Master thesis Energy Science

Implementation of low carbon energy solutions for water irrigation in India

Name: Maarten de Vlugt
Student number: 3141683
Master program: Energy Science
E-mail: m.v.devlugt@students.uu.nl

Supervisors
MSc. M.A.M. Corsten (UU)
Prof. Dr. E. Worrell (UU)
Dr. A. Kumar (TERI)

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Abstract

Water pumping for irrigation is a big contributor to Indian carbon emissions, as it is responsible for a large share of Indian electricity and diesel consumption. Incomes of most people in India are dependent on agriculture and increasing incomes through irrigation can improve their quality of living. In addition to that, irrigation is essential for India to sustain self-sufficiency in food production. Diffusion of low carbon energy solutions for irrigation in India has slowly started, but remains far below its potential. This research is concerned with options to reduce carbon emissions for irrigation in India and issues affecting the implementation of new technologies. This study concludes that solar photovoltaic (SPV) pumps, windmill pumps, solar-wind hybrid systems, increasing energy efficiency and drip irrigation are suitable low carbon energy solutions for irrigation in India. Furthermore, it shows that high initial costs and unattractive payback periods are not the main financial barrier for some low carbon energy solutions, such as windmill pumps and increasing energy efficiency. The lack of access to formal financing facilities in rural areas does form a barrier as well. Programmatic Clean Development Mechanism (CDM) and subsidies are appropriate options to increase financial attractiveness of low carbon energy solutions for irrigation. The commercialisation of microfinance can increase farmers´ access to formal credit in rural areas, although this trend should be strictly controlled by the government. From a SWOT analysis can be concluded the best low carbon solution differs per location and depends on many factors, such as annual solar irradiation, average wind speed, type of soil and crop, requirements and habits of farmers etc. This research suggests that there should be more emphasis on the needs and values of farmers. It is therefore of great importance to support local grass root initiatives, which enable famers’ access to information and knowledge about modern irrigation practices. Combining drip irrigation with renewable energy technologies and knowledge about farmer’s needs and irrigation practices will accelerate the diffusion of low carbon energy solutions for irrigation in India.

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1. Introduction

Anthropogenic climate change due to increasing greenhouse gas (GHG) emissions is one of the biggest challenges we are facing at this moment. Growing energy needs, largely met by fossil fuels, is seen as one of the biggest contributors of global GHG emissions. Estimated is that global energy demand will increase by one-third in the next 25 years (IEA, 2011). Although industrialized annex I countries are the biggest contributors of carbon emissions at this moment, non-annex I countries will be responsible for most of the growth. Only China and India will already account for 50 percent of this growth (IEA, 2011). As you may expect, energy is considered as an important driving force of economic growth, but has also a direct impact on social development, since energy influences the quality of education, health and agriculture (Chaturvedi and Samdarshi, 2011). India has a high economic growth and develops quickly, as income per capita has averaged an increase of 7.5 percent annually over the last decade with minimal impacts of the global recession (OECD, 2011; Aggarwal, 2010).

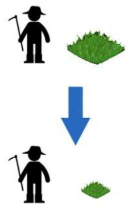
Table 1: Human Development Index

Rank	Country
1	Norway
3	The Netherlands
4	United States
101	China
134	India
142-187	Low Human Development

Besides the economic growth, India has made substantial progress on social welfare with the Human Development Indicator (HDI) increasing from 0.320 in 1980 to 0.519 in 2010 (UNDP, 2010). This indicator is a way of measuring development by combining indicators of life expectancy, educational attainment and income into a composite human development index (UNDP, 2010). Although there has been progress in social development the 134th position of India is right above low human development countries and has to improve significantly.

The growth of economic development is not homogenous distributed over different sectors, which has an impact on social development. While the service sector´s GDP as share of total GDP in India has increased from 37 percent in 1960 to 54 percent in 2010, India's agricultural GDP as share of total GDP has declined from 42 percent in 1960 to 19 percent in 2010 (Worldbank, 2012). Decreasing Indian agricultural GDP does not mean a decline in the number of people dependent on agriculture. Around 69 percent of the population and 76 percent of the poor population lives in rural areas and the lion's share depend on agriculture for their income (MHA, 2011; Sundaram and Tendulkar, 2003). The number of people depending on agriculture for their income is still growing, despite decreasing agricultural GDP as share of total GDP and an increasing share of rural population migrating to urban areas. There is a

Figure 1: Declining land-man ratio



growing number of marginal landholders (owing less than 1 hectare of land) and small landholders (owing 1 to 2 hectare of land), at the expenses of medium and large landholding farmers (MOA, 2011). Due to an explosion in agricultural population since 1960, the land-man ratio declined from 0.4 ha/person in 1900 to less than 0.1 ha/person in 2000 (Shah, 2009). Since there is a direct and obvious link between landholding size and income, efforts in social development and poverty reduction should be focused on small and marginal landholders (Chamberlin, 2008).

Besides improving the financial situation for farmers, investments in agriculture are necessary for a sustainable food production. For India, as well as globally, agriculture is of great importance as people depend on agricultural products in all aspects of everyday life, mainly by providing food. During the 'green revolution', the period between 1963 and 1975 when high yielding seeds, fertilizers and technologies were widely introduced, India became self-sufficient in food production. But its self-sufficiency is currently compromised as food demand is expected to increase by a rate of 3.5 percent per year in the next decade. India's domestic food supply is growing at a slower rate, meaning that food production has to increase (Jasani and Sen, 2008). The potential of bringing more land under cultivation in India is almost non-existing as net sown area, which was around 140 M ha in 2007, has been constant during last three decades (Kumar, 2004). Since there is an increasing pressure on land for a variety of non-agricultural requirements it is unlikely to increase the land area under cultivation to increase food production. Therefore, food production per unit area under cultivation has to increase in order to achieve food security. This can be accomplished in the form of enhanced irrigation and fertilizer.

At this moment, the level of mechanization of agricultural practices in India is still low. Water pumping for irrigation is responsible for the largest need of energy services, followed by power for farm machinery, such as threshers and tractors (de la Rue du Can et al, 2009). Estimated is that water pumping for irrigation consumes around 18-20 percent of the electricity generated in India and around 4-4.5 billion litres of diesel per year (TERI, 2010; Rao, 2009; Shah, 2009). In comparison, the amount of electricity used to pump water for irrigation in the United States was around 10 billion kWh in 1998, which was about 0.3 percent of total electricity consumption (ICF International, 2008). Looking at the trend of using ground water as the main source for water in India, it is expected that the energy consumption will further increase in the future (Shah, 2009). Although central and state governments in India invested over US $20 billion dollars since 1990 in new surface irrigation systems, the net area served by surface irrigation declined more than 3 million ha, while the net area served by groundwater has been steadily rising (Shah, 2009). Over the past three decades, groundwater has become the main source of growth in irrigated areas. In comparison to surface irrigation, pumping water from ground resources is very energy intensive. At this moment, groundwater accounts over 60 percent of the irrigated area in India (India Infrastructure Report, 2011). The rate at which Indian farmers are currently using groundwater resources will have serious implications on environmental and ecological conditions.

Low carbon energy solutions for irrigation have the potential to reduce farmers' energy requirements and lower Indian GHG emissions. Furthermore, it can play an important role in poverty reduction and sustaining self-sufficiency in food production. Despite governmental initiatives to reduce carbon emissions related to irrigation, clean technologies are adopted at a slow rate, far below their potential. In order to reduce GHG emissions, in combination with the fight against poverty and to sustain self-sufficiency in food production, low carbon energy solutions for water irrigation are needed with a focus on small and marginal landholders in India.

2. Research outline

Growth in both energy requirements and GHG emissions in non-annex I countries are increasingly being seen as an important element in future global energy and climate scenario (IEA, 2011). It is essential to delineate undesirable growth trends at an early stage in order to avert any potential threats. In India, energy and water requirements for irrigation are increasing and result in a growing carbon footprint of the agricultural sector. This research is concerned with possibilities to decrease carbon emissions in the process of water irrigation in India. Therefore, it is of great importance to know which low carbon energy solutions are suitable for small and marginal landholders in rural areas of India and to which extent they can achieve reductions in GHG emissions. Furthermore, it is important to focus on the dissemination and implementation of low carbon energy solutions in rural areas of India. In order to do so, barriers for implementation of these energy solutions should be known. This information will help future policymakers with the promotion and diffusion of these technologies. Furthermore, it is necessary knowing what experiences there are with implementation mechanisms and to which extent implementation mechanisms are able to accelerate the dissemination of low carbon energy solutions.

2.1 Research question and sub-questions

This research will answer the following question:

What are the most suitable low carbon energy solutions for water irrigation in India, and how do technical, economic, social, environmental and resource-related factors influence the application and implementation?

In order to be able to give an answer to the research question, the following sub-questions are defined:

1. What is currently the situation of irrigation in India, which technologies and techniques are used?
2. What are low carbon energy solutions for irrigation and which solutions are suitable for small and marginal landholders in India?
3. How is technology appropriateness defined and how do the defined energy solutions score on the defined characteristics of the technology appropriateness framework?
4. What are the costs and payback periods for different options and what is the paying capacity and willingness to pay of farmers?
5. Which resources are needed and available for the low carbon energy solutions?
6. What is the CO_2 mitigation potential of the solutions?

7. How are the low carbon energy solutions fitting the socio-cultural context?
8. What experiences are there with different implementation and delivery mechanisms?

2.2 Methodology and research outline

Firstly, this research will focus on the first part of the research question (What are the most suitable low carbon energy solutions for water irrigation in India) and describes the relation between energy and water irrigation. It looks at the current situation in India focused on energy consumption for irrigation. In order to find low carbon energy solutions, an in depth literature research is done to provide an overview of all available technologies, which have zero or less CO_2 emissions compared to current diesel or electric pumps (chapter 3). This overview will describe both Renewable Energy Technologies as well as Energy Conservation options. Based on literature and opinions of experts, low carbon energy solutions suitable for irrigation in India are selected.

Secondly, this research will focus on the determination of the strengths and weaknesses of the options found in the first part of the research. Suitable low carbon energy solutions for irrigation found will be analysed by literature research and interviews with experts. Furthermore, an important aspect of input for this research is the field visits performed to gain more information from Indian farmers about their experiences with low carbon energy solutions and their motivation to adapt new technologies. This information is currently not available, and therefore twelve villages were visited around Moradabad and Saharanpur to interview 48 farmers and perform 12 group interviews. It was of great value to actually experience the lifestyle of Indian farmers and to collect valuable information about their perceptions related to irrigation. All this information is used to analyse each of the following elements:

- *Technology appropriateness* (chapter 4). An important aspect is that the low carbon energy solution should provide the same functions and energy as the current technology fulfils. A framework based on literature about diffusion of innovation and factors influencing adoption of energy service improvements in rural areas is provided. This framework is used to assess to which extent low carbon energy solutions are appropriate for farmers in India. It is essential that new technologies meet the needs of the farmers in order to be accepted as a replacement technology.
- *Economic viability* (chapter 5). To get insights in economic barriers, the current costs and payback periods of energy solutions are estimated. These estimations are based on literature and information provided by manufacturers. Paying capability of small landholders in rural areas

is assessed using data made available by the Reserve Bank of India and literature. The willingness to pay for these solutions is discussed using a research performed by the Worldbank in 2001 on power supply to the Indian agriculture.

- *Resource availability and environmental sustainability* (chapter 6). Sufficient resources to provide the energy which is required for pumping water for irrigation are needed. For solar energy, this is assessed using data provided by high-resolution satellite data from NASA SSE for radiation data. For wind energy, wind speed measurements under government's program and the NCEP/NCAR Reanalysis data for wind speed data are used. Based on the resource requirements for different technologies found in literature, high potential areas are indicated. Furthermore, a rough estimation is made for the CO_2 mitigation potential based on the utilization potential of low carbon solutions, based on values found in literature. One of India's main environmental concerns is declining water tables in many regions due to over extraction, so the influence of irrigation on ground water table is assessed as well.
- *Social-cultural acceptability* (chapter 7). An understanding of cultural beliefs and views of Indian farmers is necessary to comprehend the motivational factors behind the acceptance or rejection of energy solutions for irrigation. The farmers' attitudes towards and experiences with low carbon solutions for irrigation in India is investigated during personal and group interviews. This will give insight in the barriers and problems farmers foresee.

This second part of the research is concluded by a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis (chapter 8). The SWOT analysis will highlight the strengths, weaknesses, opportunities and threats of different low carbon solutions in India.

The third part of the research focuses on implementation mechanisms (chapter 9). Once the solutions and barriers are known, implementation mechanisms are able to promote diffusion of low carbon energy solutions. In general, there are two types of approaches, namely regulatory approaches, including standards and labelling programs, and economic approaches, such as providing micro credit or carbon financing. Since initial costs are the main barrier of introducing clean technologies, the focus in this research will be on economic approaches.

3. Low carbon energy solutions

This chapter will start with an overview of the Indian agriculture, focused on irrigation. This is followed by a description of low carbon energy solutions for irrigation in India.

3.1 Introduction

India became independent from Great Britain in 1947, which announced a new era focused on agricultural growth. India's government implemented policies and program initiatives to encourage an expansion of cultivated area and an increase in food production. This extension was essential in the light of the rapid growing population[1]. In order to increase yields, new high yielding seeds, fertilizers and technologies, like irrigation systems, were introduced in the period between 1963 and 1975, often referred to as the 'Green revolution'. From 1960 to 1980, both the net irrigated area and the gross irrigated area[2] increased in India, as can be seen in Table 1. The net irrigated area continued to grow and has reached 63.2 M ha in 2009, while net sown area has been constant over the past three decades (Table 2). The increase in both net and gross irrigated land, combined with an increase in using high yielding seeds and fertilizers, allowed India to pass from a food-deficient country to one of the world's leading agricultural nations.

Table 2: Agricultural land in India

	1960	1970	1980	1990	2000	2009
Net irrigated area (M ha)	24.66	31.10	38.72	48.02	55.13	63.20
Gross irrigated area (M ha)	27.98	38.20	49.78	63.20	76.19	88.42
Net sown area (M ha)	133.20	140.86	140.29	143.00	141.36	141.36

Source: MOA (2011)

This development in agriculture resulted in a significant growth in energy consumption, as can be seen in Table 3.

[1] India's population in 1901 was about 238.4 million, which has rapidly increased by more than four times in 110 years to become second largest nation worldwide, after China, with a population of 1,210 million in 2011 (MHA, 2011).

[2] The gross irrigated area is defined as the area irrigated during a year, counting the area under more than one crop during the same year as many times as the number of crops is grown (MWR, 2005).

Table 3: Final energy consumption in agricultural sector in India

	1990	2005	2020 (projected)
Final energy consumption Indian agriculture (PJ)	378	659	940

Source: de la Rue du Can et al (2009)

The largest need of energy services is for water pumping for irrigation, followed by farm machinery, like threshers and tractors It is estimated that irrigational water pumping was responsible for around 439 PJ (67%) of the 659 PJ of final energy consumption in 2005 (de la Rue du Can et al, 2009). Most water is pumped using electric pump sets, followed by diesel pump sets. At the end of March 2012, there were about 17.7 million electric pump sets reported by the Central Electricity Authority (CEA, 2012). Due to unmetered billing in most parts of India for agricultural energy consumption, the amount of electric energy used by electric pump sets is an estimate[3]. This estimation is based on the amount of water which is pumped from the ground, the average water table, the average efficiency of pump sets and transmission and distribution losses in delivering power to pump sets (Shah, 2009). The amount of electricity consumed for pumping water for irrigation was around 87 TWh in 2001 and 104 TWh in 2008 and consists of around 15-18 percent of total electricity produced (Planning Commission 2007, TERI, 2010). Therefore, low carbon energy solutions for irrigation can have a significant impact on total electricity consumption in India.

There is high uncertainty about the number of diesel pump sets used in India for irrigation, since there are no institutions that are keeping track of this. According to values found in literature, the number of diesel pump sets used for irrigation is about 6 million in 2003 (Purohit and Michaelowa, 2005; de la Rue du Can et al, 2006), but has increased to 6.5 million pump sets used for groundwater pumping in 2009 (Shah, 2009). It is estimated that these diesel pumps annually consume around 4 to 4.5 billion litre of diesel. Despite efforts from central and state governments, the share of renewable energy technologies used for irrigation is currently negligible.

According to their annual report, the central government seems to aim for wind power and hybrid systems for pumping. In January 2011, there were 1351 windmill pumps and 1072 hybrid systems

[3] In the 1950s, state power utilities were aggressively promoting electric tubewells with meters. However, during the 1970s and 1980s when the number of electric tubewells rapidly increased, State Electric Boards found it costly and difficult to manage metering and billing. Due to high transaction costs, a flat tariff was introduced, based on the horsepower rating of the pump (Shah et al, 2004)

reported (MNRE, 2012a). The amount of solar pumps was estimated to be around 7100 in 2007, more recent numbers are not available, although the annual report of MNRE stated that the installation of more than 1600 SPV pumps is planned for 2012 (MNRE, 2012a).

Despite reforms in the power sector, electricity shortages are inevitable throughout India, which has a great effect on agricultural pumping. India's power deficit increased from 12.8 percent to 13.8 percent in the period 2010-2011, despite recent improvements in power supply (CEA, 2010). Due to low quality of electricity (i.e. voltage fluctuations and erratic power supply) many pump sets are oversized to avoid burnouts and to make sure to extract as much water as possible during the short periods when electricity is available (Purohit, 2007; BEE, 2009). Farmers even come up with innovative ways to avoid their dependence on electricity and use tractors with an internal combustion engine to power their water pump. These practices make it hard to estimate the energy consumption by agricultural pump sets. But with rising prices for diesel, solutions based on diesel or diesel pump sets are becoming less attractive as well.

Looking at the current quality of energy facilities, the highly polluting technologies and rising prices of fossil fuels, there could be a great potential for renewable energy technologies and energy efficient options for irrigation. The government has shown great effort to implement clean technologies over the past decade, by making subsidies available for farmers and support manufacturers of renewable energy technologies. But in most cases their ambitious goals were not achieved and the use of renewable energy technologies in agriculture is far below its potential.

