

Such advanced technologies are attractive given that they can be solutions for dual or multiple energy applications. Current frontier research has shown technical promises, however they have to be economical as well to be the low cost solution for the universal access.

1.2.3 Drawbacks of the technology

One of the biggest challenges for acceptance and wide implementation of the solar water heating technology is the high capital cost. The system costs will vary depending on geographic location, exact technology, size of the system, and water usage. In the United States, residential SWH can cost between $4000-$8000. In the Chinese market, the price for a single home SWH is anywhere from $100 to $1000. The huge cost disparity is primarily due to differences in complexity and reliability of the system. In the US, a SWH generally comes with a back-up heating option to guarantee continuous hot water flow. However, in developing countries, availability of continuous hot water supply may not be required. Cost comparison for different types of water heaters in China is shown in Table 1[10]. In developed countries such as USA, France, and Britain, SWH are not very popular, primarily due to the fact that electric water heaters or natural gas resources can be much cheaper and reliable options.

TABLE 1 - Cost comparison of water heaters in China

	Electric water heater	Gas water heater	Solar water heater
Hot water supply (liters per day)	100	100	100
Equipment overnight cost ($)	176	146	264
Annual operating cost ($)	73	51	0.73
Lifetime (years)	8	8	10
Average annual total cost over lifetime ($)	95	67	27

Note: cost figures have been converted using the 2009 average annual exchange rate of $1=6.83 Yuan.

Source: REN21 (2009), Energy Outlook, IEA

Apart from the capital cost issue, other concerns for SWH are:

- home orientation may not be optimum for efficient setup, as one needs mounting location with considerable sun exposure. The tilt angle has to be optimized for maximum solar gain. A tilt angle equal to the local latitude provides close to the maximum year-round solar gains and is usually appropriate for solar water heating;

- for active systems, hard or acidic water maybe a problem as it can erode water circulation pumps;

[9] Yazawa & Shakouri, 2010
[10] International Energy Agency, 2010a

- some building regulations (example: in earthquake prone zones) may limit the weight that one can put on the roof, as SWH can be too heavy;

- in very cold locations, expensive anti-freeze active heaters are required, which can be very costly.

1.3 Enabling environment

For mass use of a technology, having high conversion efficiency or good technical performance are not enough. Economical/social benefits, and correct prices are key to successful adoption of a technology, especially for developing/emerging markets. As mentioned earlier, one of the drawbacks for SWH is high capital cost. Some form of financing is required for people to buy such water heaters. Due to high penetration rates, countries like China and Israel can now have SWH without continuing incentive support, but even these countries had subsidies schemes early on. For an initial kick-start, various financial and regulatory strategies can help boost the acceptability of a technology. In this section, various enabling factors are discussed which, when in place, can help large dissemination of a technology for universal access.

1.3.1 Energy policy, regulation and governance

Policy support for renewable heat is low compared to renewable-based electricity and biofuels for transport. Significant barrier is due to lack of public understanding and awareness in many nations. High penetration rates in countries such as China (50% urban area) and Israel (90% domestic residences) are due to successful policy support. In both countries the SWH market was enabled by[11] the following points.

- Concerted research and development (R&D) effort: solar energy was given priority in R&D programs and regional strategies.

- Regulatory policies: energy efficiency and building regulations mandates for use of SWH in new constructions in the form of solar obligation; example – Israel had solar obligation in place since 1980 that required new buildings to have solar energy provide minimum share of the heating demand. In 2006, Spain began requiring that solar collectors be installed on all new or renovated buildings. Portugal followed quickly with its own mandate. In the US, Hawaii now requires all new single-family homes have SWH.

- Development of an integrated domestic supply chain: China has more than 3,000 SWH manufacturers to provide for large domestic demand.

- Favorable resource conditions (solar resources).

[11] Li, Song, Beresford, & Ma, 2011; Raisul Islam, Sumathy, & Ullah Khan, 2013

- Major cost subsidy/reduction for SWH in the form of direct financial subsidies, low-interest loans, regional investment subsidies etc.
- Awareness among end consumers and finance sector.
- Adequate training for installer and maintenance technicians.
- Stringent quality standards for system hardware with standardized product testing and product verification.

Recently, the combination of some of the above mentioned policies implemented at the right time have helped develop SWH market in other countries such as Tunisia and Barbados[12]. However, even with the right intentions, without proper regulatory support, SWH did not flourish in countries such as South Africa[13]. In South Africa, new schemes/regulations have been introduced recently (2010-2011) to boost SWH, and slower but steady progress in the adoption of the technology has been seen[13].

1.3.2 Funding and financing

Direct government or other forms of institutional grants are the most prevalent schemes for funding of solar water heaters. In South Africa, starting 2010, financing schemes, subsidies (~28% of total installed cost), rebate, and leasing schemes have been started for government's renewable energy strategy in alliance with Eskom, the countries largest utility[13]. Financing or incentives are also important to maintain the supply chain. Again, in the case of South Africa, rebates are available for domestic manufacturers meeting minimum standards. In Tunisia, successful implementation of SWH was made possible by a combination of good financial and regulatory policies. Starting 1997, capital subsidy of 35% was made available on all newly installed SWH. In 2005, efforts were made to have end-user financing facilities for SWH, where new lending opportunities were identified; domestic banks were encouraged to build dedicated loan portfolios. Initial subsidies on capital and interest rates were provided through the bank, which were slowly phased out as the demand grew to sustain the market. Currently, there are indirect tax benefits – no Value Added Tax (VAT) for SWH, and a reduced 10% custom duty on imported SWH equipment[13].

Another type of financial support can be via carbon trading mechanisms, which could make SWH technology a valuable component of climate change mitigation efforts[14]. Case studies of six countries (Barbados, Brazil, China, India, Mexico and South Africa) with active solar water heating markets, have shown the potential of meaningful contribution from the revenue of the sale of Certified Emission Reductions (CERs) towards projects involving SWH technology[14].

[12] Haselip, Nygaard, Hansen, & Ackom, 2011a; LangniB & Ince, 2004
[13] Haselip, Nygaard, Hansen, & Ackom, 2011b
[14] Milton & Kaufman, 2005

1.4 Business models

SWH is a mature technology that has been around for more than four decades. The technology has been disseminated through various channels: private business (energy service companies), non-profit organizations and government.

1.4.1 Non-governmental organizations (NGOs), non-profit

To protect natural habitat, the Annapurna Conservation Area project (ACAP) in Nepal set up a non-governmental trust that works with the locals in providing training and low-interest loans, enabling them to invest in environment friendly technologies such as SWH and efficient stoves. Most non-profit organizations' involvement in dissemination of such technologies involves free installation, where NGOs partner with other stakeholders such as the World Bank or philanthropic foundations to finance projects and bear the capital cost. SWH have been installed in various social housing projects in Argentina, Peru and Ecuador by NGOs. The biggest drawback for such dissemination model has been in terms of ownership and maintenance. If proper maintenance channels are not been established or identified, technology often by itself cannot sustain and remains neglected or unused.

1.4.2 Private, for profit

In China, one can buy SWH as a commodity product in stores. These are specialized manufacturers, middleman dealers and storeowners in the supply chain. The storeowners may provide installation service with the product, or one can hire technicians for the job. For larger installations, such as hotels, hospitals, schools etc., energy service providers working with SWH do the business of selling, installing and maintaining the system with certain warranty (typical: 2-3 years). In most cases, capital payment has to be made directly by the end customer to the seller. Different stakeholders utilize various funding and financing resources that have been mentioned above. Manufacturers take in government subsidies that reduce their overall capital cost; the end-use customer can participate in microfinance schemes, take in available energy subsidies or tax credits for the purchase of the SWH.

In terms of the supply chain, the Chinese and the European producers dominate the global solar thermal industry, with Chinese products being utilized mostly for their domestic market. Chinese export only make up 5-10% of the total production volume for rest of the world. In 2007, there were more than 3,000 manufacturers of SWH in China alone[15].

1.5 Conclusions

SWH technology can be a viable solution for water heating in many parts of the world where people do not use hot water, due to the high cost of heating options such as electric or natural

[15] Li et al. 2011

gas water heaters; or simply because such options are not available. We understand that providing hot water, especially in cold climate and winter, is going to be an integral part of the universal energy access plan. For a specific location or a region, in choosing the optimum technology for water heating, the following parameters should be taken into consideration.

Technical parameters:

- quality of fuel for heating (e.g. solar irradiance, biomass moisture content, etc.);
- heater's thermal conversion efficiency (e.g. solar energy -> heat; electrical energy -> heat, chemical energy -> heat, etc.);
- time it takes to heat certain volume of water to a desired temperature;
- maximum water temperature that can be obtained with the heater.

Financial parameters (applies for both customer and manufacturer in order to maintain supply and demand):

- capital cost, incentives and discounts;
- financing availability and interest rates;
- availability of fuel as well as material for making the heater, and their cost.

Apart from these technical and financial parameters, regulatory policies are also critical as discussed earlier.

Given the maturity of SWH technology, and the relatively smaller operating costs compared to electric and gas water heaters, this technology has the potential to provide a water-heating option for universal access. For the dissemination to be economically viable, the technical and financial parameters mentioned above have to be in favorable conditions.