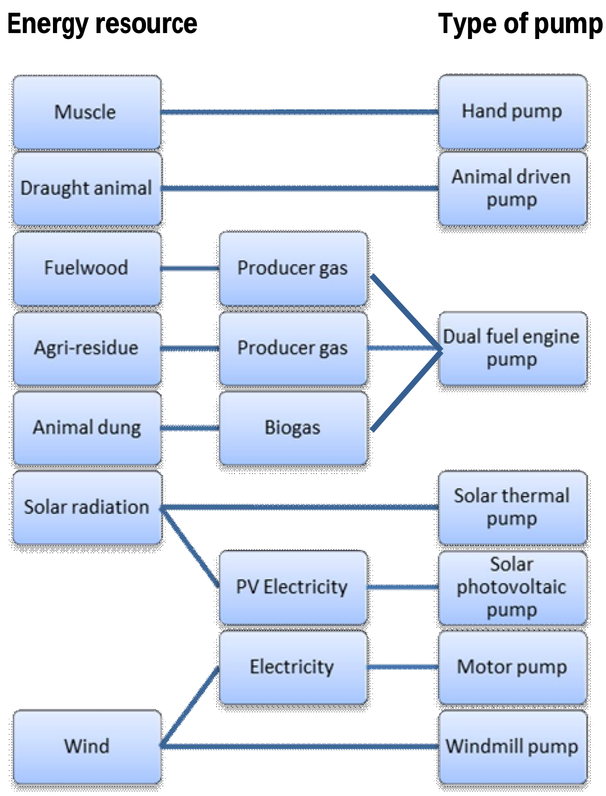
3.2 Low carbon energy solutions for irrigation

Generally, in order to decrease carbon emissions for water irrigation, there are two options applicable. The first option is to make use of renewable energy sources that have zero or reduced carbon emissions. The second option is to lower energy requirements, either by improving energy efficiency of existing pump sets or to lower water requirements for irrigation by modern irrigation technologies.

3.2.1 Renewable Energy Technologies

Energy resources for renewable energy technologies for water pumping for irrigation include man- and animal power, biomass[4], solar radiation and wind power. An overview of renewable resources and technologies combinations for irrigation water pumping can be found in Figure 2.

Figure 2: Renewable energy technologies for water pumping (based on Kumar, 2010)



The simplest form of water pumping (i.e. muscle and animal power) is a clean and simple, but labour-intensive option to pump water from the source to the field. There are many hand pumps found in India, mostly used for drinking purposes. Hand pumps and animal driven pumps are considered as an option for irrigation for small scale and domestic purposes, but are not an option for commercial farmers, as water requirements exceed capacities of those pumps. The same applies for solar thermal pumps as they have low efficiency and water output is below water requirements (Delgado-Torres, 2009). Therefore, muscle power, animal power and solar thermal pumps are not considered as options for irrigation for farmers in this research.

[4] Biomass is only considered renewable when it is sustainably grown (IPCC, 2007a)

There are four renewable energy technologies identified that can be used for irrigation in India. These options include solar photovoltaic (SPV) pumps, windmill pumps, producer gas based pumps[5] and biogas based pumps (Kumar and Kandpal, 2007; Purohit and Michaelowa, 2005; Purohit, 2007; Pathak et al, 2000). From these options, SPV pumps have the highest utilization potential in India, followed by windmill pumps (Kumar and Kandpal, 2007). The potential of SPV pumps in India is estimated between 6 and 70 million pumps[6] and windmill pumps have a potential of 4 million pumps. On the other hand, pump sets based on producer gas only have a potential of about 0.5 million and it is estimated that 36 thousand community biogas plants can be installed for irrigation pumping in India (Kumar and Kandpal, 2007). Producer gas based pumps can only be used in places where crop residues suited for these pumps are available in substantial amounts. Unfortunately, this is not the case in large parts of India (Kumar, 2004). Pumps based on biogas can only be installed when there is a substantial amount of dung available. It is assumed that households with less than 4 bovines can only contribute for a community type biogas plant and can not operate a family size biogas plant (Purohit et al, 2002). It is assumed that a significant share of Indian marginal and small landholders has less than 4 bovines. In that case, it may be better to look at decentralized generation of electricity, for example with a community type biogas plant or a small hydro plant where a part of the energy is used for pumping water for irrigation. However, this study only looks for suitable applications where the pump is directly driven by a renewable energy source. Therefore, SPV pumps and windmill pumps are seen as suitable low carbon energy solutions for marginal and small landholders in India, since they have the highest potential. A combination of the two options, a hybrid system on solar/wind energy, is taken in consideration as well, since both solar and wind resources are not always available when needed.

SPV pumps

Photovoltaic systems are installed all around the world. Total installed PV capacity world-wide reached over 67.4 GW at the end of 2011 (EPIA, 2012). This number is growing rapidly, since prices for solar modules are declining over time (Short and Thompson, 2003). Water pumping is considered as one of the most promising fields of PV application (Hamrouni et al, 2009; Short and Thompson, 2003; Purohit,

[5] Produces gas is gas extracted from crop residues. These residues are also used as fodder and fertilizer, so only the following non-fodder, non-fertilizer crop residues have been considered as potential feedstocks for produces gas: arhar stalks, cotton stalks, jute sticks, maize cobs and stalks and mustard stalks (Kumar, 2007)

[6] According to a research done by Kumar and Kandpal (2007), SPV pumps have an utilization potential of 6.03 million. However, another research by Purohit (2007) indicates an utilization potential of 70 million SPV pumps. Although they have used almost the same parameters, Kumar and Kandpal also took the affordability of farmers into account and assumed that marginal and small landholders (owing less than 2 ha) can not afford this technology. Purohit (2007) looked at the potential of using Clean Development Mechanism for the diffusion of SPV pumps and did not make this assumption, which explains the difference between the two estimations.

2007; Bucher, 1996). There are many benefits for photovoltaic water pumping, not only in rural areas where no electricity is available, but also in electrified areas. These benefits include little maintenance, no emission of greenhouse gases while pumping water, reliability, ease of installation and the autonomy of the system. Most likely, water requirements increase during hot weather, when solar radiation intensity is high and the output of the solar array is at its maximum. Main obstacles are low PV cell conversion efficiency and, related to that, high initial costs. Another disadvantage is the variable water production (Abdolzadeh and Ameri, 2009).

Figure 3: SPV pump

A SPV pump system consists of a PV array, an electric motor and a pump. In most cases a controller and a storage tank are included as well. The PV array converts sunlight in electric energy. Different materials can be used for the PV array, but at this moment the most common crystals that are used are monocrystalline Si, polycrystalline Si and amorphous Si. The capacity of the PV array for water pumping is usually between 900 and 1800 Wp, although bigger systems are available and upcoming[7] (Purohit, 2007; Kumar 2004).

The array is connected to the motor in case of a DC motor, but a controller is mandatory when using an AC motor, since it contains the inverter to convert the current from DC to AC. A controller can improve the efficiency, as it provides the motor with the optimum voltage and current for the site conditions. The controller is the most vulnerable part of the system, so the location has to be well considered. The controller should not be located on high ground, because water pumps extract lighting, which can damage the electronics in the controller. Also, it is of great importance to have proper glands around the cables to prevent ingression of water and insects (Short and Thompson, 2003).

Electric motors are used to power the pumps. Pumps can be classified based on their pumping principle. Generally, there are two types of pumps: rotating pumps and positive displacement pumps. Rotating pumps, like centrifugal pumps, make use of a difference of pressure where the high-speed rotation of an impeller sucks water in through the middle of the pump and 'throws' water out at the edge. The output

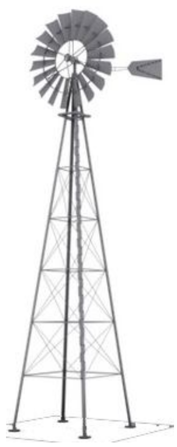
[7] In 2011, a new solar water programme started with the implementation of SPV pumps in the range of 1800 to 5000 Wp, indicating that there is a need for SPV pumps with a higher capacity (Krishi, 2011).

of rotating pumps is dependent on head[8], solar radiation and operating voltage. Positive displacement pumps transfer packets of water by a primary mover. This may be, for example, a piston or screw-type device. They are typically used for pumping water from deep wells, since their output is nearly independent of head. The type of pump most suited depends on water requirement, water height and water quality (Meah et al, 2008).

One of the advantages using solar power for water pumping is that the system does not need expensive batteries to store generated power. Water can be pumped form the source and stored in a water tank above the ground. A closed tank is preferred, since considerable evaporation losses can occur if the tank is open.

Wind power

Figure 4: American windmill design



Wind energy for water pumping is used for many years. In the Netherlands, wind energy is used for centuries to drain flooded land to gain land from the sea (Gipe, 1995). The traditional windmill has become an important icon for the Netherlands. Started in the Netherlands, the wind pump became popular around the world and it is thought that over a million windmill pumps are still in use today. Most of them have the well-known American design with a small diameter and many blades found in Figure 3 (Ziter, 2009). As for solar photovoltaic pumping, the advantages of using wind energy for water pumping include no emission of greenhouse gases, reliable systems and no dependence of fuel distribution (AlQdah et al, 2011). Wind pumping systems can be classified into mechanical and electrical systems.

Mechanical wind pump systems are used all around the world where there are low to moderate wind conditions. Mechanical windmill pumps can be categorized as systems with positive displacement and roto-dynamic pumps. The most used positive displacement pump is a piston pump, but screw pumps are also used. Centrifugal pumps are most used as roto-dynamic pumps. Positive displacement pumps, like the piston pump, are used in most of the commercial windmill pumps. The piston pump tends to have a high torque requirement on starting, because, when starting, the rotor has to provide enough torque to overcome the weight of the pump rods and water in the rising main. This high torque is provided by the high solidity multi-bladed turbine. The main advantage of this system is its simplicity. However, its main disadvantage is the mismatch between the power characteristics between the turbine and the piston

[8] In this context the term head is used to describe the total height that water has to be pumped. This includes the height from the source to the pump (static lift), from the pump to the field or tank (static height) and all friction losses in the pipes.

pump. Piston pumps have a linear power increase with rotational speed, where turbines have a cubic increase of power with rotational speed. This means that the rotor power rises steeply with rotational speed up to its peak and then declines with further increase in speed. The pump is unable to use a large portion of the increase in power developed by the turbine at higher wind speeds. This will limit the power output (Mathew, 2006). The use of centrifugal pumps instead of positive displacement pumps can solve this problem. Centrifugal pumps have the same cubic power increase with rotational speed. This means that if the pump is optimally matched with the turbine at low wind speeds, it is also optimally matched with the turbine at high wind speeds. Another advantage is that centrifugal pumps do not require the high starting torque associated with positive displacement pumps. However, since centrifugal pumps need to create a pressure difference, they operate under high rotational speeds. This requires the use of a transmission. A gear ratio has to be chosen in order to match the requirements of the pump to the optimal power delivery of the turbine at each wind speed. (AlQdah et al, 2011).

More recently, the pumping of water through small wind-electric systems has become more popular, especially in areas with deep water table levels (more than 60 meters). The main advantages include that electricity can also be used for domestic purposes and wind electric systems are suitable for deep water pumping (Raihani et al, 2011). Unfortunately, wind-electric systems have high initial costs and consist of many complex components. The easiest design for a wind electric pump system is to use a rotor, a permanent magnet synchronous generator, a common 3-phase induction motor and a centrifugal pump. Due to the high costs and complex design, wind electric water pumps are not suitable for small and marginal landholders in India, especially since water tables often not reach 60 meters. Therefore wind electric water pumps are not considered as low carbon energy solutions for India in this study.

Figure 5: Solar-wind hybrid system

Hybrid solar/wind systems

Besides water pumping on solar or wind energy, there is the option of a hybrid system working on both solar and wind power. A common drawback from systems working on either solar or wind power is the unpredictable output, as the output depends on weather. Power may be not sufficient at times when it is needed. Neither a standalone solar nor a wind energy system can provide a continuous energy supply due to seasonal and periodical variations (Ekren et al, 2009). Therefore, systems that use two or more different energy resources are considered as good alternatives.

Hybrid systems come in many combinations, like a solar or wind power system with a diesel generator as a back-up system. When looking at sustainable solutions, solar and wind are a good combination. Solar energy and wind energy alternate properly (Yang et al, 2009). Generally, good solar irradiation and poor wind energy are provided in the summer, while good wind energy and poor solar irradiation occur during winter. Also, during daytime there is high solar irradiation, while the night has relative good wind energy (Yang, 2009; Bekele and Palm, 2010; Ekren et al, 2009). The amount of electricity produced depends on both solar radiation and wind speed in general.

Hybrid PV/wind energy systems are more and more considered. For example, China has invested heavily in solar/wind hybrid systems over the past 5 year in the field of city road lighting and water pumping (Yang et al, 2009), so this technology starts to become well established. India is familiar with hybrid systems as well, as the central government set its annual target in 2012 to install more than 500 kW of wind-solar hybrid systems. Most of the solar-wind hybrid systems will be used for electricity generation in rural areas, and water pumping can be one of the applications (MNRE, 2012a).

3.2.2 Energy Conservation

Although renewable energy technologies are good options to mitigate carbon emissions, substantial reductions can also be achieved by energy conservation. A decrease in energy and water requirements will result in significant energy savings and savings in carbon emissions. Generally, there are two options to decrease energy consumption in irrigation. The first option is to increase efficiency of pump sets currently used. The second option is to decrease the water requirements by increasing water use efficiency. This can be done by modern irrigation technologies, like micro-irrigation.

Energy Efficiency

Estimated is that around 90 percent of the pump sets used in India for irrigation are very inefficient and are wasting power (Manoharan et al, 2011). According to field studies, the overall efficiency levels are around 20 to 30 percent for most pump sets, but should be around 40-45 percent in case of a normal water pump set and can be around 55 percent in case of a high energy efficient pump set (EESL, 2011; BEE, 2009) There are three different reasons for unnecessary low efficiency, namely improper size selection and installation of pump sets, the use of high friction pipes and lack of proper maintenance.

Many pump sets used in the agricultural sector in India are oversized. The main reason is that the reliability of the grid is insufficient to meet farmers' water requirements. Whenever there is electricity available, farmers withdraw as much water as possible. Therefore, motors have overcapacity and run at partial load, which pulls the efficiency down. Due to burn-outs, motors have been re-winded which also affects the efficiency of the pump set. Furthermore, the input voltage has an influence on the efficiency of the motor. The output is supposed to be 440 Volt, but field visits carried out by the Bureau of Energy Efficiency (BEE) observed that the consumer end voltage levels vary between 390 and 440 Volt[9] (BEE, 2009). Not only a change in input voltage, but also a change in water table will affect the water pump set efficiency. It is of great importance to select a pump set that operates at its best efficiency at the given water table or head.

In addition to that, it is of great importance to select pipes with an appropriate size. Smaller pipes are usually cheaper than bigger sized pipes, but the friction and therefore the additional operational costs will be higher. On the other hand, pipes with a larger diameter have higher initial costs, but friction losses will be lower. As a rule of thumb, the pipe diameter should allow water to have a velocity between 1 and 1.5 m/s (EESL, 2011). Bends should be avoided as much as possible and unavoidable bends should be wide. In India, most pipes used in irrigation pump sets are made of steel, but the use of PVC pipes is preferred, as they do not have problems with erosion, corrosion and resultant clogging (BEE, 2009; EESL, 2011).

Proper maintenance also has a great influence on the efficiency of pump sets. Fittings should be replaced regularly, as poor fittings result in leakages and increased losses. Cleaning, servicing pumps and damaged pipelines should also be part of standard maintenance in order to remove blockages (EESL, 2011).

<u>Micro-irrigation</u>

Another option to reduce carbon emissions related to irrigation is to use more efficient irrigation techniques. Micro irrigation technologies can reduce energy consumption, but are mainly developed to increase water use efficiency and yields. However, significant energy reductions can be achieved as well. Drip irrigation is one of the most promising technologies out of different micro-irrigation technologies. Water is applied directly at the root zone of plants, which will reduce evaporation and application losses. Drip irrigation in India started with initial testing at Tamil Nadu University Coimbatore in 1970, from where it started to expand (Table 4). Although there has been a significant growth in the use of drip irrigation, it is still far below its estimated potential of 21.3 M ha (Narayanamoorthy, 2004).

[9] Lower end voltage levels affect the efficiency and output of pumpsets. When voltage level decrease from 415 V to 350 V, there is an overal efficiency drop of almost 4 percent, a drop in head by about 1.6 m and a decrease in discharge of about 1.5 lps. When voltage level drops further to 280 V, there is a decrease in overal efficiency of almost 9 percent, a drop in head by about 3.6 m and a drop discharge of 2.5 lps (EESL, 2011).

Table 4: Drip irrigation area in India

	1970	1985	1992	1998	2008
Drip irrigation area (ha)	0[a]	1,500[a]	55,000[a]	225,000[a]	1,429,404[b]

[a] Polak and Sivanappan, 1998
[b] TERI, 2010

Conventional drip irrigation systems were originally designed for large farmers and landholders. These systems have a high efficiency and increase the yields significantly. However, these systems are complex and consist of many components, which make the system complex and expensive. There is a huge demand for affordable systems that work according to drip irrigation technologies, but are less complex and consist of fewer components. The most simple form of drip irrigation is bucket and drum kit irrigation. Its design can vary, but the most used design consists of a simple 20 litre household bucket attached to a pole at a height of 1 or 2 meters above the ground, which can irrigate an area of around 25 m^2 (Singh et al, 2009). This area is not big enough for commercial practices, but once farmers that are using bucket kits are convinced of its advantages they can move on to a drum kit. These systems consist of a 200 litre drum and can irrigate an area of around 125 m^2 (Polak and Sivanappan, 1998; Singh et al, 2009).

Figure 6: Bucket kit design (Jain irrigation, 2012)

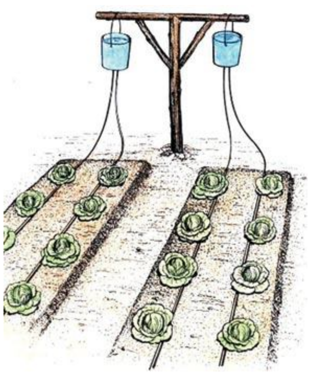
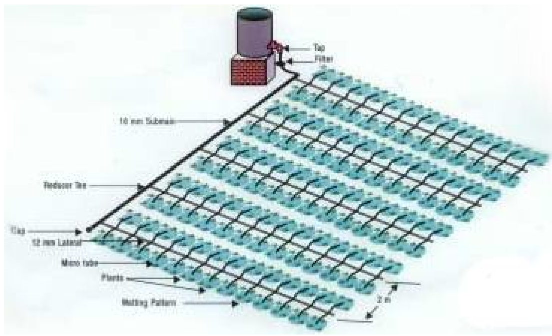
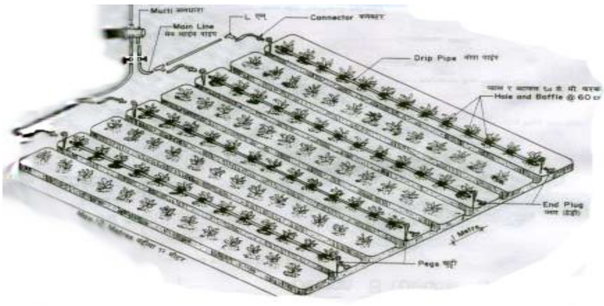


Figure 7: Stationary micro tube system (IDE, 2012)



Compared to bucket and drum kits, micro tube systems are a next step closer to conventional drip systems. There are two different kinds of micro tube systems; stationary micro tube systems and shiftable micro tube systems. In the case of stationary systems, micro tubes are attached to lateral lines allowing irrigation of four rows of crops instead of one row in conventional systems.

Figure 8: Shiftable micro tube system (IDE, 2012)



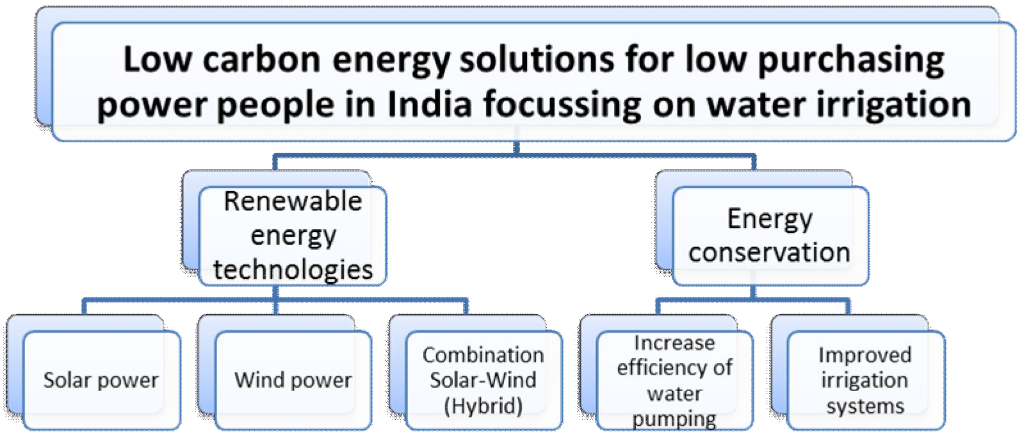
Shiftable systems use lateral lines that can move and where one lateral line is used to irrigate multiple rows of crops. The shiftable system is cheaper, but requires more labour to move the lateral lines (Polak and Sivanappan, 1998; Singh et al, 2009).

For many farmers, micro drip tube systems are still too costly and they are looking for cheaper options to apply drip irrigation. One of the solutions Indian farmers came up with was to use old bicycle inner tubes as a simple form of drip irrigation. But it did not work as well as they hoped for and this trend never picked up (Verma et al, 2004). But around 1998 a new innovation called Pepsee arrived in some states of India and started to spread. The system consists of light density plastics that are used for ice candies that are sold as ‘Pepsee’. The plastic is transparent and is placed directly at the root zones of the plants. The plastic is pierced with small holes at regular intervals, from where water reaches the plants (Verma et al, 2004).

3.2.3 Low Carbon Energy Solutions

As can be concluded from the previous paragraphs, suitable low carbon energy solution for irrigation India are renewable energy technologies, in the form of solar power, wind power and hybrid systems, as well as energy conservation, in the form of increasing energy efficiency of current pump sets and improved irrigation systems, like drip irrigation. An overview of these options can be found in Figure 9.

Figure 9: Overview of low carbon energy solutions for India focusing on water irrigation



4. Technology appropriateness

The second part of this research is to determine how technical, economic, social, environmental and resource-related factors influence the identified low carbon energy solutions. First, a framework for technology appropriateness is provided. Secondly, the low carbon energy solutions identified in chapter 3 will be assessed on the basis of the characteristics identified in the technology appropriateness framework.

4.1 Technology appropriateness framework

Social, economic, health and gender issues are relevant for the adoption of improved energy systems, but often neglected in designing a new technology, such as a pumping system (Short and Thompson, 2003). However, these factors are rather important for the implementation and application of low carbon energy solutions. According to the Diffusion of Innovation theory by Rogers, the transition to a new technology is not completed until the user can independently manage and maintain the technology (Rogers, 1986).

Rogers points out five characteristics of an innovation that determine the rate of diffusion of the technology, being: (1) relative advantage, i.e. the benefits the technology has over the existing system; (2) compatibility, i.e. the way the innovation is consistent with existing values habits and preferences on the demand side; (3) complexity, i.e. the ease understanding and operating the device; (4) trialability, i.e. the extent to which the technology can be tested or experimented with before actual adoption; and (5) observability, i.e. the degree to which potential adoptions can see the results of the innovation in terms of the benefits gained by existing adopters.

To a certain extent, the appropriateness of innovations in rural energy services can be analysed by the technology characteristics described above. Relative advantage can be gained by economic benefits like fuel expenditure savings, time saving benefits, environmental benefits, health benefits, social development benefits and increased production benefits. Design options, such as size, capacity and colour of devices, decide whether a technology fits with local habits or preferences. The simpler and less-complex a device is to understand and operate, the more people will adopt it. Similarities to current technologies can increase this simplicity. In order to increase the diffusion of new technologies, demonstrations in the field can give local people the opportunity to try devices before making the decision to adopt them. And lastly, seeing the benefits from other users is positively related to the appropriateness of a technology and can persuade the ones who do not recognize the need (Rogers, 1986).

However, in the case of innovations in rural areas, the factors mentioned by Rogers are not completely sufficient to decide the appropriateness of a technology. Therefore, some additional factors are added here to create an integrated framework of technology appropriateness based on Rogers' innovation characteristics and literature on factors influencing adoption of energy service improvements in rural areas. In the Diffusion of Innovation theory, it is implied that a need for a certain innovation is already in place. In rural and remote areas, this need is not always recognized, and a need first has to be created for a technology to be seen as appropriate (Agarwal, 1983). When people are too used to the way current processes work or too sceptic about new technologies, the diffusion process would also require overcoming this barrier and persuading them to change their attitudes. This highlights the role of communication channels and local leaders. In community development projects, people's level of adoption depends to a large extent on the influence of the promoter of the project and the approach of the local leader (Jamsari et al, 2012). Of course, the observability of a technology can catalyse this process, but only after a significant amount of adopters has been reached.

Rogers also presumes that the innovation is available anywhere to anyone, which is not applicable to rural areas where a lack of access to technologies exists or to areas where resources are limited (Kowsari & Zerriffi, 2011). Access to new technologies can be a problem due to the lack of a reliable distribution system or insufficient infrastructure. Rural areas can be hard to reach, which can affect the availability of an innovation and emphasizes the importance of local facilities. The durability of a new technology can affect the diffusion process and depends on the degree to which local facilities, like operation and maintenance, technical skills and knowledge and spare parts, are available. Furthermore, the availability of resources can influence the diffusion potential, i.e. photovoltaic systems need a minimal amount of solar radiation (Alam et al, 2003).

A third "gap" identified in the Diffusion of Innovation theory is that it considers the development of an innovation and its diffusion as two separate aspects, while they should be part of an integrated process where potential adopters and their preferences are taken into account in the generation of a technology (Agarwal, 1983). To ensure that innovations are suitable to the user's requirements, it is of great importance that the innovation is not taken as exogenously given, but is developed and adapted in the field itself (Agarwal, 1983).

Based on the above, the following integrated framework provides a list of characteristics that decide a technology's appropriateness and influence the decision to adopt or reject a new technology:

- User need
- Relative advantage
- Observability
- Availability and access to technology
- Availability of local facilities
- Trialability
- Design adaption capacity
- Simplicity

This framework can be applied to different technological innovations in rural areas, such as low carbon energy solutions. Taking into account all these factors is important to maximize the rate of adoption of a certain technology.

4.2 Renewable Energy Technologies

SPV pumps, windmill pumps and hybrid systems have the potential to reduce carbon emissions in India. However, for successful implementation, these technologies should be 'appropriate' for small farmers in India. From farmers' perspectives there is no clear need for sustainable and clean technologies. This can be concluded from field visits for this research. There is a clear need for water pumps in order to extract water from surface and ground sources, but farmers are often not aware of their carbon footprint and impacts they have on climate change. From group interviews with farmers in rural areas can be concluded that farmers think that droughts and declining water tables have nothing to do with their behaviour. Farmers have indicated that they think that lower water tables are due to less rain, which probably has religious reasons. Therefore there is a need for cheap and simple technologies to extract a significant amount of water from the source, but from the farmers perspective there is no need for low carbon solutions. There is a need for renewable energy technologies from governmental perspective though. India has one of the largest programs in the world for renewable energy technologies and has, as first country in the world, set up a ministry totally devoted to new and renewable energy (Bhide and Monroy, 2011). Renewable energy technologies are a great option to achieve their targets concerning reductions in carbon emissions.

Renewable energy technologies do have a relative advantage compared to electrical and diesel pump sets currently used. The main advantage is that there is no need for expensive fuel. Although farmers get their electricity heavily subsidized in most cases, it is expected that prices will increase, as well as diesel prices (Purohit, 2007; Manoharan, 2011). Although it is assumed that renewable energy technologies have higher investment costs, farmers can reduce their operational costs by switching to renewable energy technologies. Furthermore, farmers can save time, as SPV pump, windmill pumps and hybrid systems work almost autonomously, while electric and diesel pumps need to be switched on manually (Bucher, 1996; AlQdah et al, 2011). An automatic switch can ensure that renewable energy technology systems automatically start working when there is enough sun or wind is available to start pumping. This makes the renewable energy technologies easy to operate.

Both solar power and wind power have a high observability potential compared to the current situation, especially in the case of electric pump sets. Due to high demand for electricity in India, there is often not enough electricity available for agriculture. Farmers are not able to irrigate their land at times they need to due to a lack of electricity. This can be solved by solar and wind power. The need for water is the highest during bright hot days, when solar power is available. Hybrid systems have the highest observability potential, as they can pump water whenever there is sufficient irradiation or enough wind.

Besides farmers need for renewable technologies, their relative advantages and observability, it is of great importance that technologies and spare parts are available in rural areas of India. According to the ministry of New and Renewable Energy, there are 17 approved windmill manufacturers and 6 more are being tested at this moment (MNRE, 2012b). Furthermore, there are 14 companies that manufacture photovoltaic modules, and 45 companies that manufacture solar photovoltaic systems (Bhide and Monroy, 2011). India is not only focused on installing and implementing renewable energy technologies, but makes sure that domestic production of systems is promoted as well[10]. However, the number of manufacturers is only an indicator that technologies are manufactured in India. It is not a clear indicator of the availability of these systems in rural areas. Manufacturers of pumping systems based on solar or wind power offer their products and services on the internet, but that is not applicable for small farmers. They are dependent on local dealers and service shops, which have a limited range of products. The availability of spare parts of renewable energy technologies also plays an important role in the diffusion

[10] In January 2010, the Jawaharlal Nehru National Solar Mission (JNNSM) was launched, in order to deploy 20.000 MW of grid connected solar power in 2022. This mission does not only focus on long term policy and large scale deployment, but also on domestic production of critical raw materials, components and products (MNRE, 2012)

of the technology. Only 2 out of 12 villages visited for this research have facilities for spare parts for water pump sets and none of the villages had spare parts available for pump sets working on solar or wind power[11]. Most farmers repair their pump sets with improvised spare parts. In case with mechanical windmill pumps, this could be an option, but is impossible in case of complex electronic systems, which can be found in SPV pumps and hybrid systems. This is a good indication that the availability of spare parts need to be improved, although it is not possible to draw conclusions for every place in India.

Renewable energy technologies score low on trialability. It is impossible to install a pump set working on solar or wind energy for a short period of time to test the system. However, it is possible to install a SPV pump set on a trailer to move it around (Meah et al, 2008). In that case, a SPV pump set can drive around within a region, which gives interested farmers a possibility to test the pump and decide whether they like the new technology.

Last but not least, renewable energy technologies should be simple in use and design in order to be adopted by many farmers. From the suitable renewable energy technologies for irrigation, mechanical windmill pumps score high on simplicity. A simple designed windmill for pumping water from shallow sources does not require complex electronics, since everything works mechanical. SPV pumps and electric windmill pumps require more complex knowledge to repair and maintain, but are very simple in use as well. As expected, hybrid systems are the most complex systems and therefore score low on simplicity.

4.3 Energy efficiency

There is a need for improving energy efficiency of existing pump sets, as it can increase the water output and save on energy costs. Although farmers pay a heavy subsidized tariff for electricity in most cases, or get it for free in some exceptional cases, any improvements in energy efficiency can result in savings on electricity expenditures. However, the need and relative advantage is more evident in case of diesel pump sets, as diesel prices are increasing rapidly. But energy efficiency measures score low on observability, as it is hard to see the results of improvements for farmers in terms of the benefits gained by increased energy efficiency.

[11] During field visits, five farmers which have SPV pumps were interviewed. At the moment of interviewing, only one farmer had a SPV pump set working for irrigation. One pump set was broken down and the farmer was already waiting for 4 months to get a new motor. According to the dealer, the motor had to come from Bangalore, which is around 2000 km away. The other pump sets were not working due to insufficient irradiation or owners were using the solar panels for domestic purposes instead of irrigation.

It is important that there is access to high efficient motors and spare parts needed for maintenance are available. Field visits show that only 18% of the villages have official dealers or facilities for spare parts and maintenance, but most farmers do not see this as a problem and are able to fix pump sets when needed. However, PVC pipes, fittings and cleaning tools are available in many places and can be used to increase efficiency. The trialability of these low cost measures is high, as farmers can replace fittings or clean pipes once and assess improvements in water output and energy consumption. But high cost measures, such as the installation of a high efficient motor, score low on trialability.

High efficient motors are designed to meet the needs of the farmers. These motors are better capable in dealing with fluctuating water tables and voltages, without losing much of its efficiency. Motors are designed for specific circumstances, taking the static head, water requirements and climate conditions in consideration. Furthermore, measures for increasing energy efficiency are considered as simple, as new high efficient pump sets are working similar to old pump sets. Replacing fittings, valves and cleaning pipes is also considered as simple tasks, which farmers can perform themselves most of the time. Reducing the number of impellers, replacing long sections of pipelines and replace entire pump sets can be more complex, which will require mechanics.

4.4 Drip irrigation

As the case of the Pepsee system proofs, there is a great demand for technologies that increase water use efficiency and yields among small farmers in rural areas. Farmers will benefit from systems that apply water directly at the root zone of plants, as they can decrease the size of their pumps to pump water from the ground and reduce their energy consumption. There is a clear relative advantage in case of drip irrigation compared to flood and surface irrigation, as more crops can be irrigated with less water. Therefore, farmers can increase their production while simultaneously decrease their water and energy consumption. Micro irrigation scores high on observability when yields increase and farmers can expand the irrigated area of their land, without the need for a bigger pump.

Drip irrigation technology arrived in 1970 in India and slowly spread across the country. After more than 40 years of development, several big companies dominate the Indian market. Jain irrigation has the largest market share, around 55 percent of drip irrigation in India, and is partly focused on poor and small farmers (Jain Irrigation, 2012). They put much effort in convincing small farmers of the benefits of drip irrigation, by organizing training programs for increasing awareness in farming communities (Jain Irrigation, 2012). The focus of the biggest drip irrigation manufacturer on smallholders indicates that drip irrigation technology and spare parts are available in some parts of India. However, some farmers experience problems in getting spare parts for drip irrigation (Narayanmoorthy, 2006). This corresponds to experiences during field visits performed for this research, where several farmers indicated that they wanted to switch to micro irrigation, but did not know where to get the supplies for it. The use of thin plastics or inner tubes from bicycles is not only a solution to overcome high costs, but can also be a solution to overcome this non-availability problem. But farmers indicated that they prefer the availability of professional materials and advice how to use the technology.

It is hard to try out drip irrigation systems, as it is impossible to borrow systems from other farmers to use on your own land for a short period of time. However, there are cheap options, such as a bucket or drum kit, which farmers can use to irrigate a small part of their land to experience the benefits from drip irrigation. From there, farmers can slowly increase the area used for drip irrigation and switch to more complex and efficient systems.

According to Jain Irrigation (2012), there is a lot of collaboration between developers and farmers. They develop site-specific drip irrigation systems, taking soil, water, crop and agro-climatic conditions in to consideration (Jain Irrigation, 2012). The design of drip irrigation systems can be adapted to site-specific conditions and have therefore a high design adoption capacity. There are different degrees of simplicity in the case of drip irrigation; conventional drip irrigation systems are more complex than bucket and drum kits.

5. Economic analysis

High initial costs of renewable energy technologies for irrigation are one of the main barriers that prevent large-scale adoption, especially for poor farmers (Purohit, 2007). Although solar module prices have declined over the past years, capital costs of SPV pumps are significantly higher than electric or diesel pumps, even with current average prices of $2.29 per Watt peak (NPD Solarbuzz, 2012). Mechanical windmill pumps are considered cheaper, but are still expensive compared to conventional water pumping systems. But due to savings on fuel and maintenance costs and a long life span, renewable energy technologies can become economically viable. Options for energy conservation are usually cheaper and have a shorter payback period. Nevertheless, it is important that farmers are able to make upfront investments, have access to credit and are willing to pay for low carbon energy solutions.