2 Cooking: modern technologies

2.1 Introduction

Access to clean and affordable modern energy is critical to fostering social and economic development. Worldwide, almost 3 billion people rely on traditional biomass for cooking and heating, which is polluting as well as inefficient[16]. Globally, traditional biomass accounts for 750 million tons of oil equivalent (Mtoe) of the total 1,056 Mtoe used on a global basis. Modern biomass such as preformed wood briquettes or pellets makes the rest of the biomass use[17]. Traditional cooking fuels refer to wood-based biomass fuels, agricultural residues and dung. The use of such solid fuels in inefficient or open stoves is considered a traditional cooking method [Fig. 5]. Clean cooking fuels such as natural gas, liquefied petroleum gas (LPG) and biogas, along with advanced cooking stoves can help the goals of achieving universal access. Renewable energy approaches, such as solar cooking, can also help in some cases for achieving modern and cleaner energy solutions. Modern cooking solutions refer collectively to modern cooking fuels and advanced, clean and efficient stoves. On average, the demand for cooking energy is 35 kg $LPG_{equivalent}$ per capita for rural households. The lack of access to modern cooking solutions is a broader phenomenon that affects both the rural and urban areas. However, there are significant differences between the patterns of urban and rural use regarding the adoption of modern cooking fuels and stoves. In urban areas, achieving universal access to modern fuels will depend on the expansion of natural gas and liquefied petroleum gas (LPG) use. However, in rural areas, the path to clean cooking will require high penetration of biogas and the universal application of efficient stoves for solid fuels.

FIGURE 5 - Traditional cooking method: open fire using wood-based biomass fuel

Source: Global Alliance for Clean Cookstoves, 2011

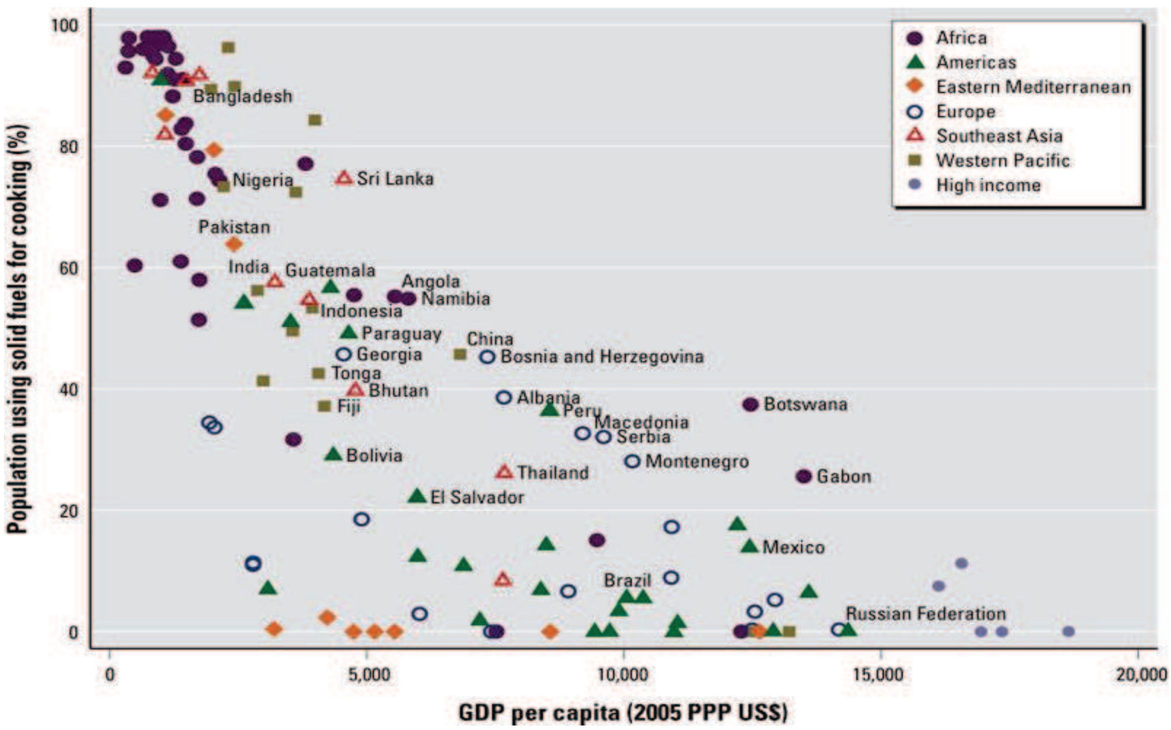
Biomass energy usage versus GDP per capita shows a close intertwined relation between traditional cooking solutions and poverty [Fig. 6]. The general pattern is that the use of biomass fuels declines as the GDP per capita increases. The lack of modern energy services for cooking hampers the provision of basic services such as health care and education. According to the World Health Organization, exposure to smoke from traditional cookstoves and open

[16] International Energy Agency, 2010b

[17] IEA, 2011

fires causes 1.9 million premature deaths annually, with women and young children being most affected. Indoor air pollution is the fourth biggest health risk in the developing world[18]. Particulate matter in indoor smoke due to traditional stoves can reach up to 20 times the safety levels recommended by the World Heath Organization. There is strong evidence supporting the causal linkage between biomass combustion emission and acute respiratory infection among children who are brought up in households using open-fire or inefficient stoves[19]. Traditional biomass cookstoves also increase pressures on local natural resources and contribute to climate change at the regional and global level. Fuel collection also consume time[20] that women and girls could spend in more productive activities, and pose security risks for them as they search for fuel.

FIGURE 6 - Household biomass energy use versus GDP per capita, 2010



Source: Bonjour et al., 2013

Barriers to improving energy access include a lack of awareness and commitment as well as institutional and financial constraints. A major barrier especially for the rural sector is the lack of low-cost, reliable clean cooking fuel supply and advanced cookstoves that poor people can afford. Natural gas and LPG are considered modern cooking fuels, and would be a key part of clean and efficient cooking in most urban areas. However, it will be difficult to expand the infrastructure for such resources to serve customers in remote rural areas, in which biogas may be the main option for a modern cooking fuel for household with adequate livestock. In urban areas, the main challenge is to develop the infrastructure for modern cooking fuels. The challenge will require significant investments in importing and processing facilities for natural gas and LPG, in addition to investment in the electricity infrastructure for electrical cooking. In

[18] WHO
[19] Adams, 2011a
[20] Women and girls can spend 20 or more hours per week collecting fuel; Global Alliance for Clean Cookstoves, 2011

rural areas, the major challenge is the deployment of efficient stoves. The challenge will be to develop and market large numbers of advanced stoves that burn coal and traditional biomass efficiently.

The main focus for universal access (especially for rural communities) in cooking has been on development, marketing, and dissemination of clean advanced cookstoves. The use of clean cookstoves and fuels can dramatically reduce fuel consumption and exposure to cookstove smoke. International, national and regional organizations have worked on various design solutions over the past number of decades. Many times, the more innovative aspect of these efforts is the successful institutional model for selling the stoves, rather than the design of the stove itself. There are a few successful institutional alliances working in this sector. The Global Alliance for Clean Cookstoves led by the UN Foundation, supports large-scale adoption of clean and safe household cooking solution as a way to save lives, improve livelihoods, empower women, and reduce climate change emissions. The Alliance works with public, private and non-profit partners to overcome the market barriers that hamper the production, deployment, and use of clean cookstoves in the developing world. It works to develop standards for cleaner stoves, increase public and policymaker awareness of the health and environmental benefits of improved stoves, and support health and climate research. Similarly, organizations such as GERES in Cambodia have been able to setup a local supply chain for the sales of more than 1 million advanced cookstoves burning charcoal from 2003 to 2010[21]. More in-depth analysis on various business models will be discussed later in this document. There are hundreds of various designs for clean cookstoves. These products vary substantially in their sophistication, durability and reliability (Fig. 7). The prominent design solutions are discussed below.

FIGURE 7 - Various types of stoves

Source: own elaboration

2.2 Technology: advanced cookstoves

Out of 3 billion people using biomass fuel, about 828 million in developing countries now use some form of improved stoves[22]. The two main technical features for advanced cookstoves

[21] GERES Cambodia's Improved Cookstove Project Reaches 1 Million Stoves, 2009
[22] WHO & UNDP, 2009

have been energy efficiency (high combustion efficient and clean burning), and removal of smoke through the use of chimneys. It has now been realized that the best approach for advanced cookstove design is to create high-combustion-efficiency and low-emissions devices, rather than traditional stoves retrofitted with chimneys. Well-operating chimneys may mitigate indoor air pollution but transfer the pollution outdoors. Now there are biomass-using stoves that produce emissions per meal that are less than one-fifteenth of traditional stoves[23]. In many designs, forced convection is used as the best way to reduce the products of incomplete combustion emitted by traditional stoves, increasing the combustion efficiency. Improved biomass cookstoves with better technological designs feature grates, insulation, induced draft or forced airflow, and are made from more durable materials to provide a cleaner burning, more efficient device. For long-term reliability, the stoves must use either advanced ceramics or metal alloys that are made in centralized manufacturing facilities with good quality control and modern mass production techniques. One company in Sri Lanka has sold more than six million high-efficiency biomass cookstoves that substantially reduce indoor smoke. Some common and successful improved stove designs are explained below.