5.1 Renewable Energy Technologies and energy efficiency

High initial costs are a well-known problem for the diffusion of renewable energy technologies. For SPV pumps, prices of popular pump sets are known for the year 2006 and based on those prices, current prices are estimated (Purohit, 2007). An overview of prices for SPV pumping systems and components can be found in Table 5.

Table 5: Prices for SPV systems and components

	1200 Wp AC system	1800 Wp AC system	1200 Wp array	1800 Wp array	Inverter (1200 Wp system)	Inverter (1800 Wp system)
Prices in 2006 (Rs.)	297,500	422,000	214,000	321,000	36,000	54,000
Prices in 2012 (Rs.)	287,000	387,000	154,000	231,000	48,000	72,000

(Based on Purohit, 2007; MSPI, 2012)

It is assumed that prices for the array and inverter have decreased over time and prices for other components have increased over time due to inflation. The costs for the array account for a large share of the SPV pumps' cost, as solar modules are the most expensive component of a SPV pumping system[12]. Besides the array, the inverter is an important cost component of a SPV submersible pump. Like arrays, the costs for inverters have decreased of the last years[13]. So prices for SPV pumps in 2006 that are corrected for inflation are still lower than prices in 2006, due to the decreasing costs for arrays and inverters[14].

Capital costs for mechanical windmill pumps are significantly lower as can be seen in Table 6.

Table 6: Prices for non-SPV water pumps

	Windmill APOLY-12-PU-500	Windmill AV-55	Solar-wind Hybrid system	Diesel pump	Electric pump
Prices found in literature (Rs.)	45,000 (2006)	86,200 (2010)	500,000 (2012)	32,000 (surface in 2006) 42,000 (submersible in 2006)	24,000 (surface in 2006) 30,000 (5 hp submersible in 2006) 42,000 (10 hp submersible in 2006)
Prices in 2012 (Rs.)	80,000	99,000	500,000	57,120 (surface) 74,790 (submersible)	42, 840 (surface) 53,550 (5 hp submersible) 74,790 (10 hp submersible)

(Based on Purohit, 2007; MNRE, 2012; Trunz, 2010; MSPI, 2012)

Two windmills that are widely used across India are the APOLY-12-PU-500 and the AV-55. Compared to SPV pumps and windmill pumps, solar wind hybrid systems have the highest initial costs of all low carbon

[12] In 2006, the prices per Watt peak were around $4 (Odeh et al, 2006). That means that a 1200 Wp array was around Rs. 214,128 and an 1800 Wp array costs around Rs. 321,192 in 2006. This is calculated to determine the share of costs for the system excluding the costs for the array and inverter. With a current average price of solar modules of $2.29 per Watt peak, the costs for an array have dropped significantly (NRD Solarbuzz, 2012).

[13] In 2006, the price of an inverter needed in a 1200 Wp system were around Rs. 35,688 and for an 1800 Wp AC SPV system around Rs. 53,532 (Mondol et al, 2006). This is calculated to determine the costs of the whole SPV system excluding the costs for the array and inverter. The current prices of inverters needed in similar systems are Rs. 47,813 and Rs. 71,719 respectively, which is a decrease compared to the prices in 2006 taking inflation rates into account (NRD Solarbuzz, 2012; MSPI, 2012).

[14] To calculate current prices based on older prices, the Consumer Prices Index (CPI) is used. According to the Ministry of Statistic and Program Implementation, average prices have increased by 78.5 percent from April 2006 to March 2012 and around 15 percent between August 2010 and March 2012 (MSPI, 2012).

energy solutions. As can be seen in Table 5, electric and diesel pumps have the lowest initial costs of all water pumps available.

Solar and wind systems are considered highly reliable and therefore have lower maintenance costs. The annual maintenance costs are estimated at 1 percent of capital costs in case of SPV pumps, and 2 percent in case of mechanical windmill pumps (Kumar, 2007). The annual maintenance costs for solar wind hybrid systems are not known and are estimated at 1.5 percent of initial costs[15]. Electric pumps and diesel engine pumps require more maintenance and have higher annual operation costs. The estimated O&M costs are around 10 percent (Purohit, 2007; Kumar and Kandpal 2007). These costs are consistent with values found during field visits.

The costs related to pumping water for irrigation using renewable energy technologies can be found in Table 7. Note that electric and diesel pump sets used for comparison have higher rated capacities than the renewable energy technologies used in this research. The reason for this difference is the facts that 5 hp and 10 hp electric and diesel pump sets are mostly used in India. Renewable energy technologies often have a lower rated capacity, but will pump water for more hours per day and annual water output will be equal.

[15] The annual maintenance costs for SPV pumps are around 1 percent of initial costs and 2 percent for wind powered pumps. The O&M costs for solar-wind hybrid systems are therefore estimated at an average of 1.5 percent of initial costs.

Table 7: Initial and O&M costs renewable technologies and technologies currently used

	Capital Cost (Rs)	Annual maintenance costs (Rs)	Capital costs similar electric pump (Rs)	Annual maintenance costs similar electric pump (Rs)	Capital costs similar diesel pump (Rs)	Annual maintenance costs similar diesel pump (Rs)
Solar (1200 Wp AC submersible)	287,000	2,900	53,500 (5 hp)	5,300	75,000 (10 hp)[16]	7,500
Solar (1800 Wp AC submersible)	387,000	3,900	75,000 (10 hp)	7,500	75,000 (10 hp)	7,500
Wind (APOLY-12-PU-500)	80,000	1,600	42,800 (5 hp)	4,300	57,000 (5 hp)	5,700
Wind (AV-55)	99,000	2,000	53,500 (5 hp)	5,300	75,000 (10 hp)[16]	7,500
Solar/Wind Hybrid	500,000	7,500	75,000 (10 hp)	7,500	75,000 (10 hp)	7,500

Besides the implementation of renewable energy technologies, carbon emissions can be reduced by increasing the overall efficiency of water pump sets. In general, the costs involved with increasing energy efficiency are lower than switching to renewable energy technologies. There are different options to increase efficiency of electric and diesel pump sets. These options can be classified based on their costs.

[16] Both the Solar 1200 Wp AC submersible system and the windmill AV-55 are compared with an electric pump with a rated capacity of 5 hp and a diesel pump with a rated capacity of 10 hp. According to Purohit (2007), electric submersible pumps are used in 5 hp and 10 hp versions, while most submersible diesel pumps are around 10 hp. According to field visits, the average size of a diesel pump is around 9 hp. Therefore, small submersible pump sets for deep pumping, like the SPV 1200 Wp and the AV-55 are compared with a 5 hp electric pump and a 10 hp diesel pump. A SPV pump or windmill will have a significant lower capacity than a 10 hp diesel pump, but with more daily working hours, the annual water output will be equal.

There are four categories; no costs, low costs, medium costs and major costs (EESL, 2009).

- No cost category: consists of actions without any extra costs. This includes work done as part of regular maintenance, such as cleaning and servicing the pumps to remove blockages. These actions do not include extra costs, but will result in an increase of efficiency if done properly.
- Low cost measures: include replacement of small parts, like meters, valves and damaged pipe sections.
- Medium cost measures: include major modifications to the pump set, like reducing the number of impellers (in case of overcapacity) or replacing long sections of pipeline.
- Major cost measures: include purchases of new equipment, like new pumps, motors or variable speed drives.

In case of diesel pumps, low and medium costs measures can result in a reduction in fuel consumption of about 50 percent, while retaining the same discharge of water. The overall efficiency of electric and diesel pump sets is estimated at 27.5 percent, but can be around 55 percent in case of high efficiency pumps, which is a reduction in fuel consumption of 50 percent. The average costs of these modifications were around Rs. 300 in 2001 (Bom et al, 2001). Taking the CPI into account, these modifications currently cost around Rs. 650 (MOSPI, 2012). By just installing pipes which are properly sized can reduce fuel consumption by 20 percent and overall efficiency can be increased from 27.5 percent to 34.4 percent. This results in annual savings between Rs. 2,400 and Rs. 4,800 in case of electric pumps and Rs. 5,500 and Rs. 11,000 in case of diesel pumps (Sant and Dixit, 1996).

In case of electric pumps, when efficiency is below 30 percent and can not easily be improved by low and medium cost measures, it is economically best to replace the pump set with a high efficient pump set (EESL, 2009). Replacing existing electric motors with high efficiency motors falls under major costs measures. Therefore, replacing the motors is not always the best economical option. Motors that are moderately oversized and work at 50 to 75 percent of their load should only be replaced in case they fail or break down. The same counts for motors that are properly sized, but of standard efficiency. However, in the case of significantly oversized motors (lower than 50% loading), it is best to replace the motor with more efficient, appropriately sized models at the next opportunity, such as scheduled pump downtime (EESL, 2009).

In order to calculate the payback period of renewable energy technologies and energy efficiency measures, the annual costs for fuel are estimated. The costs for fuel are site specific, as Indian states have their own regulations and subsidies. In case of electricity, many states charge farmers based on the rated capacity of their pumps (Shah et al, 2004). According to the Central Electricity Authority (CEA), farmers with a 10 hp electric pump pay an average price of Rs. 2,016 per month and farmers with a 5 hp electric pump pay Rs. 995 on an average per month (CEA, 2009). This results in yearly cost for electricity of Rs. 11,936 and Rs. 24,192 respectively. In case of diesel pumps, diesel consumption is between 600 and 1,500 litre per year, dependent on the size of their diesel pump[17] (Purohit, 2007; Shah et al, 2004). In this research, the average diesel consumption per diesel pump is estimated at 675 litre per year in case of a 5 hp diesel engine pump and 1,350 litre per year in case of a 10 hp diesel pump. The annual costs for diesel are Rs. 27,675 and Rs. 55,350 respectively[18].

Farmers are more likely to invest in low carbon energy solutions when the investment is profitable. The formula that is widely used to calculate the pay-back period is (Blok, 2007):

$$PBP = \frac{I}{B - C}$$

where:

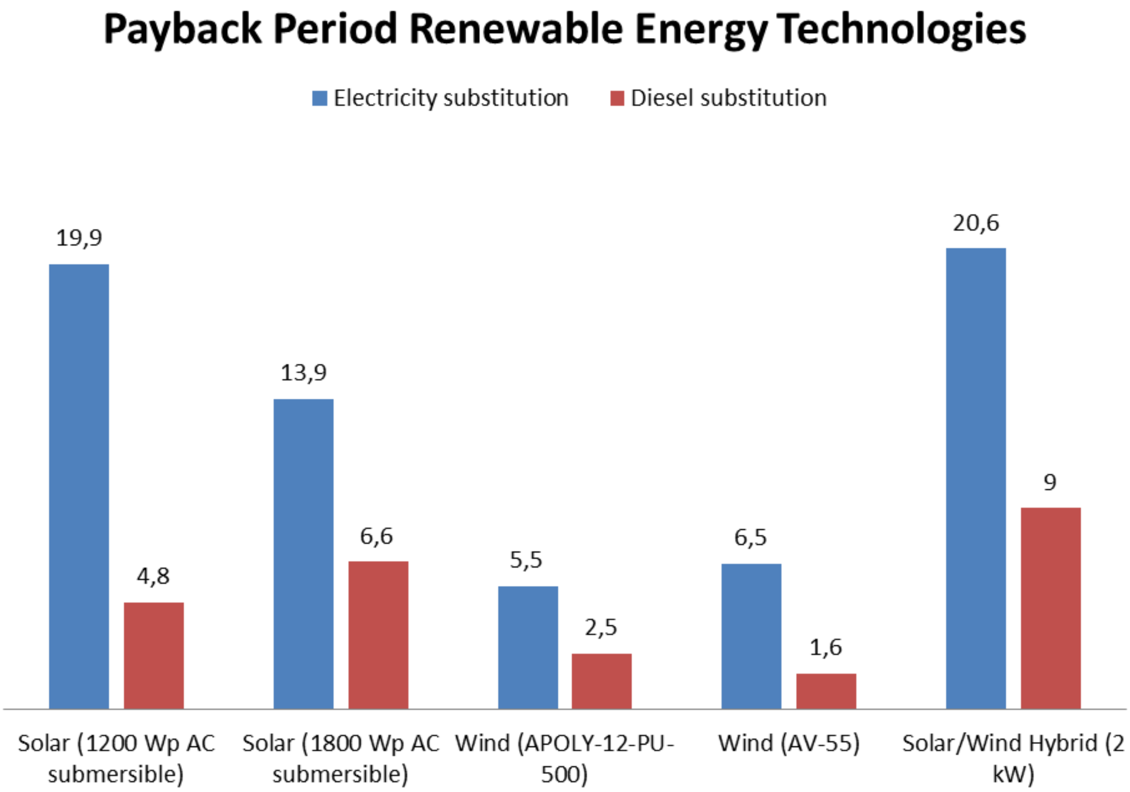
I = Initial investment
B = annual benefits
C = annual cost

In the case of water pumps working on renewable energy technologies, the initial investment is the price of the system, the annual benefits are the costs for electricity or diesel in case of a similar pump set working on electricity or diesel and the annual costs are the annual operation and maintenance costs. In case of overall efficiency improvement, the initial investment is the costs for the modification. Furthermore, the annual benefits are the annual costs for fuel in case of a pump set without modifications and the annual costs are the annual fuel costs for the modified system. The payback period of the different renewable energy technologies and energy efficiency measures can be found in Table 4.

[17] According to Purohit (2007), the average diesel consumption in a diesel engine pump is 0,3 l/bhp-h. According to Shah et al (2004), the average pump operation is around 400-500 h/year. These values are slightly higher in Shah (2009). This results in a diesel consumption of 600-750 liter in case of a 5 hp diesel pump and between 1200 and 1500 liter in case of a 10 hp diesel pump.

[18] 1 liter diesel = Rs. 41 (IndianOil, 2012)

Figure 10: Payback periods for renewable energy technologies in years



As can be seen in Figure 10, wind energy has the lowest payback period, followed by solar energy and hybrid systems. In case of electricity substitution, the APOLY-12-PU-500 has the lowest payback period of all renewable energy solutions and is around 5.5 years. In case of diesel substitution, the AV-55 windmill has the lowest payback period and is even less than 2 years. This is because the AV-55 is a cheap design for deep well pumping up to 60 meter head and can substitute submersible pumps. Diesel consumption in case of deep well pumping is high, which makes the annual benefits in case of the AV-55 windmill high as well. In general, the payback periods with diesel substitution are significant more attractive than with electricity substitution. This is because prices for electricity are lower than diesel.

Table 8: Payback periods energy efficiency measures

	Electric pumps	Diesel pumps
Low and medium cost measures	40 days (5 hp) – 20 days (10 hp)	17 days (5 hp) – 8.5 days (10 hp)
Replacement pump set (original pump set efficiency 5 – 10 percent)	5 months[a]	-[b]
Replacement pump set (original pump set efficiency 20 – 30 percent)	2.3 years[a]	-[b]

[a] EESL (2009)
[b] Unfortunately, there is no information available about replacing inefficient diesel pump sets with high efficient pump sets and therefore the PBP is only calculated for electric pump sets.

Looking at the costs and payback periods to increase energy efficiency of existing pumps in India, it can be concluded that most options to increase efficiency should be implemented immediately. In economic and environmental terms there is much to gain. The problem does not seem to be the high initial costs, but more a lack of awareness and knowledge. More about this social barrier can be found in chapter 7. From the economic analysis can be concluded that governments and NGOs do not necessarily need to focus on financial issues is case of improving energy efficiency, but the emphasis should be on extending knowledge and information provision to farmers how to improve efficiency, increase water output and decrease operational costs.

Another option to determine the economic viability of pumping systems is by calculating the unit cost of water. This gives a clear overview of the costs involved in pumping a certain amount of water. The unit cost of water can be estimated using the formula (Purohit, 2007):

$$UCW = \frac{C\left((d(1+d)^t)/((1+d)^t-1)\right)+Ci}{AUE/\rho gh}$$

where:

UCW = Unit Cost of Water (Rs./m^3)
C = Capital Cost (Rs.)
d = Discount rate
t = Useful lifetime (yr)
Ci = Annual repair and maintenance costs and annual fuel costs (Rs.)

AUE = Annual Useful Energy (J)[19]
ρ = Density of water (kg/m^3)
g = Acceleration due to gravity (m/s^2)
h = Effective head of ground water (m)

Most input parameters are found in literature. The capital costs and annual repair and maintenance costs are found in Table 6. Other parameters are found in Table 9 and Table 10. The UCW of different technologies can be found in Figure 11.