2.2.1 Key successful technologies

Efficient bucket stove

These are the earliest examples of improved cookstoves from 1990s. Primarily made from clay/ceramic/metal buckets [Fig. 8], they are still very common in Southeast Asia and many African nations. Low cost, ease of manufacturability and ease of use are some of its best attributes. Compared to traditional homemade mud stoves, the improved design has features for even air flow through the biomass (charcoal) for better combustion, and clay/rice husk exterior prior to metal casing for better insulation. Successful implementations have been recorded in Thailand and Cambodia through GERES.

FIGURE 8 - Clay/metal bucket stove (Thailand)

Source: http://stoves.bioenergylists.org

[23] Venkataraman, Sagar, Habib, Lam, & Smith, 2010a

Gasifier stove

In such stoves, gases and smoke that result from incomplete combustion are forced back into the cookstove's flame, where complete combustion gives high efficiency. These are two-stage combustion stoves. Top Lit Updraft stove [Fig. 9] is an example of the gasifier stove, where some fuel is lit on the top of the stove such that any incomplete combustible product burns completely before being emitted into the air.

FIGURE 9 - Top Lit Updraft stove (MWOTO stove – Uganda)

Source: http://www.mwotostove.com

2.2.2 Advanced technologies

Advanced cookstoves with thermoelectric modules (successful implementation: Philips[24] and BioLite[25]): a biomass burning cookstove that can convert a small amount of thermal energy produced by the stove into electricity makes the improved stove a stronger value proposition [Fig. 10]. The stove itself to power a fan, for forced convection, can use electricity.

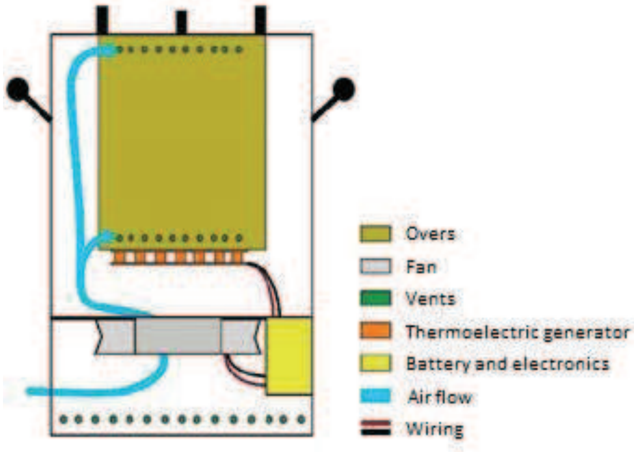
The fundamentals of thermoelectricity can be utilized to convert thermal energy into electricity, which is based on the Seebeck effect.

By applying a temperature gradient across a thermoelectric module, direct current can be produced to run a fan, which can be fitted near the combustion chamber to increase the airflow.

The BioLite unit also provides a USB connector to power external electronics like cell phone or LED lightings.

[24] http://www.english.ecofogoa.com.br/modelos.html
[25] http://biolitestove.com/homestove/overview

FIGURE 10 - Thermoelectric module integrated cookstove



Source: Philips

The limiting factor for the use of thermoelectric modules in cookstoves is the cost. Commercial thermoelectric modules are still very expensive (US \$2-3/W_p), which makes the total price for the stoves beyond the reach of much rural population. Philips blower stove cost about US \$70. Other thermal engines such as steam or Stirling engines have been studied for cogeneration of heat and electricity. However, such sophisticated machines add high acquisition cost, as well as maintenance and operation costs.

These are some examples of portable cookstoves showing fundamental design strategies. There are many improved stoves in the market with minor design changes catered to a specific region or community[26]. Some large permanent installations within kitchens are also efficient cookstove designs. Generally they come with a chimney attachment for better indoor air quality. All efficient cookstove designs are geared towards higher combustion and low fuel consumption.

2.2.3 Drawbacks of the technology

For clean cookstove technology, the major drawbacks come from socio-political and cultural practices, and supply-chain problems more than actual technical shortcomings. The main challenges for a large-scale distribution and use of clean cookstoves are:

Lack of momentum among national institutions to promote advanced cookstoves: few countries have national institutions/agencies to promote cookstove programs. A national level push is essential for a successful implementation of a clean cookstove program in a region. In China, during 1980s and 1990s, the government implemented the National Improved Stove Program (NISP) in which over 100 million people adopted improved cookstoves.

[26] http://www.stoves.bioenergylists.org

Channels for providing credit for the manufacture or purchase of advanced stoves, and for marketing widely are underdeveloped. For rural communities that make the "bottom-of-the-pyramid", often times the cleaner modern cooking fuels and advanced stoves are not affordable. For businesses, it is not financially attractive to sell either modern fuels or advanced stoves to these relatively poor populations. Thus, increased attention is being given to developing novel business models that promote modern cooking solutions for the poorest households.

There are no widely accepted standards or certifying institutions to qualify the stoves as safe, durable, efficient and clean burning. Many products in the market are not well designed, and there is very little quality control during installation. Some cookstoves have short working lives because they were built with limited expertise entirely of local materials.

Financial support for the technical development and dissemination of advanced stoves is limited. Even within organizations such as World Bank, between 2001 to 2008, less than 1 percent of its financing was directed towards clean cooking[27].

The lack of awareness among households in developing countries regarding the benefits of clean cookstoves and fuels is a key barrier to widespread adoption.

Many improved stoves have a narrower tolerance to biomass size and moisture content. Thus, they generally require more fuel processing at the household into pellets or briquettes.

Apart from good technical performance, field studies have shown that market development is equally if not more important for large dissemination of the technology. More attention needs to be paid to household social characteristics, along with the desirability and affordability of stoves. More discussions on enabling environment and business models are done later in this document.

Advanced cookstoves will be the first step towards cleaner energy access for millions of people in developing countries that currently use primitive inefficient biomass stoves, especially in rural areas. Clean biomass burning stoves with chimneys can make a huge positive impact on people's lives and environment. With proper financial and regulatory incentives, and business models advanced cookstoves can be a norm in most rural households, as a first step towards universal energy access. For location-specific needs, optimum cookstove design can be chosen based on the following parameters.

Technical parameters:

- heat transfer and combustion efficiency of the stove design;
- quality of fuel required for cooking (e.g. biomass moisture content, requirement for particular structure – pellets/briquettes etc.);

[27] Barnes, Singh, & Shi, 2010

- air pollution particulate emission;
- household drudgery (time and fuel savings) that can be replaced by the use of improved stove: cooking time and fuel consumption.

Financial/environmental/social parameters:

- environment and climate change factors: directly related to fuel consumption and particulate emission;
- capital cost, and availability/manufacturability of product (supply chain);
- availability of financing and discounts;
- consumer-demand features such as convenience, perceived performance and local maintenance.

2.3 Technology: solar cooker

Solar cooking is the simplest and most convenient way to cook food without consuming any biomass or fossil fuel. It can provide energy security for rural households that mostly use biomass or expensive commercial fuels such as paraffin. A lot of research has proven the utility of solar cooker as a renewable and pollution free technology. Many developing nations in Africa and south Asia receive mean daily solar radiation in the range of 4-7 kWh/m^2 and have more than 275 sunny days in a year[28]. With more than 60% of the total energy use in these regions, mostly in rural areas, being consumed for domestic cooking, solar cookers have a high potential, and offer a viable option in the domestic sector[29]. Solar cooking can be timesaving as well, when one considers the amount of time that families, especially women and children, have to spend collecting biomass and other fuel sources.

According to reports from the Solar Cookers International (SCI), solar cooking has been introduced in 114 countries with more than 3 million cookers being currently used worldwide[30]. Nearly one-third of the used cookers can be found in China and India alone[28 30]. Solar cooking has been especially successful in the concept of community cooking, where considerable amount of fuel can be easily saved in places such as schools, cafeterias, and refugee camps in Chad, Sudan, Kenya, Malawi, Namibia, Afghanistan and India. Portable solar cookers are also used for community cooking in pilgrimage such as Hajj (Saudi Arabia), and Shirdi temple (India)[31]. Another successful use of solar cooker is for pasteurizing water and milk in many countries[32].

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[28] Pohekar, Kumar, & Ramachandran, 2005a
[29] Carmody & Sarkar, 1997a
[30] www.solarcookers.org
[31] Panwar, Kaushik, & Kothari, 2012; Toonen, 2009; www.solarcookers.org, last visit: 2013
[32] Bansal, Saini, & Khatod, 2013a

Solar cookers are a subset of solar collectors that have been widely studied in various engineering fields. There are more than 350 designs, and 175 solar cooker manufacturers worldwide[33]. The cooker designs vary from box-style cooker (thermal efficiency ~ 20%) to parabolic shape (thermal efficiency ~ 70%)[34]. A metal reflector in a box or dish shape can be a cheap source of concentrated solar energy in developing countries. The maximum cooking temperature (100-400°C) achieved with a solar cooker varies depending on the geographic location, concentrator type and the reflector quality. Different types of solar cookers are described in the next section.