Table 9: Lifetime and annual useful energy renewable energy technologies

	Solar (1200 Wp AC submersible)	Solar (1800 Wp AC submersible)	Wind (APOLY-12-PU-500)	Wind (AV-55)	Solar/Wind Hybrid (2 kW)
Useful lifetime (yr)	20[a]	20[a]	25[a]	25[a]	20
AUE (MJ)	2851	4277	3305	873	3011

[a] Purohit (2007)

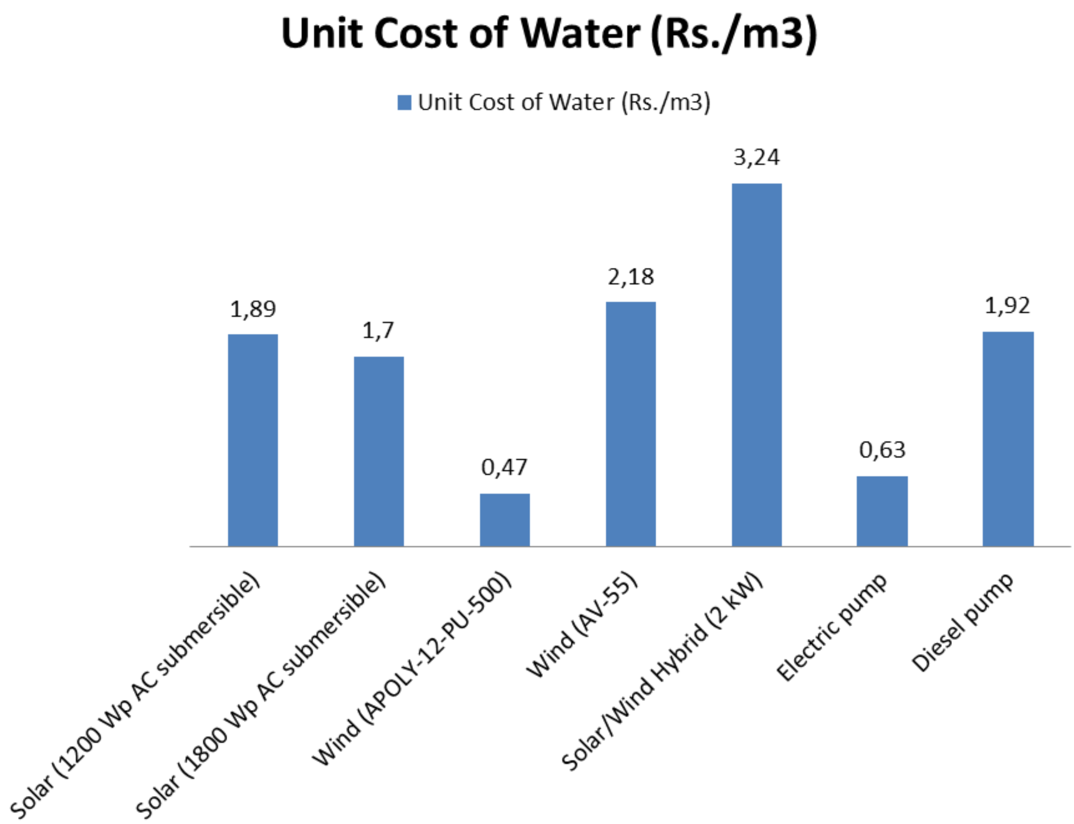
Table 10: Input parameters

Parameter	
Discount rate	0.1[a]
Density of water (kg/m^3)	1000
Acceleration due to gravity (m/s^2)	9.81
Effective head of water (m)	15[a]

[a] Shah (2009)

[19] This is the amount of energy available per year to pump water.

Figure 11: Unit Cost of Water for renewable energy technologies



As can be seen in Figure 11, the APOLY-12-PU-500 windmill has the lowest unit cost of water, followed by the 1800 Wp submersible SPV pump. The reason for the low unit cost of water in case of the APOLY-12-PU-500 windmill is because of its high annual useful energy. This is site specific and differs between locations. The input parameters used in this study are based on an analysis made for the location of Indore, Madhya Pradesh. This location was selected, as it is a windy area (Mani and Mooly, 1983). The cut-in wind speed and rated wind speed are higher in case of the APOLY-12-PU-500 windmill compared to the AV-55 windmill (Purohit, 2007). The average wind speed in Indore is relatively high, making the APOLY-12-PU-500 more suitable. However, in areas with a lower average wind speed, the AV-55 windmill can be a more attractive option.

The average unit costs of water in case of electricity are estimated around Rs. 0.55 and Rs. 0.70. For diesel these values are estimated around Rs. 1.82 and Rs. 2.02. This means that the APOLY-12-PU-500 windmill is a competitive with both electric and diesel pump sets. SPV pumps are only competitive with diesel pump sets. This is due to the high costs for diesel and the high initial costs for SPV pumps. The windmill AV-55 and hybrid systems are not competitive with electric and diesel pump sets at this moment as their unit cost of water is higher than the unit cost of water for electric en diesel pump sets.

5.3 Drip irrigation

There are different types of drip irrigation, suited for different types of crops. Drip irrigation can achieve significant energy savings, since there are less evaporation losses and water is delivered directly at the root zone of plants. This decreases the water requirements for irrigation and less water has to be pumped from the source. The savings in energy consumption can contribute to the reduction of CO_2 emissions, as well as at the expenditures of farmers. Small drip irrigation kits, like bucket and drum kits, are too small to pay themselves back by energy savings. However, they can be economic viable due to increases in yield. The installation costs for a bucket kit are currently around Rs. 235 and can cover an area of 25 m^2. Drum kits cover an area of 125 m^2 and cost around Rs. 1,675 currently[20] (Singh et al, 2009). However, more complex and sophisticated irrigation systems, like shiftable and stationary drip irrigation systems, can save a significant amount of energy, since less water needs to be pumped from the source for the same output in terms of yields. Capital costs for drip irrigation systems partly depend on the type of drip irrigation used. Prices for shiftable drip irrigation systems are estimated between Rs. 27,979 and Rs. 31,252 per hectare. Initial costs for stationary drip irrigation systems are slightly higher, around Rs. 41,967 and Rs. 45,196 (Singh et al, 2009; Sankaranarayanan et al, 2011).

Besides the type of drip irrigation system used, the energy consumption and energy savings depend on the type of crop, because some crops, like cotton and sugarcane, are more suited for drip irrigation than other crops, like bananas. The energy consumption and the energy saving potential for some typical crops suited for drip irrigation are given in table 11.

[20] Prices are converted from USD to Rs. At June 1, 2008 the conversion rate was $1 = Rs. 42.5. Prices increased by 58% on average between June 2008 and June 2012, based on CPI data (MOSPI, 2012)

Table 11: Comparison of energy consumption for different irrigation techniques

	Electricity consumption with flood irrigation (kWh/ha)	Electricity consumption with drip irrigation (kWh/ha)	Energy savings (%)
Banana	8348	5913	29
Grapes	3959	2483	37
Sugarcane	2385	1325	44
Cotton	769.1	422.8	45

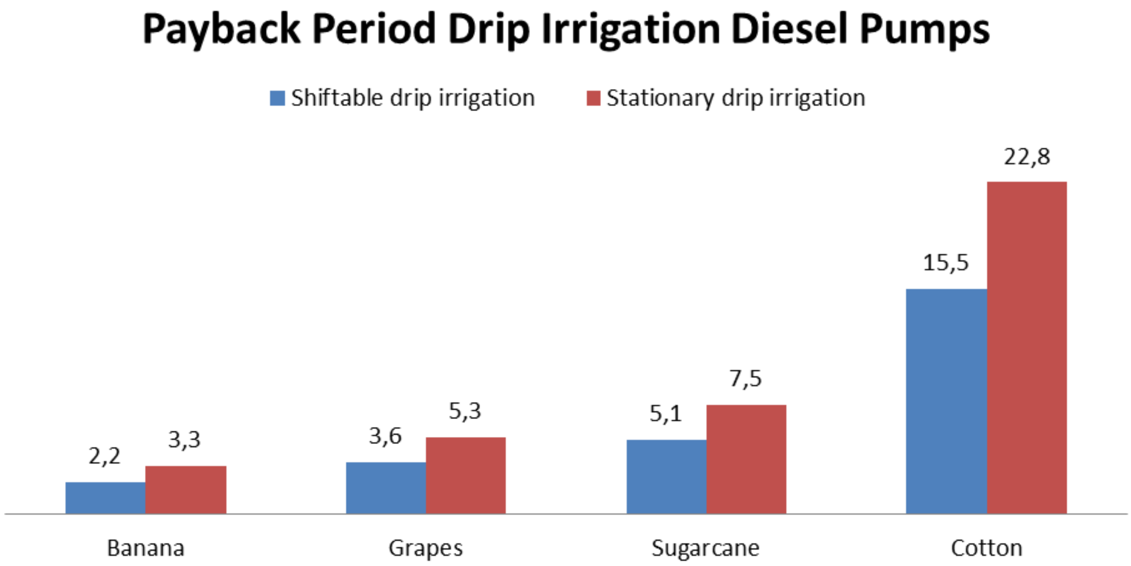
Energy savings with drip irrigation are in the range of 29-45 percent, depending on the type of crop that is cultivated. These energy savings result in lower annual costs for electricity or diesel. Although many farmers pay their electricity based on the rated capacity of their pump, the average electricity price farmers pay is around 1 Rs/kWh (CEA, 2009) [21]. In order to calculate the diesel consumption, the energy content of diesel is set at 36 MJ/l (Blok, 2007). The annual savings with the use of drip irrigation can be found in Table 12. The payback period in case of shiftable or stationary drip irrigation systems is given in Figure 12.

Table 12: Energy savings per crop

	Annual electricity savings (kWh/ha)	Annual cost savings for electricity (Rs/ha)	Annual diesel savings (l/ha)	Annual cost savings for diesel (Rs/ha)
Banana	2434	2434	316.5	13,450
Grapes	1476	1476	191.9	8,155
Sugarcane	1060	1060	137.8	5,855
Cotton	346.3	346.3	45	1,913

[21] The CEA has published the average electricity tariffs for each state. The total average electricity price farmers pay in India is based on this publicitation, but is a rough estimation, as there are many different electricity tariffs between states. Furthermore, many farmers pay a fixed tariff based on the rated capacity of their pump, increasing the uncertainty of the rate they pay per kWh. Other researches that are focused on energy savings, such as Narayanamoorthy, 2005, use higher values for annual cost savings due to energy savings, as those researches use the market price of electricity. However, many farmers pay a heavily subsidized tariff for electricity and annual savings are significantly lower for them.

Figure 12: Payback periods of different drip irrigation systems based on energy savings



As can be seen in Table 14, the payback period based on energy savings can be as low as 2.1 years, when expensive diesel is used in case of banana cultivation. But, in case of electric pumping, there are fewer incentives to switch to micro irrigation to reduce energy consumption. However, increasing yields and therefore increasing incomes can significantly further decrease payback periods of drip irrigation.

5.4 Agricultural access to credit and willingness to pay

Although most low carbon energy solutions for irrigation in India attractive payback periods, it is of great importance that farmers are able and willing to make the investment required for adopting these energy solutions. In order to make the investments, credit is needed. Credit is an important input for the development of agriculture and consequently in employment generation. The supply of credit can bring better yields which include better usage of technology and advanced farm inputs in farming operations (Krishna, 2007).

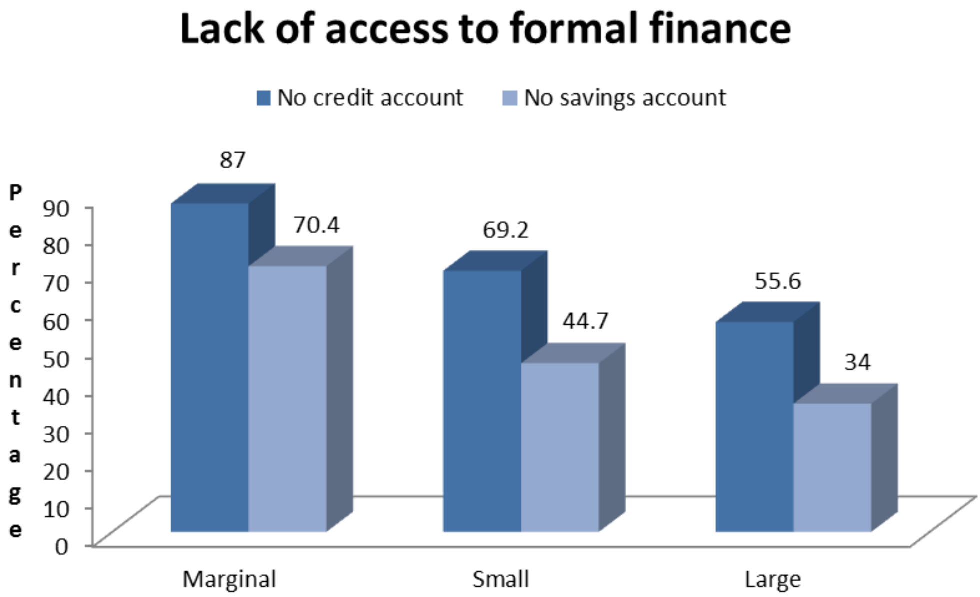
The Indian rural credit delivery system consists of a large number of agencies, including cooperatives, regional rural banks, commercial banks, non-banking financial institutions, self-help groups, micro finance institutes and informal credit outlets. Informal lending represents a large share in providing credit to marginal and small farmers in India. It includes credit extended by friends, relatives, moneylenders, etc. Informal money lending in rural areas of India is a serious problem. Although informal moneylenders meet the needs of farmers that are not reached by formal financial institutions, they can be a threat for the stability of the financial system. Their uncontrolled growth and unlawful activities makes policy less effective. Moreover, informal money lenders charge usurious rates of interest and use unethical ways for recovery of loans, which can lead even to suicide by indebted farmers and causes other social problems (Jeromi, 2007)

Despite increasing informal money lending, outstanding formal credit to agriculture has increased over the last decades from Rs. 186 billion in 1971 to Rs. 2,193 billion in 2008 (RBI, 2011). In 1969, commercial banks were nationalized by the Government of India and Regional Rural Banks were instituted to increase the access to people in rural areas. There were targets formulated that individual banks were supposed to achieve, like priority sector lending with 18 percent accounted for agriculture. In other words, banks should aim to lend 18 percent of total outstanding credit to agricultural purposes. Furthermore, the National Bank for Agriculture and Rural Development (NABARD) is developed in 1982 to further increase the credit flow to rural areas in India and stimulate development. It has the role in providing financial assistance, facilitating institutional development and encouraging promotional efforts in the area of rural credit. However, in 1991 the financial sector was again reformed and led to the liberalization of banks, in order to create a more competitive financial system. Priority sector lending is abolished and interest rates are deregulated, as banks should be more market-driven. This resulted in a reduction of rural banking and outstanding rural credit has declined since 1991 (Krishna, 2012).

Although there is a wide network of rural bank branches, large number of poor households is still not using formal banking facilities and they remain out of the formal banking system. According to the Rural Finance Access Survey held in 2003, around 87 percent of the marginal farming households do not have access to formal credit and more than 70 percent has no access to savings from a formal source. Figure 13 shows that large landholders have more access to credit than small and marginal landholders (Basu, 2006). Reasons for a lack of credit for marginal and small farming households include high transaction costs to banks and borrowers, non-client friendly formalities and farmers are not able to provide banks necessary guarantees (Krishna, 2012).

The lack of formal access to credit and dependence on informal money lenders causes a barrier for the implementation and diffusion of low carbon energy solutions. Most marginal and small farmers do not know where they can borrow money from an official institution and most farmers are at the mercy of informal credit. Improvements in access to credit can result in an increased adoption of new technologies and therefore reduce carbon emissions, energy and water consumption and money spent on fuels.

Figure 13: Rural access to formal finance in India.



(Marginal farming households = landholding < 1 acre; small = 1 to 4 acres and large = > 4 acres (Source Basu, 2006, based on the Rural Finance Access Survey, 2003))

Besides the capability to invest in low carbon energy solutions for irrigation, it is important that farmers are willing to invest in solutions that reduce carbon emissions. Willingness to pay is an economic concept and aims to determine the amount of money someone is willing to pay for the supply of a service of product, like electricity or water (Chandrasekaran et al, 2009). It is one of the approaches used by economists which enables them to place a value on products or services which do not have a market-based pricing mechanism.

Although there is no literature available about the willingness of farmers to pay for lower carbon emissions, during field visits performed for this research it is found that around 50 percent of the farmers is willing to switch to SPV pumps. All places visited during field work were around farmers that had switched to SPV pumps for irrigation purposes during subsidy arrangements from the government in the period 2001-2003. So most farmers interviewed were familiar with the technology of pumping water with solar power. From the 12 villages visited, farmers in 6 villages were willing to switch to pumping on solar energy, but only when subsidies were still available.

Furthermore, it is found that they are willing to pay for improved quality of electricity services. A study by the Worldbank showed that in Haryana farmers' willingness to pay for improved energy services and availability is quite high, especially among small and marginal farmers (Worldbank, 2001). In 2001, it was estimated that marginal and small farmers were willing to pay between Rs. 9400 and Rs. 9700 for an additional hour per day increase in availability of power (Worldbank, 2001). This is an indication that marginal and small farmer are constrained by the available power supply. Another study performed by Chandrasekaran et al showed that farmers are also willing to pay for improved water supply. The results of a survey held in the state Tamil Nadu in 2009 revealed that a majority of farmers were willing to pay for improved water supply. In the wet season, nearly 50 percent of the farmers were willing to pay for improvements. Two-third of the farmers was willing to pay in the dry season. The average price they were willing to pay for improved water supply was estimated at Rs. 218.50 ha/year (Chandrasekaran et al, 2009).

Therefore, Indian farmers seem to be willing to pay extra for increased availability in power supply, and water availability which can be achieved by using renewable energy technologies or by using available energy more efficient by increasing efficiency of pump sets or by using more efficient irrigation technologies. If low carbon energy solutions increase the reliability and the availability of water output, marginal and small farmers' willingness to pay is not a barrier for implementing and adopting these low carbon energy solutions.

It can be concluded that there is a lack of access to formal finance for farmers in rural areas of India. This lack of access will slow down the diffusion of low carbon energy solutions for irrigation, as informal moneylenders are the only source of credit for many farmers. The attitude of farmers is positive, as they are willing to invest in more reliable water output and power availability. This means that an increase in accessibility to formal credit could accelerate the diffusion of low carbon energy solutions for irrigation in India.

6. Resource availability and environmental sustainability

In order to use renewable energy technologies for pumping water for irrigation, sufficient resources should be available. This chapter will give an overview of the amount of the average solar radiation and wind speed in India and high potential areas are indicated. Besides resource availability, the environmental sustainability of different low carbon energy solutions is of great importance. Therefore, a rough estimation is made for the CO_2 mitigation potential of the energy solutions. This estimation is based on the utilization potential and values found in literature. Another environmental issue in India is declining water tables due to over extraction of ground water. This chapter will describe the current situation in India and how low carbon energy solutions can contribute to improve present situation.

6.1 Resource availability

The renewable energy technologies suited for irrigation in India are based on solar and wind energy. This study is focused on both solar photovoltaic and windmill pumps and resources available for these renewable energy technologies are therefore investigated.

6.1.1 SPV pumps

The solar resource potential or availability of a region depends on the intensity of insolation, also known as the irradiation. Sufficient solar radiation is necessary for all devices based on solar energy. Solar radiation is usually measured in the amount of kWh/m^2/day and depends on the location on earth. The irradiation can vary between 4-10 GJ per square meter per annum, which equals 3-7.6 kWh/m^2/day (Blok, 2007). Taking the location into account, India is considered a good recipient of solar energy. But due to the size of the country, there are big differences between different locations and detailed solar radiation data for a specific location should be used before installing a SPV pump.