The standard used for characterization and comparison of different solar cookers is heating power and efficiency. The average heating power ($\dot{Q}_{heat}$) of a solar cooker is calculated as the total power required for boiling a certain volume of water.

$$\dot{Q}heat \quad = \frac{m_w.c_p.\Delta T_{(95-ambient\ temp).}}{t}$$

Where, m_w is mass of water (kg), c_p is specific heat capacity of water (Joule/kg°C), ΔT is temperature difference (°C), and t is time (s). To avoid the uncertainty of the boiling point, heating power is measured from ambient temperature up to 95°C.

The overall thermal efficiency (η_o) of a solar cooker is calculated as the ratio of the heating power to the incoming power:

$$\eta_o = \frac{\dot{Q}_{heat}}{I_s A}$$

Where, I_s is the solar incidence (W/m^2) and A is the total absorber area (m^2). Loss factors that reduce efficiency are the following.

- *Reflector property*: reflection coefficient determines how much of the incidence sunlight actually falls on the cooking spot. For a clean mirror, reflection coefficient can be as high as 95%, where as for metal reflector sheets or Mylar, the reflection coefficient can be in the range of 40-70% depending on the condition.

- *Convective loss*: due to airflow around the cooking pot, heat is lost to the environment. Thus, having an oven-like enclosed structure can help reduce such loss.

- *Radiative loss*: re-radiation from a hot pot can reduce the overall efficiency. As the temperature increases, the radiation loss also increases. Having a black pot surface

[33] www.solarcookers.org , 2013
[34] Bansal, Saini, & Khatod, 2013b; Panwar et al., 2012

helps in absorbing most of the sunlight, however the emissivity of the pot has to be low as well in order to suppress radiation loss.

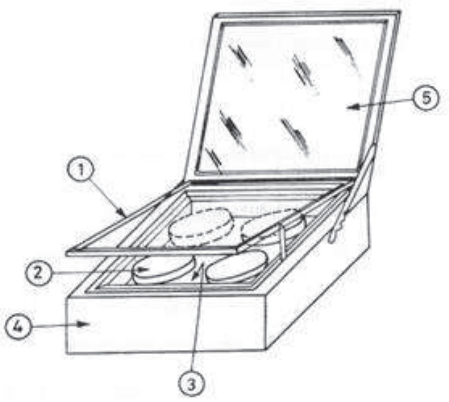
2.3.1 Types of solar cookers

Box cooker

The simplest and often the cheapest option for solar cooking is with a box cooker. A classic box cooker is made of fiber reinforced plastic/sheet metal/wood or cardboard outer casing, aluminum interior casing, double tempered glazing and a single mirror reflector lid (Fig. 11). This type of cooker is based on the green house effect in which the transparent glazing allows shorter wavelength solar radiation to heat the cooking pot, but is opaque to most of the longer wavelength solar radiation coming from relatively low temperature heated pot. Box cookers without reflectors are primarily used for drying or slow cooking purposes. Larger number of external reflectors increases the overall achievable temperature at the cooking spot. Even with booster mirrors, typical concentration ratio is low for box cookers (C~10x). Many such box cookers have airtight enclosures, which diminish the convective loss around the cooking pot. Box solar cookers are slow to heat up but work satisfactorily where there is diffuse radiation, convective heat loss due to wind, intermittent cloud cover and low ambient temperature. Box cookers are limited for baking, and slow cooking purposes. Due to their portable nature and ease of manufacturing, box cookers are very popular, even though there are limitations to cooking due to temperature limits (100-150°C). Such cookers are well suited for the farmers for their noon meal cooking. Large numbers of single-reflectors boxes have been sold in India, partly as a result of government subsidies amounting up to 60% of the price[35].

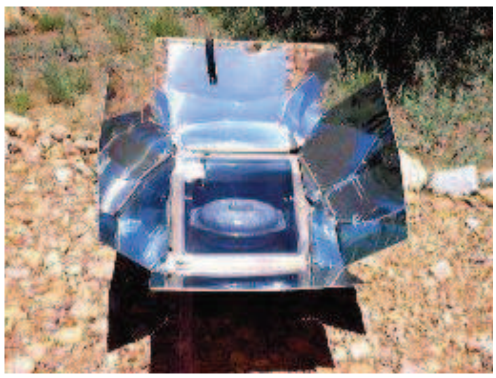
FIGURE 11 - (a) Schematic for a single mirror box cooker; (b) Classic box cooker with 4 reflectors

(a)



(1) Double Glazing; (2) Cooking Utensils;
(3) Absorer Plate; (4) FRP Casing;
(5) Booster Mirror

(b)



Source: http://www.cookwiththesun.com

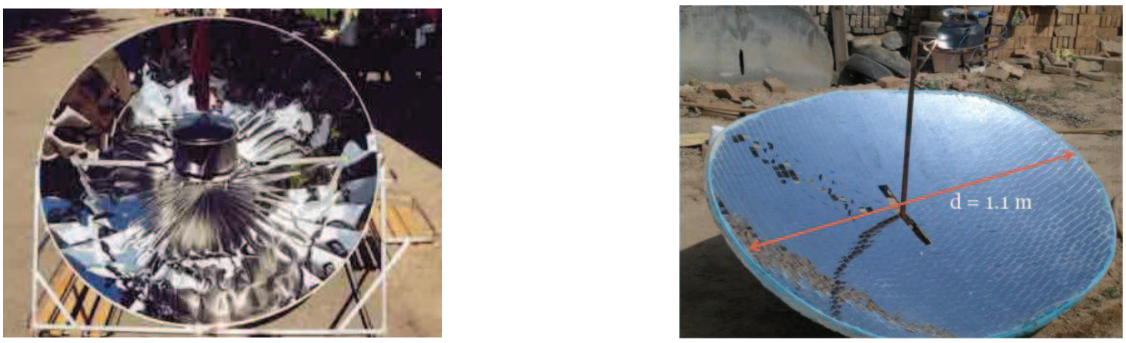
[35] *Solar Cooking*

Concentrating cooker

Many simple designs such as parabolic cookers are based on optical imaging, where the sunlight is reflected to a focal point to increase the intensity at that particular spot. Concentrating cookers utilize multifaceted mirrors, Fresnel lenses or parabolic reflectors to attain higher temperatures. Due to single reflection, the acceptance angle is relatively small and a tracking system is needed in this kind of solar collector to get efficiencies in the range of 70%. The concentration ratio and subsequently the maximum achievable temperature at the focus depend on the size of the collector/reflector. Widely deployed solar cookers such as the SK-14 solar concentrators (area ~ 1.5 m^2) can deliver approximately 600 W of thermal power to a 28 cm diameter focal spot (Fig. 12). This power input is within the range of open fires and conventional stoves. Thus, parabolic solar cookers are suitable for the types of food that require high temperatures such as frying, and standard cooking techniques can be used. There is a trade-off between the concentration ratio (C) and the half acceptance angle (θ_c). If the acceptance angle is decreased, a tracking system is required to maintain high concentration ratio. The relationship between the concentration ratio and the half acceptance angle for such parabolic geometry is given by:

$$C = \frac{1}{sin\theta_c}$$

FIGURE 12 - (a) SK-14 solar cooker (popular in South Asia; designed in Germany); (b) concrete base solar cooker (popular in Western China)



(a) (b)

Source: http://www.solarinspiration.de

The half acceptance angle of the sun is ~¼°, thus, the maximum concentration achieved from an ideal parabolic concentrator is ~ 213. More advanced non-imaging optics with multiple reflections, such as in the case of compound parabolic mirrors, is needed to achieve higher concentrations. Table 2 summarizes the properties of two types of solar cookers.

TABLE 2 - Comparison for various concentrators

	Concentration (typical value)	Acceptance angle (°c)	Tracking	Efficiency	Cost ($/m2)
Box type cooker	~10 (max)	Wide	None	20-30%	10-50
Parabolic dish	¼ C	1-7 °	Two-axis	65-70%	50-300

Source: Reja Amatya, 2012

A cooker's price can increase by 30-40% with a two-dimensional electrical tracking device. For example, a parabolic cooker can be bought for US $72 vs. $100 with and without an electric tracker[36]. For cooking purposes, the overall thermal input power increases by only 20-25% with automatic tracking versus manual tracking done every 15-20 minutes. Relatively cheaper mechanical tracking systems can add reliability issues and increase maintenance cost due to moving parts. Periodic manual tracking is feasible for small-scale systems, which are used primarily for single household domestic application. Even though concentrating solar cookers are expected to demonstrate high performance due to larger collection area and higher concentration ratio, many times convective heat loss from the cooking pot negates high solar input flux. Pots within glass containers have been designed to reduce convection loss. However, this adds to the overall cost and durability of the system. Thus, this leads to a design trade-off.

2.3.2 Advanced technologies

Apart from traditional box and dish cookers, there are some indirect types of cookers, where the pot is physically displaced from the collector and a heat-transferring medium is required to convey the heat to the cooking pot. Solar cookers utilizing evacuated tube collector or flat plate collector with water/oil as the heat transfer medium are some commercial examples. Such indirect cookers are mostly used for large-scale community cooking where outdoor-cooking can be a hassle. Heat flow to the pot can be controlled with such indirect heating. However, a suitable indoor cooking unit for all time cooking similar to the conventional mode is yet to be developed.

Some solar cookers can be equipped with conventional electric heaters for cloudy days or nighttime cooking. Such hybrid systems are developed primarily for use in developed countries where both solar energy and electricity usage is abundant, making solar cookers more reliable.

[36] Chinese vendors – www.alibaba.com date accessed: 8/9/2013

However, due to high cost and unreliable electricity in developing countries, such hybrid systems have not been introduced in many parts of the world.

Another example of a hybrid system is a solar cooker with photovoltaic cells, where the PV can recharge a battery while a solar cooker is being used for cooking during daytime[37]. Instead of PV, other thermal to electrical conversion mechanisms can also be utilized for the dual purpose of cooking and electricity generation, such as thermoelectrics[38]. Limited conversion efficiency and high price have been limiting the use of such hybrid technology.

A class of solar cooker not mentioned previously is solar cooker with thermal storage. Solar cookers described earlier face a convenience issue i.e. the availability of solar energy does not always coincide with the cooking and eating habits of its user. Best cooking times are mid-day or early afternoon, both early for morning and evening meals. Thermal energy storage becomes attractive when there is this mismatch between supply and consumption of energy.

Latent heat storage in sand, vegetable oil, and phase change material (PCM) have been attractive for heat storage using solar cookers[39]. Thermal energy stored by raising temperature of a solid or liquid is the easiest option for storage. A material with a large specific heat capacity is ideal, since it would slowly loose the heat back to the environment once the sun is down.

The main disadvantage for such storage is the fact that the output heat cannot be controlled and is dependent on the convective forces around the system. There is also a decline in the effectiveness of cooking as the temperature of the storage material decreases during discharge. Latent heat storage makes use of the energy stored during the phase change.

The use of PCM helps in providing constant operating temperature for uniform cooking for a longer time in comparison to non-phase change material. However, the maximum temperature for PCM in storing heat for solar cooking has been reported only around 120°C.

Recent research progresses have been made in identifying new materials such as PCM A-164, which can give uniform surface heating around 140-150°C[40]. Other related research is focused on the development of unique storage materials, which can be triggered/controlled for discharge to provide high quality solar thermal fuels[41]. The initial investment for such storage system will be high due to the complexity of the system and the material cost. However, in the long run it may become cost effective if proper thermal storage can be provided to make solar cookers the ultimate solution for cooking.

[37] Joshi & Jani, 2013
[38] R. Amatya & Ram, 2010
[39] Muthusivagami, Velraj, & Sethumadhavan, 2010
[40] Saxena, Lath, & Tirth, 2013
[41] Kolpak & Grossman, 2011

2.3.3 Drawbacks of the technology

Solar cooker as a current technology cannot be a single solution for all the cooking needs, and that is its biggest drawback. The intermittent nature of solar energy forces the need for backup energy source for cooking for those who use solar cookers. Cutting-edge research on energy storage as discussed in the previous section could help solar cookers be the universal solution where applicable. Generic pros and cons for solar cooking can be listed as follows:

TABLE 3 - Pros and cons of solar cookers

Advantages	Disadvantage
1. No recurring cost	1. Resistance to acceptance, not a single solution to all cooking needs
2. Potential to reduce drudgery	2. Intermittent nature of sunshine
3. High nutritional value of food	3. Limited space availability in urban areas; bulky storage/theft issues
4. High durability	4. Higher initial costs
	5. Convenience issues: daytime cooking; time taken to cook a meal can be very long; cooking has to be undertaken outside when traditionally it has been done indoors

Source: Pohekar, Kumar, & Ramachandran, 2005b

Many times solar cooking has been viewed as a solution that is pushed onto consumers, and it has been criticized as a technology developed without sensitivity to user's needs. Recent attempts have moved to introduce and demonstrate solar cookers as a viable option for consumers rather than the ultimate solution to all their cooking needs[42]. Many initiatives and efforts have placed consumer needs and priorities ahead of technical considerations to promote solar cooking as a part of an integrated solution to the cooking problem. Some of the lessons from years of field trials have lead to following conclusions:

Solar cookers should not be presented as a total solution to cooking problems, but should be promoted as an add-on cooking device with specific potential benefits and offering more choices and flexibility to consumers. In South Africa, solar cookers are offered as part of an integrated cooking package with a fuel-efficient stove and a heat retention device.

It should be a well-made product comparable to other household cooking appliances. The product must instill confidence in the user and be well made, finished and packaged. Respected authorities should define quality standards.

[42] Panwar et al., 2012

Users must be well informed and manufacturers should be able to give technical back up in the form of product warranty.

Demonstrations are key to solar cooker sales. There should be a well-managed product distribution chain such that the cookers are widely available in shops and outlets. Transport and distribution prove to be one of the most difficult challenges for cookers dissemination.

There have been studies to show the impact of solar cookers, and their economical benefits[43]. The primary parameters generally include solar cooker use rate and savings associated with solar cooker use. Overall financial feasibility and monetary annual benefits can be evaluated in terms of the meals cooked, and fuel saved per meal. The cost per unit of useful energy delivered by a solar cooker can be obtained as the ratio of the total annual cost of the solar cooker to the annual amount of useful energy delivered by it. The denominator can be estimated by multiplying the total number of meals cooked by the solar cooker with the useful energy required to cook a single meal.

$$[\$/kWh] = \frac{Price\ of\ solar\ cooker\ (annual\ cost)}{\#\ meals\ cooked\ \times\ energy\ required\ for\ cooking\ a\ meal}$$

Various references have shown the monetary evaluation of solar cooker’s utility[43]. Such tangible and monetary savings serve as an important motivator for households to use solar cookers. However, for families using “free” locally available biomass source for traditional cookers, the savings are often in safety and health, which are harder to quantify with monetary values. Often times, this is the main cause for poor adaptability of the technology in rural areas. Studies have looked at various correlations between indoor biomass cooking, health related problems and life expectancy. Similarly the benefits of less time spent for wood gathering can be correlated with safety, more productive time for education, and income-generating work. Such benefits maybe obvious to an outside person, but for the end-user they are not always the highest priority, thus the acceptability of the technology is low. Thus marketing the product as a desirable commodity is one of the key factors for successful implementation. More about marketing and business models are discussed later in this document.

The capital cost for a solar cooker varies for the different types, and is often the barrier for acceptance, especially in rural poor communities. The market price for a solar cooker varies anywhere from $10 for a solar box oven to $300 for a parabolic solar cooker[44]. Governments and non-profit organizations involved in solar cooking have been providing financial assistance on box, dish and community cookers to increase the presence and influence of this technology[45]. Locally made products can help reduce the capital cost, at the same time boost local economy. Short payback periods (0.5-1 year) can make solar cookers economically viable depending upon the fuel they replace. In this aspect, box cookers are much more popular due to the fact that they can be produced locally with less skilled workers, and they have less machinery requirement than the concentrated reflective cookers. End-user finance

[43] Hutton & Rehfuess, 2006; Rubab & Kandpal, 1997
[44] Carmody & Sarkar, 1997b; www.sun-and-ice.sdrom.ru/en/
[45] Balachandra, Kristle Nathan, & Reddy, 2010

mechanisms through normal credit channels or tailor-made micro-finance options are essential to enable very poor households to purchase solar cookers. The price of conventional fuels used for cooking plays a decisive role in the use of solar cookers. Apart from domestic use, solar cookers have flourished in some countries for food cart businesses. In Argentina, wheeled trolleys with portable parabolic solar cookers have been a huge success in carnivals, street festivals and in tourist sites. Such income generating resources can help boost dissemination of the technology.

2.4 Modern cooking fuels

Apart from clean burning efficient cookstoves, the ultimate modern energy access will be gained through using cleaner fuel and efficient stoves. Adoption of modern fuels and advanced cookstoves depend on three key factors: income level/pricing policy (affordability), physical access to fuel (availability), and cultural preference. With higher income in urban areas, households can be expected to switch to modern fuels such as liquid petroleum gas (LPG) and different electric cooking appliances. Fuel taxes and subsidies also have major impacts on energy consumption patterns for cooking. If a country is required to import a fuel, it is likely to be taxed. If the fuel is produced within the country, price subsidies are more likely, and would be used extensively. A modern distribution system is equally important for transition from traditional biomass use to modern energy forms. LPG penetration rates are slow in many developing countries, partly because the distribution infrastructure is lacking. There are various types of fuels that can substitute for the biomass as the key energy source for cooking in a household. All modern fuels are some form of fluid hydrocarbon fuel. Fluid fuels provide cleaner means of cooking services than solid fuels, and have much higher efficiency[46]. Table 4 shows some key modern fuels with their costs/characteristics.

2.4.1 Liquefied Petroleum Gas (LPG)

LPG (simply propane or butane) is a flammable mixture of hydrocarbon gases used commonly for cooking applications in urban sector of developing countries. Many times LPG is the preferred fuel source due to economic reasons and convenience factors. Even though it is produced from fossil fuel sources, it has less environmental impact that burning straight up coal or oil (for example: burning LPG emits 70% less CO_2 per kWh compared to coal burning). Most petroleum fuel companies lack incentives to provide access to such fuels as LPG in rural areas. Use of LPG is prohibitively costly for rural poor.

Even for poor population in urban areas, they cannot afford the upfront cost of an LPG stove and fuel cylinder. The cylinders often contain a month’s supply. Distribution of fuels in large containers can make these fuels unaffordable to poor people, who are used to buying small amounts of kerosene several times a month. To improve household access to LPG, some governments, such as Morocco, have been subsidizing gas bottled in small canisters[47].