According to previous research, it is recommended that for installing SPV pumps, the average daily solar radiation in the least sunny month should be greater than 3.5-4 kWh/m^2/day on a horizontal surface and the daily average solar radiation in the rest of the year should be at least 5.5 kWh/m^2/day (Purohit, 2007; Purohit and Kandpal, 2005; Kumar and Kandpal, 2007). This is equal to 1000 W/m^2 for 5.5 hours a day and this solar irradiation level is assumed to be sufficient to meet the energy and water requirements of farmers. In order to find out which locations meet the condition of daily average solar radiation availability, the annual average global insolation map of India is used. This map is derived from Ramachandra et al (2011) and shows high resolution satellite data from NASA SSE in India across federal boundaries and agro-climatic zones[22]. This map can be found in appendix A. Not only the daily average solar radiation is of importance, but also the average monthly solar radiation should be taken into account when finding out which locations are suited for SPV pumping. Therefore, monthly average global insolation maps of India can be found in appendix B.

From the radiation maps found in appendix A and B can be concluded that during the winter months Northern India receives the least insolation. Most parts of South India still receive above 4.5 $kWh/m^2/day$, but averages in the Northern regions and Himalayas are around 2.3-3.5 $kWh/m^2/day$. In April and May, most of the country receives more than 5 $kWh/m^2/day$. But this level of radiation decreases in June, due to the monsoon. During the months June, July and August, the Southern and North Eastern areas of India are most affected by the monsoon and global insolation can decrease to 3.9 $kWh/m^2/day$. The Northern part of the country remains hardly affected by the monsoon and radiation is between 5-7 $kWh/m^2/day$. The North-eastern monsoon brings radiation below 4 $kWh/m^2/day$ in the Eastern and Northern tip of the country, while the Himalayan foothills and the rest of India still receive above 4.7 $kWh/m^2/day$. This is a result of the Himalayas, which act as a barrier to this winter monsoon (Ramachandra et al, 2011).

Looking at the annual average global insolation map of India in appendix A, it can be concluded that not many parts in India excess the requirement of 5.5 $kWh/m^2/day$. The areas that are coloured red have an annual average radiation around 5-5.5 $kWh/m^2/day$. Only the far Eastern Himalaya region and the Northern tip of India receive an average radiation less than 4 $kWh/m^2/day$. Taken both the annual average radiation and the monthly average radiation into account, it can be concluded that the Agro-climatic zones of the Middle, Upper and Trans Gangetic plain region as well as the East and West coast plains and the Western Plateau are most suited for SPV pumps. This includes the states of Bihar, Uttar Pradesh, Haryana, Punjab, Andhra Pradesh, Tamil Nadu, Karnataka, Goa and Maharashtra.

6.1.2 Wind Energy

India is not only considered as a good solar recipient, it is also ranked among the top five countries in the world in wind energy generation, next to Germany, Spain, USA and Denmark (Carolin Mabel and Fernandez, 2008). In terms of historical development and wide spread availability, wind turns out to be

[22] The Food and Agriculture Organization (FAO) defined an agro-climatic zone as a land unit delineated in terms of major climate and growing period, which is climatically suitable for certain range of crops and cultivars (FAO, 1983). The Planning Commission initiated the Agro-climatic Regional Planning Project in June 1988. Under this system, the country is divided into 15 Agro Climatic Zones, on the basis of a commonality of factors such as soil type, rainfall, temperature, water resources, etc., 14 in the main land and remaining one in the islands of Bay of Bengal and Arabian sea

one of the most viable resources in India. But, similar to the case of SPV pumps, there are big differences in availability of wind between locations in India and detailed wind data for a specific location should be used before installing a windmill. In general winds are relatively strong in India during the period between March and August, as winds in India are influenced by the monsoon. During the period between November and March, winds are weaker in India, except for the coastline of Tamil Nadu (Carolin Mabel and Fernandez, 2008).

The resource requirements for wind mills for pumping water depend strongly on the type of wind mill used and design of the wind mill. Electricity generation from wind energy requires a wind speed above 5 m/s, but for windmill pumps lower wind speeds can be sufficient. In case of water pumping using wind mills, a cut-in wind speed (the wind speed which is sufficient to start pumping) of 1.50 m/s can be achieved. Most wind mills have a rated wind speed around 3 m/s and a cut-out wind speed around 10-15 m/s[23]. Wind mills that are used in India, like the APOLY-12-PU-500 and the AV-55, are designed to have a low cut-in wind speed. (Omer, 2008; Purohit, 2007). In order to indicate locations in India that meet the wind speed condition, a wind speed map of India is used. This map is derived from Hossain et al (2011) and is composed by an innovative approach using GIS platform, wind speed measurements under government's program and the NCEP/NCAR Reanalysis data[24]. This map can be found in Appendix C. Besides average wind speed, the plant load factor (PLF) is used as another indicator for assessing locations for wind mills[25]. Therefore, a wind power potential of India by plant load factor can be found in Appendix D.

From the average wind speed map in Appendix C can be concluded that the Western regions in India receive more wind than the Eastern parts of India, except for the Southern Peninsula. Average values in the North-eastern parts of India are below 4 m/s, but can reach 10 m/s at some places of Tamil Nadu and in Gujarat. These values are measured at a height of 80 meters, as this is the most interesting height for large scale wind turbines that generate electricity, but most wind mills that are used for water

[23] The rated wind speed is the wind speed at which the wind mill reaches its rated power output. The cut-out wind speed is the maximum which at which the wind mill can operate. If the wind speed exceeds the cut-out wind speed, the wind mill will not operate in order to avoid damage.

[24] The NCEP/NCAR Reanalysis Project is a joint project between the National Centres for Environmental Prediction (NCEP, formerly "NMC") and the National Centre for Atmospheric Research (NCAR). The goal of this joint effort is to produce new atmospheric analysis using historical data and as well to produce analysis of the current atmospheric state (Hossain et al, 2011)

[25] This factor is used for determining the monthly and annual energy output of wind energy conversion system. The Plant Load Factor (PLF) is defined as the ratio between the actual power available in the wind and the rated power of the wind mill (Hossain et al, 2011). The PLF is sometimes referred to as Capacity Utilization Factor (CUF)

pumping have a height around 10-20 meters. Although wind speeds at 80 meters are assumed to be higher than at a height of 10 or 20 meters, this map can be used as an indicator for high potential areas with relatively high average wind speeds.

Looking at the plant load factor of India, it also can be concluded that the Western and Southern Peninsula part of India score better than the North-eastern part. According to literature, only regions that have potential for wind energy are considered with a PLF of more than 15% (Hossain et al, 2011). Taking only the PLF values in account, this means that large parts of the agro-climatic zones of the Western and Southern plateau, the East and West coast plains and the Gujarat and the Western dry region have potential for wind mills. Looking both at the average wind speed and the plant load factor in India, it can be concluded that southern parts of the East coast plains and the Western parts of the Gujarat plains have the highest potential for wind mills. However, as wind mills for water pumping have relatively low cut-in wind speeds, large areas of the Eastern and Southern parts of India are suited for wind energy water pumping. This includes large parts of the states of Rajasthan, Madhya Pradesh, Gujarat, Maharashtra, Goa, Karnataka, Kerala, Tamil Nadu, and Andhra Pradesh.

6.1.3 Hybrid systems

As solar-wind hybrid system use both solar and wind energy, there are many places in India suited for this technology. Areas with relatively low radiation or low average wind speed are still a possibility for solar-wind hybrid systems, since the combination of the two can be a sufficient energy source for pumping water. Looking at both the average wind speed map and the global insolation map of India, it can be concluded that the Western and Southern part of India have the highest potential for hybrid systems. The lowest potential for solar-wind hybrid systems can be found in the most Northern parts of India and the Eastern plateau and Hills region.

6.2 CO_2 mitigation potential

The main objective of low carbon energy solution is to reduce carbon emissions in the process of irrigation. In order to know the difference of CO_2 reductions between different solutions, a rough estimation is made for the total CO_2 mitigation potential in India based on the utilization potential of low carbon solutions, based on values found in literature.

6.2.1 Renewable Energy Technologies

Renewable energy technologies reduce carbon emissions, as they do not use fossil fuels which emit carbon dioxide. But the CO_2 mitigation potential differs per renewable energy technology, since there is a difference in utilization potential in India. The utilization potential of different renewable technologies for pumping water is found in a research performed by Kumar and Kandpal (2007). Unfortunately, their study did not look at hybrid systems and the utilization potential of solar-wind hybrid systems is not known. Therefore, the CO_2 mitigation potential calculations are restricted to SPV pumps and windmill pumps. According to previous research, SPV pumps have the highest utilization potential in India, namely 6.03 million (Kumar and Kandpal, 2007). The utilization potential takes into account factors such as resource availability, ground water requirements for irrigation and its availability, affordability and propensity of farmers to invest in renewable energy devices (Kumar and Kandpal, 2007). It also takes into account the density of farmers of the states where the potential for solar and wind technologies is high compared to the states where this potential is relatively low.

In order to calculate the total CO_2 mitigation potential of pumps working on renewable energy technologies in India, the annual CO_2 emissions of pump sets which can be replaced by renewable energy technology pumps is calculated. The following formula is used to calculate the annual CO_2 emissions for electric pump sets that can be substituted by pumps working on renewable energy technologies:

$$ACE = HEC \times AHO \times SCE \times N_{Electric,RET}$$

where:

ACE = Annual CO_2 Emissions of electric pump sets that can be substituted by SPV pumps (kg CO_2)
HEC = Hourly Energy Consumption (kWh)
AHO = Annual Hours of Operation (h)
SCE = Specific Carbon Dioxide Emission (kg CO_2/kWh)
$N_{Electric,\ SPV}$ = The number of electric pump sets that can be substituted by renewable energy technologies (5 hp or 10 hp)

To calculate the annual CO_2emissions of diesel pump sets that can be substituted by renewable energy technologies, the following equation is used:

$$ACE = ADC \times SCE \times N_{Diesel,RET}$$

where:

ACE = Annual CO_2 Emissions of diesel pump sets that can be substituted by SPV pumps (kg CO_2)
ADC = Annual Diesel Consumption (l)
SCE = Specific CO_2 Emission (kg CO_2/l)
$N_{Diesel,SPV}$ = The number of diesel pump sets that can be substituted by renewable energy technologies (5 hp or 10 hp)

First the CO_2 mitigation potential for SPV pumps is determined. According to literature it is assumed that in India on average both 5 hp and 10 hp electric pumps are used for 800 hours per year, but the estimated values of annual operating hours of pumps in India are widely spread. There is more consensus in the case of diesel pumping (400-600 hours per year), but in the case of electric pumping, the estimated values are between 400 hours (Shah et al, 2004), 600-1600 hours (Shah, 2009), 2000 hours (Sant and Dixit, 1996) and 2880 hours (EESL, 2009). The high uncertainty is partly caused by the unmetered system, the unreliable supply of electricity to farmers and many electric pumps are automatically switched on when there is electricity available. The carbon emissions per kWh of electricity are estimated, taken the energy mix and the transmission and distribution losses into account. As on May 31st 2012, the Indian energy mix for electricity generation consists of coal (56.54%), gas (9.18%), oil (0.59%), hydro (19.24%), nuclear (2.35%) and renewables (12.07%). Renewables consist of small hydro power, biomass, waste power, solar energy and wind energy (MoP, 2012). Transmission and distribution (T&D) losses are the losses that occur between power generation and water pumps and are assumed to be around 25% (Shah, 2009). The CO_2 emissions per litre diesel are found in literature[26].

[26] In case of electricity, the transformation and distribution losses are taken into account, but this is not the case for the value for carbon emission per liter diesel. It is assumed that there are significant carbon emissions during the transportation of diesel, but average values are not available and therefore not estimated. However, it is assumed that carbon emissions in case of diesel pumping are higher than calculated values in this report.

Table 13: Input parameters CO_2 mitigation potential calculations

Parameter	
Utilization potential SPV pumps	6.03 million[a]
Utilization potential SPV pumps high capacity (1800Wp)	4.29 million[a]
Utilization potential SPV pumps low capacity (1200Wp)	1.74 million[a]
Utilization potential windmill pumps	2.39 million[a]
Hourly energy consumption electric pump set (10 hp)	7.3 kWh[b]
Hourly energy consumption electric pump set (5 hp)	3.83 kWh[b]
Annual hours of operation (electric pump sets)	800 hours
CO_2 emissions per kWh (electric pump sets)	1.49 kg[c]
Annual diesel consumption (5 hp)	675 litre
Annual diesel consumption (10 hp)	1350 litre
CO_2 emissions per litre diesel	2.68 kg[c]

[a] *Kumar and Kandpal (2007)*
[b] *Shah (2009)*
[c] *Nelson et al (2009)*

The annual CO_2 emissions of pump sets that can be substituted by SPV pumps is equal to the CO_2 mitigation potential of SPV pumps, as this is the amount of CO_2 that is avoided when all potential SPV pumps are installed.

In the case of wind energy, the utilization potential of windmill pumps in India for irrigation is estimated at 2.39 million (Kumar and Kandpal, 2007). The study of Kumar and Kandpal (2007) does not make a division between large and small pumps in case of windmill pumps. Therefore, it is not possible to calculate which share of the potential windmill pumps can replace 5 hp pumps and which share can replace 10 hp pumps. Hence, the range of CO_2 mitigation potential is estimated. First, it is assumed that the total utilization potential of windmill pumps will only replace either 5 hp electric pumps, 10 hp electric pumps, 5 hp diesel pumps or 10 hp diesel pumps. Secondly, to become more specific and narrow down the range of the estimated CO_2 mitigation potential of both SPV pumps and windmill pumps, it is assumed that the number of electric and diesel pumps replaced by a renewable energy technology is proportional to the division of electric and diesel pumps in India.

Table 14: Average CO_2 mitigation potential windmill pumps

	Electric pump (5hp)	Electric pump (10hp)	Diesel pump (5hp)	Diesel pump (10hp)
Number of pumps that can be substituted by SPV pumps	1,740,000[a]	4,290,000[a]	1,740,000[a]	4,290,000[a]
CO_2 mitigation potential SPV pumps (million tonnes CO_2/yr)	8.0	37.3	3.2	15.5
Number of pumps that can be substituted by windmill pumps	2,390,000[a]	2,390,000[a]	2,390,000[a]	2,390,000[a]
CO_2 mitigation potential windmill pumps (million tonnes CO_2/yr)	10.9	20.8	4.3	8.6

[a] *Kumar and Kandpal (2007)*

So if all SPV pump sets will substitute electric pump sets (4.29 million electric pumps of 10 hp and 1.74 million electric pumps of 5 hp), the annual CO_2 reductions would be estimated around 45.3 million tonnes/yr. If all SPV pump sets will substitute diesel pump sets (4.29 million diesel pumps of 10 hp and 1.74 million diesel pumps of 5 hp), the annual CO_2 reductions would be estimated around 18.7 million tonnes/yr. If all windmill pumps will substitute 10 hp electric pump sets, the total CO_2 mitigation potential would be 20.8 million Mt/yr. But if all windmill pumps will substitute 5 hp diesel pump sets, the annual CO_2 mitigation potential would be estimated at 4.3 million Mt/yr.

To give a more specific estimation of the CO_2 mitigation potential of the renewable energy technologies, it is assumed that the number of pumps that is replaced by a renewable energy technology is proportional to the number of pumps in India. Overall, there are around three times more electric pumps than diesel pumps in India. In case of SPV pumps substitution, this will mean that 4.52 million electric pumps are replaced and around 1.51 million diesel pumps. In case of windmill pumps, this will mean that 1.79 million electric pumps are replaced and 0.6 million diesel pumps. The more specific annual CO_2 mitigation potential of SPV pumps and windmill pumps can be found in table 15.

Table 15: CO_2 mitigation potential of SPV pumps and windmill pumps Renewable Energy Technologies

	SPV pumps	Windmill pumps
Number of electric pumps that are replaced (million)	4.52	1.79
Number of diesel pump that are replaced (million)	1.51	0.6
CO_2 mitigation potential (million tonnes CO_2/ yr)	38.6	9.3 – 17.7
% of total CO_2 emissions for irrigation	31	7.5 – 14.3

The annual CO_2 mitigation potential of SPV pumps is estimated at 38.6 million tonnes. For windmills, the annual CO_2 mitigation potential is estimated at 9.3 million tonnes if all 5 hp pumps are replaced and around 17.7 million tonnes if all 10 hp pumps are replaced. Note that there are some pumps that can be replaced by both SPV pumps and windmill pumps. This means that there is some overlap in the CO_2 potential of these renewable energy technologies and therefore it is not possible to add the CO_2 mitigation potential of SPV pumps and windmill pumps to calculate total CO_2 mitigation potential.

The reasons for the relatively high values found in the case of the substitution of electric pumps is due to high T&D losses, inefficient energy use due to low electricity prices and old electric pumps. The total annual carbon emissions for groundwater pumping for irrigation in India were estimated to be 33.9 million tonnes in 2010, which equals 124.2 million tonnes CO_2 emissions (Nelson et al, 2009). This means that it is estimated that SPV pumps can reduce carbon emissions for irrigation by 31 percent. In case of windmills, carbon emissions for irrigation in India can be reduced between 7.5 and 14.3 percent.

6.2.2 Energy efficiency

A reduction in carbon emissions can also be achieved by increasing energy efficiency and therefore decreasing energy consumption. As mentioned in chapter 3, it is estimated that overall efficiency of pump sets is around 20-30 percent in India. Detailed data for all of India is not available, but field visits conducted by the Bureau of Energy Efficiency (BEE) in Solarpur, Maharashtra and the Energy Efficiency Services Limited (EESL) in Dausa and Chomu, Rajasthan give good insights in the current situation. In the area of Solarpur, the overall average operating efficiency for all existing electric pump sets is 28 % (BEE, 2009). In the area of Dausa and Chomu, the overall average operating efficiency for all existing electric pump sets is 27% (EESL, 2009). It is assumed that in India, existing electric pump sets have an average operating efficiency of 27.5%. According to the BEE, the overall weighted average operating efficiency for new energy efficient pump set is 48.9%, meaning that there is a potential to increase the overall weighted average operating efficiency by more than 20% (BEE, 2009). It is assumed that diesel pump sets have a low average operating efficiency as well, but unfortunately there is no data available about the efficiency of existing diesel pump sets.