[46] Larson & Li
[47] Pachauri & Brew-Hammond

Reducing the upfront cost of LPG cookstoves is also important to accelerate use of LPG in the urban sector.

Access to modern cooking fuels in some countries is also related to import policies. Until the early 1990s, China limited the import of LPG to conserve foreign exchange. This policy meant that LPG was informally rationed, even for people who could afford it. According to the World LPG Association, increasing access to LPG would require a concerted effort by industry and government to address issues related to local resources, financing, building capacity in local energy entrepreneurs, and increasing public awareness with the right mix of policy changes.

For countries that have the good fortune of being the producer of cleaner fuel, promotion and implementation of such modern cooking fuels should be a simpler process. In the case of LPG, Thailand has had a successful approach.

- The price of LPG was set at the cost of production, which included regulated profit margins, rather than at world market prices.

- To promote LPG in semi-urban and rural periphery areas, uniform wholesale pricing policy was set in place.

- The government was able to provide a subsidy for the cost of transportation of LPG from the main production/storage facilities to the regional distributors.

- In order to grow the market (distribution network) for LPG supply, under government's order, the state-owned oil companies allowed private distributors to use their storage facilities free of charge. As a result, the number of LPG suppliers/distributors in the country doubled.

LPG has higher calorific value (J/m^3) than natural gas, and can be easily substituted for natural gas burner stoves by mixing with air to make synthetic natural gas (SNG). In developed nations, LPG-based SNG is used in emergency backup systems for many public, industrial and military installations. Countries with low or no natural gas resources can easily use LPG as modern fuel for cooking and heating purposes.

2.4.2 Biofuels

People in developing countries have been using various forms of biofuels for a long time. Scientists have worked on efficient ways of producing biofuels (biogas, ethanol, biodiesel, and gelfuel) from all kinds of organic matters. It is a renewable energy source and can be produced locally with available raw materials, easing the supply chain and distribution.

The concept of 'gobar gas' (biogas) is not new in South Asia; it is gas produced by the breakdown of animal waste and other organic matter in the absence of oxygen. A digester or a small-scale digestion facility is often times located in close proximity. The gas pipe from the digester is directly connected to the kitchen fireplace through control valves.

Even though such fuel burns with very little odor and smoke, culturally, this fuel source has not been very acceptable for cooking purposes, and is primarily used for other applications, in the transport sector and for electricity generation.

The use of biogas systems for cooking is based on methane gas that can be used in a manner similar to LPG. The technology can transform biomass into clean burning gas for modern cooking.

Even though the technology is well proven, the limitation comes from the input requirements, for instance farmers who own two or more farm animals.

The manure feedstock limits the market to households that are animal owners. China is one of the biggest markets for biogas system with more than 25 million systems in use. Biogas plants have been implemented on a project basis in many African nations; the integration of agricultural farmland and biogas plants seem to be successful in Rwanda[48].

A major emphasis on marketing and promoting biogas energy systems is needed in rural areas. In Eastern and Southern Africa, ethanol gelfuel (ethanol with a gelling agent) was introduced with a strong government initiative (the Millennium Gelfuel Project), however wider dissemination did not follow due to severe flaws in the technology itself.

The efficiency of using ethanol gelfuel compared to LPG and kerosene was found to be significantly lower. The retail price of the fuel would have to be well below the current level, and compared to kerosene and LPG to make it competitive in the market.

2.4.3 DiMethyl Ether (DME)

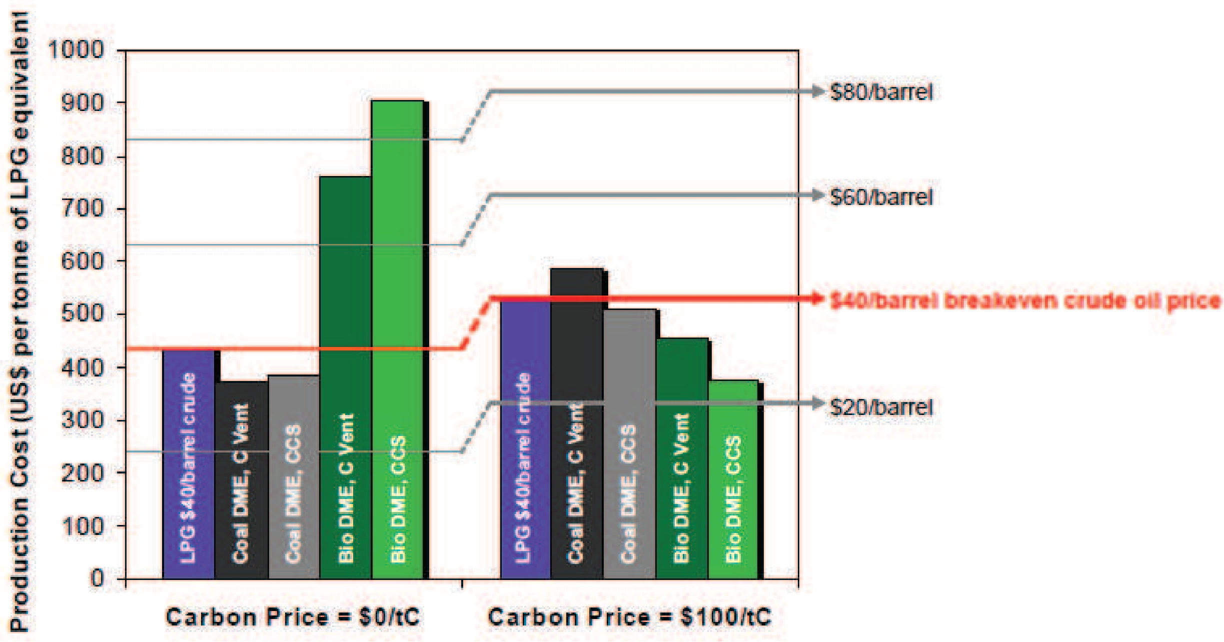
DME is primarily manufactured by dehydration of methanol derived from natural gas or coal. It has similar energy content and characteristics as LPG. It can be blended with LPG for use as a household fuel, where DME mixed up to about 25% by volume would need no change to end-use combustion equipment. DME and synthetic LPG (propane/butane) can also be produced from biomass via the gasification-based production[49].

Even though most gasification designs are primarily for synthetic transportation fuels, significant quantities for lighter hydrocarbons are produced as intermediate products, which can be separated from the heavier transportation fuel for sale as synthetic LPG or DME. Because of the similarities with LPG, DME could provide 'technological leapfrogging' opportunity for developing countries to provide modern cooking fuel for universal access. With gasification-based process, low-value feedstock could be converted to high-value fuel product.

48 Pachauri & Brew-Hammond, 2012
49 Larson & Li, 2012

Even though the production cost for biomass based DME would be very high compared to LPG or coal-based DME, by taking into account greenhouse gas emission and using carbon financing, such DME options can be comparable or cheaper than LPG in many cases (Fig. 13).

FIGURE 13 - Production cost of LPG vs. DME with and without carbon pricing



Source: Williams, n.d.

Another modern cooking fuel is compressed natural gas (CNG). CNG is methane stored at high pressure that can be used in place of LPG. CNG is superior in safety and produces fewer undesirable greenhouse gases compared to LPG. However, at present economics of the fuel are not favorable in comparison to LPG and DME. CNG is primarily found in developing countries as a fuel choice for the transportation sector. Table 4 shows cost and characteristics for selected fuels.

TABLE 4 - Cost and characteristics of selected fuels

	Capital Cost *	Fuel Cost	Notes
LPG	$45-60	$0.55-$0.70 per kg	Commercially available; more widely used in urban sector; issues of affordability, refill cost, and supply chain in rural sector
DME	$45-60	$0.25-$0.35 per kg	Similar to LPG; demonstration phase
Biogas	$100-1000 (Cost of digester)	0	Commercially available; direct fuel cost is zero (available biomass, organic matter used); economic in village scale
Ethanol gel	$2-20	$0.30-$0.70 per liter	Deployment phase; location specific where large sugar cane plantation is available

*Note: * Cost of stove and cylinder; Source: International Energy Agency, 2010b*

As mentioned previously, the criteria for choosing a specific fuel will depend on various factors. Key parameters are listed below:

- availability of the resources/fuel;
- economic viability (for both end consumer and investor),
  - comparison with the current situation and the alternatives: a large number of households still resort to solid fuels for cooking since they are more affordable relative to LPG and electricity,
  - time to recover the investment,
  - possibility of subsidies or other financial support (like Clean Development Mechanisms under the Kyoto Protocol);
- suitability for local users, taking into account their habits, cultural preference etc.;
- sustainability (fuel supply chain, maintenance conditions, robustness, durability, replacement conditions for stoves);
- scalability;
- security of supply/quality of service.

2.5 Environmental impact

According to a World Bank's 2011 survey, the average amount of biomass cooking fuel used by a typical family can be as high as 2 tons per year[50]. Reliance on such traditional biomass cookstoves can lead to a wide variety of environmental problems. In many countries, much of the native forest cover has been stripped to support charcoal production (e.g. Cambodia). Reliance on wood fuel can lead to increased pressures on local forests and natural resources. The unsustainable collection of wood for charcoal production can contribute to mudslides, loss of watershed and desertification. Charcoal production has been in rise in many African nations. Notably charcoal export to Gulf countries is a thriving business in Somalia. Studies by the Ministry of Pastoral Development & Environment, and the United Nations Environmental Program (UNEP) have linked this charcoal production to excessive flooding, soil erosion, loss in local flora and fauna, and droughts in many parts of the country[51,52]. Similarly, Tanzania and

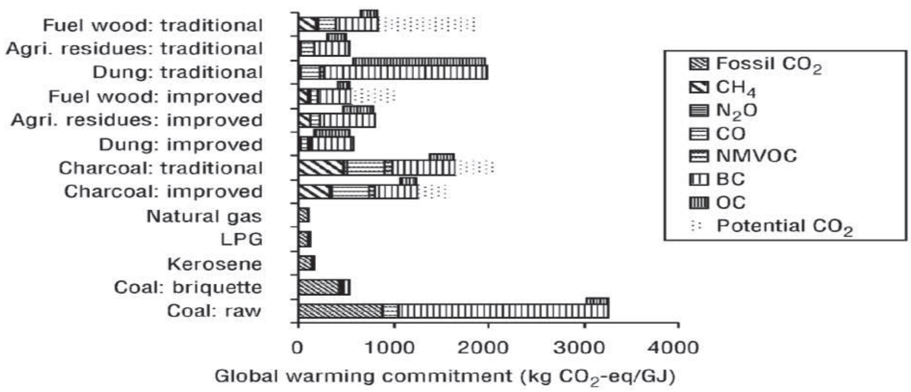
[50] By contrast, a family that uses LPG as its cooking fuel requires only about 0.2 tons per year.
[51] *Impact of Charcoal Production on Environment and the Socio Economy of Pastoral communities of Somaliland*, 2004
[52] *The State of the Environment in Somalia - A Desk Study*, 2005

Kenya also face sever environmental effects due to excessive charcoal production to support their energy demand[53,54].

There is mounting evidence that biomass burned inefficiently contributes to climate change, suggesting that the climate change debate needs to take household energy issues into consideration. There is evidence[55] that biomass fuels burned in traditional ways contribute to a buildup of greenhouse gases and black carbon in the atmosphere. In developing countries, about 730 million tons of biomass are burned each year, amounting to more than 1 billion tons of carbon dioxide (CO_2) emitted into the atmosphere[56]. Similarly, open fires using biomass are responsible for 75% of the black carbon in the atmosphere in the developing countries. Researchers from the University of California, Berkley, estimate that the burning of household fuels for cooking causes almost half of ambient health-damaging particulate air pollution in India[57]. The burning of solid fuels also produces significant quantities of emissions that impact the climate in the short-term, including gases such as methane, carbon monoxide, and nitrous oxide. Reduction of black carbon and other products of incomplete combustion is an attractive approach to mitigation of the effect of global warming and air pollution.

The increasing use of intermediary products such as charcoal also has environmental impact. Charcoal is heavily used in Eastern and Southern Africa; not only in rural areas but urban dwellers also prefer charcoal for cooking purposes. High demand has lead to scarcity and overharvesting, contributing to forest and soil degradation. Sustainability, not just economical but environmental, has to be considered when thinking about providing for billions for universal access. Prior studies have looked at global atmospheric impacts of residential fuels (Fig. 14), and shown modern cooking options such as LPG and natural gas to be least environment damaging. Not only the types of fuel, but cookstove types (traditional vs. improved) can make a huge difference (example: dung-traditional vs. dung-improved in Fig. 14).

FIGURE 14 - Global warming commitment by 1 GJ of energy delivered to a cooking pot for 20-year time scale



Source: T. Bond, Venkataraman, & Masera, 2004

[53] Msuya, Masanja, & Temu, 2011
[54] Bailis, 2005
[55] Ramanathan & Carmichael, 2008; Venkataraman, Sagar, Habib, Lam, & Smith, 2010b
[56] Adams, 2011b
[57] Global Alliance for Clean Cookstoves, 2011

Scientists believe that reaching the goal of universal access to modern energy services for cooking will have a relatively small impact on energy demand and production, and CO_2 emissions worldwide [58]. Even though the emission characteristics of biomass burning cookstoves are considered critical for climate science, there is significant uncertainty about whether black carbon emissions from burning biomass in cookstoves have a net warming effect on climate globally[59]. Certain uncertainty is due to information gap, i.e. lack of data for attributes such as total amount of biomass combustion, and exact type of technology for burning. Larger uncertainty comes from the lack of knowledge of the ratio of black carbon to organic carbon during combustion. Radiative forcing due to black carbon causes temperature to rise. However, organic carbon cools the climate. Since both particles are released during combustion process, the ratio is essential to make correct environmental impact studies. The best estimate of climate forcing due to black carbon is $+1.1W/m^2$ with 90% uncertainty band of $+0.17W/m^2$ to $+2.1W/m^2$. For comparison, climate forcing due to CO_2 is $+1.56W/m^2$ and methane (CH_4) is $+0.86W/m^2$ [60].

2.6 Enabling environment

Cooking is an energy service that is often associated with strong and highly specific fuel and appliance preferences. Many times cooking is only one of a range of services that are delivered from a stove or a fire in a rural household. For example, coal or wood stoves can serve multiple functions including cooking, space heating, water heating, lighting and social focus.

The multi-functionality of some stoves is one of the key reasons why households are averse to substitution of their old stoves for newer more efficient technologies. Fuel price and availability have a very significant impact on energy consumption patterns for cooking as well. For example, in China, coal is readily available and has a relatively low price. Thus, close to 30% of people in both urban and rural areas in China use coal as their main cooking fuel. Similarly in Cambodia, charcoal is the primary fuel for cooking. Thus, the improved cookstoves are designed specifically to burn charcoal. Apart from fuel cost and availability, various regulatory and financing issues have to be dealt with a top-down approach i.e. from the institutional level with international/national policies, national mandates etc. These are discussed below.

2.6.1 Energy policy, regulation and governance

Country or region specific regulatory policies have helped in the wide acceptability of a technology. In India, Gujarat became the first state to have a promotion program for solar cookers in 1979. The program provided insights to product designing, distribution, pricing, and marketing to a network of dealers and users to support the sales of the solar cookers. This was the beginning of solar cooking in India.

[58] International Energy Agency, 2010
[59] Adams, 2011; Bond, Venkataraman, & Masera, 2004
[60] T. C. Bond et al., 2013

Through the Jawaharlal Nehru National Solar Mission (JNNSM), a total of around 0.5 million m^2 of solar collector area has been installed by the end of 2010. Since 2002, physical targets have been set for the total number of units of solar cookers to be in use in the national five-year plan. Similarly in China, solar cooker is an important part of the technology portfolio under renewable energy, and it is highly subsidized (50-75% of the unit cost) by the government.

Key institutional and regulatory barriers for successful deployment of any cooking technology can be listed as follows:

- limited capability to train adequate numbers of technicians/workers to effectively work to support manufacture, transport and supply chain of cookstoves;

- limited understanding among key national and local institutions of basic system and finance;

- procedural problems such as the need to work with several public sector agencies (e.g., in India: MNRE, Planning Commission, JNNSM, and the Ministry of Rural Development);

- heavy subsidies on cooking fuels, such as kerosene, discourage the use of any new technology for cooking;

- difficulty in expanding the infrastructure for natural gas and LPG in remote rural areas will leave only biogas as the main option for modern cooking in these regions.

The major drawbacks mentioned in the previous section for various technologies can guide the design of proper energy policies and regulation that will help in making advanced clean cookstoves and other modern technologies a household commodity product in rural areas. The following steps have helped many countries in raising the profile of advanced cookstoves for example, and some combination of such energy policies can help increase the contribution of modern technologies to the overall cooking use.

- Raising global awareness of the health and environmental benefits of clean cookstoves and fuels.

- Setting ambitious but practical goals and roadmaps for technology adaption: For example - the Global Alliance for Clean Cookstoves has a ten-year goal to foster the adaption of clean cookstoves and fuels in 100 million households by 2020[61].

- Possibly provide capital grants and subsidies for stoves but not for fuel. Policies can be placed to improve affordability by providing microcredit or loans to lower upfront payments.

- Advancing the use of innovative finance mechanisms for large-scale dissemination of clean stoves: For example - a successful business model based on microcredit finance

[61] Global Alliance for Clean Cookstoves, 2011

was developed for distribution of the ceramic charcoal stove (Jiko) in Kenya, which enabled the product to move from an NGO domain to a for-profit business.

- Supporting capacity building for stove production and marketing including working with women's collective and NGOs: For example - the bucket stove in Cambodia was successfully distributed by identifying women organization as an important part of the supply chain by GERES, where women from various local organizations would do door-to-door sales and promotion.

- Addressing import tariffs and trade barriers: Often times, to conserve one's foreign exchange for other goods and products, small countries have very limited capacity to import cooking fuels. The solution to such obstacle is to adopt appropriate cooking fuel import polies and provide subsidies or loans to the poor to pay the upfront cost of both modern and advanced fuel cookstoves. China's policy to loosen restrictions on the import of LPG in the early 90's is an example of enabling environment that promoted clean cooking fuel within the country.