The total carbon emissions for ground water pumping for irrigation are mainly caused by electric pump sets and `to a lesser extent by diesel pump sets. It is estimated that electric pump sets are responsible for 77.1% of total CO_2 emissions and diesel pump sets are responsible for 22.9% of total CO_2 emissions (Shah, 2009). To calculate the CO_2 mitigation potential of improved energy efficient electric pump sets, the following formula is used:

$$CO_2\ Mitigation\ Potential = TCE - \left(TCE \times SEC \times \frac{CAE}{IAE}\right)$$

where

CO_2 mitigation potential = the amount of CO_2 that would have been emitted by electric pump sets if efficiency is not improved (million tonnes CO_2/yr)
TCE = Total Carbon Dioxide Emissions for water pumping for irrigation (million tonnes CO_2/yr)
SEC = Share of Carbon Dioxide Emissions emitted by electric pump sets
CAE = Current Average Efficiency of existing electric pump sets
IAE = Improved Average Efficiency of improved electric pump sets

Table 16: CO_2 mitigation potential of SPV pumps and windmill pumps increasing energy efficiency

Parameter	
Current average operating efficiency existing pump set	27.5 %[a]
Average operating efficiency for new efficient pump set	48.9%[a]
Share of carbon emissions electric pump sets	77.1%[b]
Share of carbon emissions diesel pump sets	22.9%[b]
Total annual CO_2 emissions for irrigation	124.2 million tonnes[c]
Annual CO_2 emissions electric pumping	95.8 million tonnes
CO_2 mitigation potential electric pump sets	41.9 million tonnes/yr

[a] BEE (2009); EESL (2009)
[b] Shah (2009)
[c] Nelson et al (2009)

If all electric pump sets would be improved to an average operating efficiency of 48.9%, this would result in a significant decrease in carbon emissions. The energy consumption would decrease with 43.8% and the CO_2 mitigation potential for increasing energy efficiency of electric pump sets would be around 41.9 million tonnes per year.

6.2.3 Drip irrigation

A decrease in energy consumption will result in a decrease in carbon emissions. In chapter 3 it was mentioned that the estimated potential of drip irrigation in India is 21.3 million ha. Also, energy savings depend on the type of drip irrigation and the type of crop, which was mentioned in chapter 5. To make an estimation of the total CO_2 mitigation potential of drip irrigation, it is assumed that drip irrigation on average will decrease energy consumption by 40% (Narayanamoorthy, 2006; Narayanamoorthy, 2008). Currently, only 1.4 m ha of net irrigated area in India is under drip irrigation (TERI, 2010). This means that there is a potential of 19.9 m ha which is suitable for drip irrigation in India, but currently not used for drip irrigation. To estimate the CO_2 mitigation potential of drip irrigation in India, the following equation is used:

$$CO_2\ Mitigation\ Potential = \frac{TCE}{NIA} \times PAD \times DEC$$

where

CO_2 mitigation potential = the reduction of CO_2 emissions by installing drip irrigation installations (million tonnes CO_2/yr)
TCE = Total CO_2 Emissions for water pumping for irrigation (million tonnes CO_2/yr)
NIA = Net Irrigated Area in India (million ha)
PAD = Potential Area for Drip irrigation in India, minus the area already used for drip irrigation (million ha)
DEC = Decrease in Energy Consumption

The input parameters needed to calculate the CO_2 mitigation potential for drip irrigation in India can be found in Table 17 and the results can be found in Figure 14.

Table 17: CO_2 mitigation potential of SPV pumps and windmill pumps Drip Irrigation

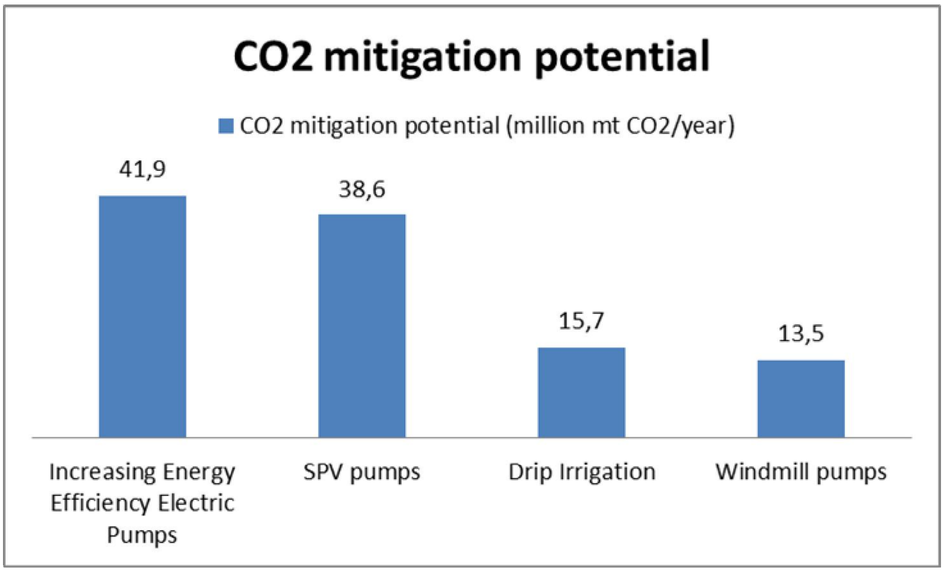
Parameter	
Estimated total potential of drip irrigation (million ha)	21.3[a]
Current area used for drip irrigation (million ha)	1.4[b]
Remaining potential of drip irrigation (million ha)	19.9
Net irrigated area India (million ha)	63.2[b]
Estimated decrease in energy consumption (%)	40[c,d]
Total carbon emissions for irrigation (million tonnes/yr)	124.2[e]
CO_2 emissions per net irrigated area (million tonnes CO_2/m ha)	1.97
CO_2 emissions for the area which is suited but currently not used for drip irrigation (million tonnes CO_2/19.9 m ha)	39.1
CO_2 mitigation potential for drip irrigation (million tonnes CO_2 /yr)	15.7

[a] *Narayanamoorthy (2004)*
[b] *MOA (2011)*
[c] *Narayanamoorthy (2006)*
[d] *Narayanamoorthy (2008)*
[e] *Nelson et al (2009)*

The total CO_2 mitigation potential for drip irrigation is therefore estimated at 15.7 million Mt per year. This can be achieved when drip irrigation potential for India is fully exploited.

Compared to other low carbon options for irrigation in India, drip irrigation has a relatively low CO_2 mitigation potential, as can be seen in Figure 8.The highest CO_2 mitigation potential belongs to increasing energy efficiency, followed by SPV pumps.

Figure 14: CO_2 mitigation potential of low carbon energy solutions in India



Looking at the CO_2 mitigation potential of drip irrigation in more detail, there are big differences between the CO_2 mitigation potential of different crops. This is due to differences between crops in energy consumption, total area of production and energy savings. An overview of the results can be found in Table 18.

Table 18: Total theoretical CO_2 mitigation potential of drip irrigation for different types of crops

Banana's	
Electricity consumption (kWh/ha)	8348[a,b]
Energy savings with drip irrigation (%)	29[a,b]
Total area of production in India (million ha)	0.8[c]
Carbon emissions per kWh (kg CO_2/kWh)	1.49[d]
Total theoretical CO_2 mitigation potential (million tonnes CO_2/yr)	2.9

Sugarcane	
Electricity consumption (kWh/ha)	2385[a,b]
Energy savings with drip irrigation (%)	44[a,b]
Total area of production in India (million ha)	5[c]
Carbon emissions per kWh (kg/kWh)	1.49[d]
Total theoretical CO_2 mitigation potential (million tonnes CO_2/yr)	7.8
Cotton	
Electricity consumption (kWh/ha)	769[a,b]
Energy savings with drip irrigation (%)	45[a,b]
Total area of production in India (million ha)	12[c]
Carbon emissions per kWh (kg/kWh)	1.49[d]
Total theoretical CO_2 mitigation potential (million mttonnes CO_2/yr)	6.2

[a] *Narayanamoorthy (2006)*
[b] *Narayanamoorthy (2008)*
[c] *MOA (2011)*
[d] *Nelson et al (2009)*

As can be concluded from Table 18, the combined theoretical CO_2 mitigation potential of banana's, sugarcane and cotton in India is already larger than estimated total CO_2 mitigation potential of 15.7 million tonnes CO_2. The actual CO_2 mitigation potential of crops is significantly lower than the theoretical potential calculated in Table 15, since some source of irrigation is essential for adopting drip irrigation. This means that when there is no water source available for irrigation, irrigation is not possible and therefore there is no drip irrigation potential. This prerequisite is included in the total CO_2 mitigation estimation of 15.7 million tonnes CO_2, but excluded in the estimation per crop. However, table 18 shows that most CO_2 with drip irrigation can be saved with sugarcane.

6.3 Groundwater availability

Over the past three decades, groundwater has become the main source of growth in irrigated areas. The use of groundwater for irrigation developed mostly through individual initiatives and was not governmental or policy driven, making it largely unnoticed. But recently, more and more attention is given to the critical situation of groundwater irrigation in India, which needs an urgent attention and understanding. Currently, groundwater accounts for over 60 percent of the irrigated area in the country (Shah et al, 2004; Shah, 2009; India Infrastructure Report, 2010). The amount of groundwater currently extracted will have serious implications in some areas of India for future growth and development. Although at most places in India the amount of groundwater extraction is not alarming at this moment, there are some very critical places in Punjab, Rajasthan and Haryana and the number of critical places is increasing[27].

Micro irrigation, like drip irrigation, was mainly introduced as water-saving technology. As stated in an article in 1994 by Sivanappan, there are many wells that show decreasing water levels and in order to maintain the groundwater level, it will be necessary to switch to micro-irrigation in these states (Sivanappan, 1994). It seems obvious that when there is less water consumption, because of decreasing evaporation losses and more concentrated applied water, ground water conditions will improve. But over the past decade, there has been a discussion whether micro irrigation really is a solution for the critical groundwater situation. It turns out that micro irrigation can increase water use efficiency, meaning there is more yield with the same amount of water, but it is not a solution for depleting ground water level tables (Molle and Tural, 2004).

There are two reasons for this. First, some of the water 'saved' would have percolated into the groundwater table from where it would later be reused by farmers through pumping. So, in case of micro irrigation, less water is 'spilled' next to the crop, but most of this water would be absorbed by the ground in case of flood irrigation. This means that with micro irrigation, less water is needed and extracted from the ground, but less water is absorbed by the ground as well. So the effect of micro irrigation to ground water level tables is minimal. Second, the increased crop water productivity due to micro irrigation for medium and large scale farms has made water use more profitable and hence *increased* water demand and groundwater depletion through expansion in cropped area (IWMI, 2007). This rebound effect, also known as 'the Jevons Paradox', has the result that the use of micro irrigation

[27] In India, the total replenishable groundwater resources is 433.02 billion cubic meters (BCM) and the utilizable groundwater resources for irrigation in net terms is 381.16 BCM. At this moment, the annual draft is estimated to be about 243 BCM, from which 221 BCM is used for irrigation and 22 BCM is for industrial and domestic draft (CGWB, 2012). Although this number does not appear to be very alarming, only 63.8% of the groundwater resources are used, it does not reveal the true picture of geographic variation. The Ganga basin alone accounts for nearly 40 percent, so resources are highly concentrated. In 2007, there were three states that had a higher yearly net draft than the total replenishable groundwater resource. The level of groundwater development is already as high as 141 percent in Punjab, 111 percent in Rajasthan and 105 percent in Haryana (India Infrastructure Report, 2010).

tends to increase the ground water consumption. So in order to improve the groundwater condition, one of the preconditions is that the area under irrigation can not increase. This is not a guarantee that this will 'save' water, because otherwise it would have percolated into the groundwater table, but in that case it would not have been reused through pumping, meaning a decrease in energy consumption and carbon emissions.

As it turns out, micro irrigation can not be seen as a solution for the critical ground water situation. In order to improve current ground water level conditions, farmers should extract less water from the ground and use other water sources, like rain water, more efficient. Another option would be to increase regulation from the government in order to decrease the use of ground water irrigation. However, according to Rostee (2012), water pricing is not a solution for the critical ground water situation in India, as the price elasticity of water is very low (Rostee, 2012). In order to limit water consumption from ground water resources for irrigation with price regulation, prices should be unacceptably high. It turns out that water pricing can work for drinking water, as price elasticity for drinking water is higher than for irrigation. According to Rostee (2012), the best option to regulate ground water consumption for irrigation is to use a quota system (Rostee, 2012). He suggests a system where the government allows a farmer to use a certain amount of water each year, depending on land size, crop type etc. However, currently there is no experience with quota systems for ground water consumption and there is a lack of knowledge how to implement this system (Rostee, 2012).

6.4 Overview of results

The most important results of Chapter 5 and Chapter 6 can be found in Table 19 below.

Table 19: Results of Chapter 5 and Chapter 6

	SPV pumps				Windmill pumps				Solar-wind Hybrid pumps		Increasing Energy Efficiency						Micro-irrigation			
Type	1200 Wp		1800 Wp		APOLY-12-PU-500		AV-55		2 kW		Electric pumps			Diesel pumps			Shiftable drip irrigation		Stationary drip irrigation	
	ES[a]	DS[a]	ES[a]	DS[a]	ES[a]	DS[a]	ES[a]	DS[a]	ES[a]	DS[a]	LMC[b]	RLE[b]	RME[b]	LMC[b]	RLE[b]	RME[b]	EP[c]	DP[c]	EP[c]	DP[c]
Payback period (years)	19.9	4.8	13.9	6.6	5.5	2.5	6.5	1.6	20.6	9.0	20-40 days	0.4	2.3	17-8.5 days	-	-	11.5-12.8[d]	2.1-2.3[d]	17.2-18.6[d]	3.1-3.4[d]
Unit Cost of Water (Rs./m^3)	1.89	1.89	1.7	1.7	0.47	0.47	2.18	2.18	3.24	3.24	-	-	-	-	-	-	-	-	-	-
CO_2 mitigation potential (million mt CO_2/year)	38.6				9.3 - 17.7				-		41.9			-			15.7			
Resource Availability	• Least sunny month should exceed 3.5-4 kWh/m^2/day • Daily average solar radiation should be at least 5.5 kWh/m^2/day • Most Southern, Western and Himalayan foothill regions in India have high potential				• Cut-in wind speed 1.5 m/s, rated wind speed around 3 m/s and cut-out wind around 10-15 m/s. • Most Southern, Western and Eastern coastline regions in India have high potential				All regions have high potential, except for most Northern and Eastern parts of India		Most electric pump sets can be found in Southern and Western regions of India[e]			Most diesel pump sets can be found in Himalayan foothill and Eastern regions of India[e]			During field work conducted for this study some farmers indicated that they were willing to switch to micro irrigation, but did not know where to get the supplies for it			

[a] ES = Electricity Substitution, DS = Diesel Substitution
[b] LMC = Low and Medium Cost measures, RLE = Replacement of Low Efficiency pump set, RME = Replacement of Medium Efficiency pump set
[c] EP = Electric Pump sets, DP = Diesel Pump sets
[d] These values are 'best' values found with using micro irrigation to grow banana's. Other crops, like grapes, sugarcane and cotton, have longer payback periods

[e] Shah (2009)

7. Social barriers

Many examples show that well developed energy technologies, such as SPV pumping, do not live up to their potential in certain rural areas. This is partly due to the way that technology transfer is carried out[28](Fedrizzi et al, 2009). Often, it is not considered that the social context in which the technology is introduced wants and accepts the technological solution. Therefore, an understanding in the cultural beliefs and views of the farmers is necessary to understand the motivational factors behind the acceptance or rejection of energy solutions for irrigation. The attitude towards and experiences with low carbon solutions of farmers for irrigation in India is investigated during personal and group interviews in the region of Moradabad and Saharanpur. These location were selected, because there were some farmers that adopted SPV pumps and their experiences were investigated as well.

7.1 Theft/Vandalism/Corruption

One of the problems with the introduction of new technologies in rural areas is the fear that equipment gets stolen or damaged. Solar panels are seen as valuable possessions and farmers do not like to leave expensive materials in the field. The same applies to drip irrigation systems, although less valuable, they are easily stolen or damaged. In case of wind pumping there is no such problem. Diesel pump sets are often placed on some kind of a trailer and electric pump sets are seen as less valuable. Most small landholders do not live next to their land, so they are incapable to keep track on their assets. Protecting installations can be a solution, but it will make the capital costs even higher. For example, in Africa solar water pumping locations required security fencing of some kind, some with electrified fences and motion detectors (Short and Thompson, 2003).

Switching from flat tariff to metered electricity tariff for farm supply is often seen as a prerequisite in order to successfully switch to low carbon energy solutions. It will not only increase the economic attractiveness of the renewable energy technologies, it will also help energy companies to restore their balance sheets[29]. However, there is some resistance towards metered tariff. It will not only have high transaction costs for power utilities, most farmers also have their doubts. Some farmers expect that their

[28] There are many definitions of 'Technology Transfer' available in literature. Generally, technology transfer is the process where concepts move from the laboratory to the market, so that one party gains access to another's technical information and successfully learn how to use it.

[29] Low prices for electricity in agriculture were a powerful weapon for chief ministers to gain more popularity when power supply to agriculture emerged as a major driver of irrigated agriculture. However, unable to raise flat tariff for years and under pressure to supply enough electricity to farmers, power utilities began to find their balance sheets turning red (Shah et al, 2004). This is a major concern for power utilities and state governments.

annual expenditures for electricity will decrease in case of metered tariff, because they have over sized water pumps and they are not using it that often due to the reliability of the grid. As can be concluded from field work conducted for this research, most farmers are against metered tariff, as they think that officials can not be trusted and they are overcharged by power utilities. Some villages visited for this study had that experiences from the past and are not willing to switch back to metered tariff.