- Mobilizing effective sales, distribution, and supply chains, and engaging women as key allies in the cookstoves business chain.

2.6.2 Funding and financing

The financing strategy is one of the key aspects for a successful dissemination of any technology. Due to the higher cost of all the alternatives (improved cookstoves, solar cookers and modern fuel cookstoves) compared to traditional cookstoves, which are build at no cost by most (rural) households, some financial support is needed to help consumers lower or spread out technology/fuel costs. Financial aspects would need to balance loans and grants, taking both cost and affordability into consideration. For a financing scheme that is common in developing countries, there are three main players: institutions to manage energy funds that can provide financing (World Bank, other national/regional banks); microfinance organizations or NGOs that can organize demand, provide customer support and collect loan payments; and retailers that can sell equipment for cash and provide product guarantees. Microcredit has been proven to be a successful solution to the rural finance problem when implemented correctly. Grameen Shakti in Bangladesh is an example of a successful microcredit-lending agency that has helped millions get small loans for energy service system (solar home system).

The idea of reducing high-quality stove costs through mass production is a promising trend, one that has worked successfully for other commodity items such as cell phones. However, many "successful" cookstove technologies are in the early stages of learning curve in terms of both design and dissemination. Most of the mass-manufactured stoves are made in China. Mass manufacturing can also elevate quality, which is an important factor for adaption of any technology. To lower the overall cost, such mass manufacturing capabilities will have to be expanded to other countries as well.

'*Enterprise*' financing can also help lower the cost structure and enable positive returns at a lower price point, where financing is used to support a local entrepreneur who wishes to become distributor for a technology/fuel thus supporting supply chain.

Since improved cookstoves and other modern cooking technologies/fuels have shown evidence of lower CO_2 emittance, the role of climate-finance instruments needs to be further explored. '*Carbon-finance*' works through carbon offset programs that provide credits to developed world buyers for greenhouse gas reductions from improved technologies deployed in developing countries. Within the World Bank, the Carbon Funds and the Climate Investment Funds are some examples that can play major roles in coordinating and implementing possible funding source.

2.7 Business models

International organizations, NGOs and governments have mainly distributed advance cookstoves. A successful for-profit business model for such cookstoves is harder to find due to the small profit margins. Local entrepreneurs with local manufacturing and good distribution chains can probably make a good business case for advanced cookstoves. Similar is the case for solar cookers, as well as for cookstoves for modern fuels.

2.7.1 Government

Many countries have energy policies and mandates that allow for large distribution of advance cookstoves directly by the government or through public/private sector with subsidies and other financial incentives. The Chinese National Improved Stove Program (NISP) is the most successful example of broad dissemination by a government, where nearly 166 million households adopted improved stoves[62]. The program did rely on rural private stove companies for its success.

The government provided support for design, stove construction, training, administration and promotion support through local energy offices. One of the key mandates for these energy offices were to foster self-sustaining rural energy enterprises that manufactured, installed and serviced the stoves. However there have been failures on the government part as well. The Indian National Program on Improved Chulhas (NPIC) is seen as an example of things that can go wrong with government-run cookstove initiatives. NPIC was criticized for poor stove design, high program cost, low uptake rates, and undermining of pre-existing local markets for stoves with heavily subsidized stoves[63].

Successful transition from kerosene to LPG stoves over a four-year period was observed in Indonesia in 50 million households as a part of a government initiative, where the Indonesian National Oil Company played a key role in supply and distribution, and was the main

[62] Foell, Pachauri, Spreng, & Zerriffi, 2011a
[63] Shrimali, Slaski, Thurber, & Zerriffi, 2011a

implementer[64]. Apart from providing improved household cooking fuel, the government was able to reduce the huge subsidy for petroleum fuels. Similarly, significant penetration of LPG as cooking fuel was made possible in Brazil through a government run program that included fuel price administration and subsidies.

2.7.2 Non-governmental organizations (NGOs), cooperative, non-profit

Introduction of improved cookstoves at a reasonably large-scale is possible via NGOs working in different countries. Successful dissemination of more than 500,000 stoves in Uganda through a GTZ project is an example, where 'scaling up' occurred due to long-term investments in the supply chain and other ancillary activities such as information campaigns, research and testing centers, and capacity development[62]. However, reality on the ground is that many times NGO efforts remain small-scale and unused in the medium term due to insufficient attention to scalability and sustainability.

2.7.3 Private, for-profit

Historically, the government and NGOs have been the primary players in dissemination of technology meant for universal access. With growing recognition of the market opportunities, new private players have come forward with innovative business models; these are small and large energy corporations. For successful business, important external factors are: low risk and stable environment, and transparency and good governance at the national level.

The Kenya Ceramic Jiko charcoal stove is an example of a successful commercial venture that was initially developed with substantial NGO funding in the early 1980s but over time made the leap to commercial sustainability. By 2002, approximately 2 million units are in use in Kenya alone with additional 8 million sold across Africa[65].

A recent study of Indian market has shown influences of six key elements in a business model: design (technology), customers targeted, financing, marketing, channel strategy (quality and maintenance in the supply chain), and organizational characteristics[66]. Commercial efforts are slowly taking the market share for providing technologies to the Bottom-of-the-Pyramid (BOP). Many times, the customer who has to spend $10-$50 on modern improved technologies for cooking do not value things that may look important from outside such as value of health-improving characteristics, or time saving aspects.

For commercial success, marketing of these technologies have to be such that they become desirable commodities or "status goods" that are aspirational. The business model of '*anchor-*

[64] Budya & Yasir Arofat, 2011; Foell, Pachauri, Spreng, & Zerriffi, 2011b
[65] Pachauri & Brew-Hammond, 2012; Shrimali, Slaski, Thurber, & Zerriffi, 2011b
[66] Shrimali et al., 2011b

customer', popular in rural electrification, can also be utilized for selling cooking technologies, where commercial customers (school cafeteria, hotels, hospitals etc.) can cross-subsidize for household customers with less purchasing power.

Social marketing is an integral part of a successful business plan for universal access products. It can be used to create awareness of the product and its benefits. To reach rural customers, companies may need to do client/location specific promotion, joint or cooperative promotions involving rural organizations such as Panchayat, women specific organizations, etc.

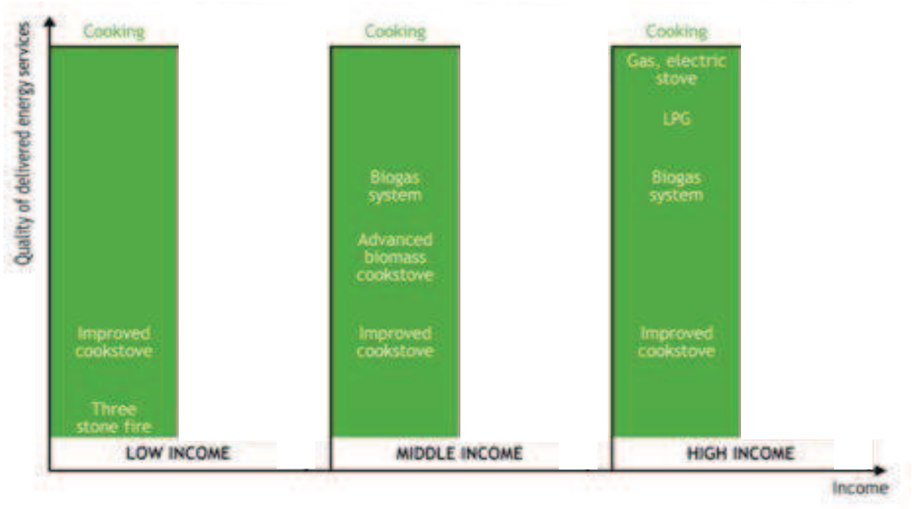
2.7.4 Public Private Partnerships (PPP)

Public Private Partnerships (PPP) are increasingly becoming a common choice in such endeavor where just one entity cannot handle all the issues on its own, and it is the means for addressing salient issues and sharing risks. Two examples of PPP in recent times are LP Gas Rural Energy Challenge and Global Alliance for Clean Cookstoves. With such partnerships, as the risks are distributed, with proper organizational setup, various challenges of technology dissemination can be handled to ensure higher dissemination rate for universal access.

3 Conclusions

Even though there are various choices – improved stoves, solar cookers, biofuels, LPG, and sometimes they are in competition, all are needed to achieve universal access. No single solution fits all in improving access to energy for development. As shown in Figure 11, various solutions work for different economic strata. This division roughly indicates rural and urban solutions as well, with improved cookstove and biogas systems being the modern solution for rural households, whereas LPG and electric stoves will be the ultimate solution for urban population.

FIGURE 15 - The quality of energy services (for cooking) and household income



Source: International Energy Agency, 2010b

Along with technical developments aimed at higher efficiency and performance, supportive policies and institutional frameworks need to be created to encourage both public and private sector participation, with focus on replicability and scale-up of successful programs. A wide portfolio of technologies, and a variety of innovative business models, which are adapted to local circumstances are required to meet the universal access challenge.

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Enel Foundation
Energy for Knowledge

Via Arno, 64
00198 Rome
(Italy)

P. (+39) 06 83054575
F. (+39) 06 64445622

info@enelfoundation.org

www.enelfoundation.org

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