7.2 Information and awareness

Another barrier found during field visits is the lack of information and awareness among farmers. First of all, it was found during group interviews that farmers are concerned about their incomes. Farmers have water requirements for irrigation, which enables them to grow crops and earn money. The farmers that were interviewed are not really concerned about the carbon emissions of their pump set. Some farmers did not understand the concept of global warming, while others were aware of it, but did not see it as their main concern. Furthermore, the interviews also revealed that farmers have a lack of knowledge about renewable energy technologies and micro-irrigation. Some farmers have heard about the concept of micro-irrigation, but none of the farmers that were interviewed did know where to buy the materials. Farmers are concerned that micro-irrigation will hinder them in growing different kind of crops during the year, which is actually the case when working with shiftable and stationary drip irrigation systems. Another reason is that farmers believe that the size of their land is too big. This does not have to be a problem. Farmers could adopt a low cost drip irrigation system, like a bucket or drum kit, and apply it to some of their land. At the same time, they can grow other kind of crops on the other part of their land. Also, most farmers have the misconception that micro-irrigation is only applicable for vegetables and are therefore not willing to switch to micro irrigation[30].

From field visits can be concluded that farmers base their decision about what to cultivate on family tradition. It seems that farmers are not really concerned what kind of crops they grow and, generally, do not change the pattern of their cropping system. The water requirements of crops are not taken into account when deciding which type of crop is grown. The exception is found in the village of Mubarakpur, where people are trying to cultivate high value crops, like fruit and vegetables. The problem they face is the fluctuations in the price they get for the vegetables. Whenever they get a low price for their high value crops, they switch back to low value crops, like sugarcane and wheat.

[30] Most farmers interviewed for this study cultivated sugarcane. According to literature, sugarcane is suitable for drip irrigation, although all farmers interviewed were convinced that it is not a possibility (Singandhupe et al, 2008). This is a clear indication that there is a knowledge barrier.

There is much uncertainty about the availability of schemes on renewable energy technologies in rural areas. It is clear that most farmers are confused about the schemes applicable at this moment. There was always a lot of discussion between villagers when answering the question which subsidies for renewable energy technologies and micro irrigation there were at that moment. Some said there are still schemes to apply for solar power, but others agreed that this scheme is no longer available.

It is clear that there is a great need for more information and to create awareness among farmers. Although most Indian farmers are more concerned with making a living instead of their environmental impact, it is assumed that an increasing awareness about their role on decreasing water tables and climate change can contribute to their willingness to switch to low carbon energy solutions. There is much uncertainty about state governmental subsidies and schemes for renewable energy technologies and micro-irrigation. Furthermore, farmers have a lack of recent knowledge about modern irrigation techniques and do not know where they can gain this information. Shortcomings in access to information and awareness are seen as another barrier for the diffusion and adaptation of low carbon energy solutions for irrigation in India.

8. SWOT analysis

This chapter will describe a SWOT analysis of different low carbon energy solutions for irrigation in India. This is done to highlight the strengths, weaknesses and opportunities of low carbon solutions in India.

8.1 SPV pumps

Water pumping is a well-known and promising application of PV power. In India, SPV pump have the highest utilization potential of all renewable energy technologies. With more than 7000 SPV pumps currently installed, it is a well-established technology, although far below its potential of 6 million SPV pumps. SPV pumps do not only have zero carbon emissions while they are pumping, they are also considered to be a time saving option, as SPV pumps are reliable and autonomous and have low maintenance requirements. Also, the water output is high at moments when water requirements are high as well. The problem that Indian farmers have indicated during field work about owning several pieces of land can be solved by SPV pumps that are mounted on a trailer. Furthermore, the array and pump can be placed at different locations, which mean that the array can be placed, within reasonable distance, at a location with more radiation potential. Compared to other low carbon energy solutions for irrigation in India, SPV pumps have a high CO_2 mitigation potential.

However, SPV pumps have some weaknesses as well. PV cells have a low conversion efficiency, around 15%, and therefore the array takes up much space, which can no longer be used for cultivation. This problem can be solved by placing the array on places which are not suited for cultivation, such as the roofs of houses, or by increasing the efficiency. There are some innovative ways to increase the efficiency of the PV array, because by increasing the conversion efficiency, initial costs can decrease, since the PV array area can decrease. One promising method, especially in case of water pumping on solar power, is cooling the PV cells by spraying water over the cells. In this way, both temperature and cell reflection will decrease. A study by Abdolzadeh and Ameri has examined the performance of a 225W photovoltaic water pumping system with water spray over the PV cells. In the case of a system without water spray over the cells the flow rate at 16 m head was about 479 l/h during the test day, whereas it reached 644 l/h in the case of system with water spray over the cells. The mean volume of water used for spraying over the cells in the latter case was about 50 l/h (Abdolzadeh and Ameri, 2009). Although water output is high at moments when it is needed the most, the water output is still variable and not continuous. Furthermore, SPV pumps consist of complex components, such as inverters and cables, and are therefore vulnerable and more difficult to use and maintain. Because of the relatively high price of solar cells and inverters, SPV pumps have high initial costs and a long payback period. The valuable solar panels make SPV pump more vulnerable for vandalism and theft.

SPV pumps do have some opportunities in India. As prices for fossil fuels are expected to increase in the future, the economic viability will increase and SPV pumps will become more financial attractively. Looking at the average irradiation in India, SPV pumps have great potential in nine states, but can be used at many places during most months of the year. There are around 45 companies that manufacture solar photovoltaic systems in India, meaning that there are enough companies to design and deliver SPV pumps, which can be modified and adjusted to Indian conditions and preferences. It is assumed that an increase in the number of SPV pumps will also cause a growth in the Indian solar industry. This can be a great opportunity for India, as global demand for PV technologies is growing as well. This means further developments in the PV industry, which can also be used for domestic purposes as well.

However, there are some threats that can slowdown the diffusion of SPV pumps in India. First of all, there is no clear need from farmer's perspective, as they are not really concerned about their carbon footprint. Furthermore, at some places in rural areas of India is a low availability of spare parts, which is experienced as a problem by current users of SPV pumps. Central and state governments are trying to accelerate diffusion of SPV pumps by making them more financially attractive with schemes and subsidies, but farmers are not aware of current regulations. This lack of information causes less motivation among farmers to adopt SPV pumps. At this moment, SPV pumps are not financially attractive to substitute electric pump sets, as there are high subsidies for electricity.

Figure 15: SWOT analysis of SPV pumps in India

Strengths	Weaknesses
• Well established technology in India (more than 7000 SPV pumps installed) • Low maintenance • Reliable • Autonomous • Possible to mount it on a trailer • Array can be placed at different location than the pump • Relatively high CO_2 mitigation potential	• Low conversion efficiency • Variable water output, especially low at night • Consists of complex components • High initial costs • Long payback period • Vulnerable for vandalism and theft • The array needs a lot of space which can not be used for cultivation
Opportunities	**Threats**
• No dependency on fossil fuels • Sufficient irradiation in most places in India • Many manufacturers of both solar modules and SPV pumps in India • Stimulates industries e.g. panels, modules, maintenance • Can be used for domestic purposes as well • Solar module costs will decrease over time	• There is no need from farmer's perspective • There is low availability of spare parts • There is high uncertainty and low degree of knowledge among end users about current schemes and subsidies • Only financially attractive with governmental subsidies

8.2 Windmill pumps

Windmill pumps have been used for decades for pumping water. They are known for their simple design, since there are no complex electrical parts involved. Mechanical windmill pumps are not only simple to use and to understand, they are reliable and work autonomous as well, which make them time saving options. In India, windmill pumps have relative low initial costs and low payback periods, making them more suitable for marginal and small landholders, compared to more expensive renewable energy technologies. Due to the large and robust design, windmill pumps are less vulnerable for theft and vandalism. It is also the reason that windmill pumps have a relatively long life span.

Unfortunately, windmill pumps have some weaknesses as well. In case of mechanical wind pumping, the turbine has to be placed above the water source. This means that the turbine can not be placed in areas near the water source with a greater wind resource potential and that windmill pumps can not be used at different locations. Due to the large and robust design, farmers can experience windmill pumps as visual pollution and the large moving parts produce some noise, which can be annoying for neighbours. Furthermore, the highest water output is when the wind speeds are at highest, which is often at night and not during warm summer days, when water requirements are highest. Also, due to the lower utilization potential in India, windmill pumps have a lower CO_2 mitigation potential in India.

Opportunities for windmill pumps include global increasing prices of fossil fuels. This will increase the financial attractiveness of windmill pumps. Contrary to SPV pumps, wind mills are not dependent on subsidies, as payback periods are already around 6 years in case of substitution of electric pump sets and only around 2 years with substitution of diesel pump sets. Furthermore, it is assumed that there is a significant amount of spare parts available in rural areas of India, as there are only mechanical parts in windmill pumps[31]. And windmill pumps are produced and manufactured in India, as there are 17 approved windmill manufacturers and 6 more are being tested at this moment.

But there are some threats for the diffusion of windmill pumps in India. At this moment, there are around 1300 windmill pumps installed, which means that there is less experience with windmill pumps than with SPV pumps. There is a lack of need for windmill pumps from a farmer's perspective. The utilization potential of windmill pumps is relatively low, as windmill pumps have the most potential with centrifugal pumps, which limit the depth from which the windmill can pump the water from the source. Declining ground water tables can therefore be a threat for the diffusion of windmill pumps. Wind mills are financially most attractive to substitute diesel pumps, but diesel pumps are mostly found in North eastern part of India, where the wind potential is low. It is expected that prices of windmill pumps will increase in the future, as materials like steel are becoming more expensive.

Figure 16: SWOT analysis of windmill pumps in India

Strengths • Simple design • No electrical parts, only mechanical • Reliable • Autonomous • Low initial costs • Considerable payback period • Not vulnerable for vandalism and theft • Relatively long life time	**Weaknesses** • Has to be placed above the water source and pump • Visual pollution • Noise • No mobility • High water output when water requirements are low • Lower CO_2 mitigation potential
Opportunities • No dependency on fossil fuels • Availability of spare parts • Sufficient amount of manufacturers	**Threats** • Less established technology in India • No need from farmer's perspective • Not many high potential areas in India • Will become more expensive, as materials become more expensive (steel)

[31] According to Wood (1994), the reason why the diffusion of handpumps in India was more successful than in Africa was because India has a long tradition in cycling. The popularity of bicycles has encouraged a culture of village bicycle repair shops, whose mechanics are ideally suited to repair handpumps. So there is enough experience and materials to repair mechanical handpumps, which can easily be extended to windmill pumps.

8.3 Solar-wind hybrid

As wind and solar energy are not always available when needed, hybrid systems are developed to provide a more continuous supply of energy. Solar-wind hybrid systems are considered to be reliable, work autonomous and can be time saving. As solar-wind hybrid systems can work on either wind or solar energy, it is estimated that this technology can be implemented at many places in India. Therefore, it is estimated that the utilization potential is high and the CO_2 mitigation potential is significant, although due to a lack of information, this is not calculated in this study. Furthermore, the array and wind turbine can be placed at places with more radiation and wind potential and are not limited to be placed at the same place as the water source is. Note that mechanical windmill pumps are limited to be placed above the water resource, but in case of electric windmill pumping the wind turbines can be placed at a different location. Electricity generated can also be used for domestic purposes when irrigation water requirements are low.

Nevertheless, solar-hybrid systems for irrigation in India have some drawbacks. The combination of solar and wind energy makes this technology rather complicated. Inverters consist of complex software, making it difficult to repair when an installation is broken down. Initial costs of hybrid systems are high, due to the combination of expensive solar modules, a wind turbine and a complex inverter. This causes high payback periods as well. Furthermore, solar-wind hybrid systems are vulnerable for theft and vandalism, as they consist of expensive solar panels.

There are some opportunities for solar-wind hybrid systems for irrigation in India. These systems have a high observability degree, as other farmers can easily see the benefits of hybrid systems. When other farmers are limited in the irrigation practices due to a lack of electricity or solar or wind power, they are more likely to switch to hybrid systems, as they are the most reliable systems. Furthermore, economical attractiveness is likely to increase in the future, due to increasing fossil fuel prices. The diffusion and development of solar-wind hybrid systems can accelerate in the future, as domestic energy requirements are likely to increase in India.

However, at this moment, solar-wind hybrid systems are the least established renewable energy technology in India for irrigation purposes. Therefore, there is not much experience with these systems and this can affect the availability of solar-wind hybrid systems in rural areas. According own experiences from field work, spare parts for SPV pumps are not available in some parts of India, which is likely to apply for hybrid systems as well. Furthermore, similar to SPV pump and windmill pumps, there is much uncertainty about applicable subsidies and schemes for solar-wind hybrid systems.

Figure 17: SWOT analysis of solar-wind hybrid pumps in India

Strengths	Weaknesses
• Reliable • Autonomous system • Can be implemented in many parts of India, because it uses both solar and wind resources • High estimated CO_2 potential • Can be placed at different locations than pump	• Complex technology • Vulnerable parts • High initial costs • Long payback period • Vulnerable for theft and vandalism
Opportunities	**Threats**
• High observability degree • No dependency on fossil fuels • Can be used for domestic purposes as well	• Least established technology • No spare parts available in rural areas • High uncertainty among end users about schemes and subsidies

8.4 Energy Efficiency

Increasing energy efficiency by selecting and installing a proper sized motor and pump, removing high fractioned and unnecessary pipes and proper maintenance can decrease carbon emissions. Increasing energy efficiency has a high degree of trialability for small improvements. When implementing small and medium cost measures, farmers can directly observe an increase in water output and a decrease in energy requirements and operating costs when performing low and medium cost efficiency improvements. These improvements have low initial costs and short payback periods, as low as 8.5 days, especially in case of diesel pump sets. As average operating efficiency of existing pump sets are estimated to be very low, the average CO_2 mitigation potential is estimated to be significant.

But not all farmers consider increasing energy efficiency, as it has a low degree of observability. It is hard to see the advantages of increasing energy efficiency among other farmers. Furthermore, some pump sets have a low efficiency as they are improperly sized and need to be substituted by a new pump set, which can be expensive for small and marginal farmers, especially when substituted by a high efficient pump set. Although the adaption of high efficient pump sets will result in significant fuel cost reductions, initial costs are often too high for small and marginal farmers. While increasing efficiency of existing pump sets can be a good solution to decrease carbon emissions, pump sets are still depending on fossil fuels.

The opportunities of increasing efficiency of pump sets include that there is a clear need from farmer's perspective. As electricity services are unreliable in rural areas and diesel prices are increasing, farmers are interested in solutions which can increase water output and decrease their expenditures for fuel.

Increasing efficiency can result in increasing yields and incomes, which makes it possible to further improve efficiency. Rising fuel prices ensure that improving the efficiency becomes financially more attractive.

However, in case of increasing energy efficiency, there are some threats involved regarding decreasing carbon emissions. Improved energy efficiency can result in less incentives for farmers to switch to renewable energy technologies. Furthermore, an increase in energy efficiency does not necessarily result in less energy consumption and carbon emissions. An increase in energy efficiency can result in more irrigation practices and therefore an increase in energy consumption. This rebound effect is well known in case of improving energy efficiency.

Figure 18: SWOT analysis of increasing energy efficiency of existing electric and diesel pumps in India

Strengths • High degree of trialability for small efficiency improvements • Low initial costs • Considerable pay back periods in case of diesel substitution • High CO_2 mitigation potential • Decreases operational costs	**Weaknesses** • Still depend on fossil fuels • Low degree of observability
Opportunities • There is a need from a farmer's perspective • Increasing yields and incomes	**Threats** • Farmers have less incentives to switch to renewable energy technologies • Rebound effect (More energy efficient, so more energy consumption)

8.5 Drip irrigation

Drip irrigation is becoming more and more popular in India. Although the area under drip irrigation is far below its potential, there has been significant growth in the use of drip irrigation. Drip irrigation has a high degree in observability and trialability. Farmers can easily notice when other farmers have earlier and better full grown crops and can try drip irrigation with very simple and cheap bucket kits. The simplest forms of drip irrigation, like bucket and drum kits, have low initial costs and a short payback period. Drip irrigation causes not only energy savings, it will also increase yield, which reduces the payback period even more.

However, more complex drip irrigation systems have higher initial costs and longer payback periods. In case of electric pumps, payback periods based on energy savings are not considerable. Furthermore, drip irrigation systems usually require more labour, as it requires much effort to install and maintain these systems. Drip irrigation systems are not suitable for all crops and soils types, like clay soils, cereals and pulses. Once drip irrigation systems are installed, it is not possible to grow different types of crops at the same land and farmers are limited to the types of crops which are suitable for the drip irrigation system. Some farmers own multiple pieces of land and for them it is more expensive to install several drip irrigation systems.

Drip irrigation is a well-established technology in India. More than 40 years of experience has resulted in some world leading big manufacturing companies . This has increased the availability of drip irrigation systems and the knowledge to install and maintain them. This will also create more employment, as India can become one of the world leading countries in the development and manufacturing of micro irrigation technologies. There is a clear need from farmer's perspective for higher yields with less water, as groundwater tables are declining and energy prices will further increase, which will strengthen the demand for drip irrigation. Furthermore, as consumption patterns are changing in India, drip irrigation can gain more potential as well. According to the IFPRI, consumption patterns in India are shifting towards high-value agricultural commodities, such as fruits, vegetables and dairy. This shift is caused by income growth and urbanization (IFPRI, 2007). The demand for fruit and vegetables is growing, which are both suitable for drip irrigation, while the demand for staples and cereals is declining, which are not suitable for drip irrigation. Therefore, this will increase the potential for drip irrigation.

But, looking at threats for energy efficiency as well, an increase in water use efficiency can cause a rebound effect and water use may increase. As water is used more efficient, it is found that farmers will expand the size of their land and increase irrigation practices, which can be beneficial for farmers, but a threat for ground water tables. Furthermore, there is a lack of knowledge about drip irrigation systems. Farmers do not know where to get the materials and how to install drip irrigation systems. Most farmers are unaware of on-going schemes and subsidies, which can slow down the diffusion of drip irrigation technologies.

Figure 19: SWOT analysis of drip irrigation in India

Strengths	Weaknesses
• High observability • Low initial costs for low budget drip irrigation • High Trialability • Short payback period in case of diesel substitution	• High initial costs for more complex systems • Long payback period in case of electricity substitution (due to subsidized tariffs) • Only suitable for some type of crops, not all crops can use drip irrigation • Not possible to grow different types of crops on the same land
Opportunities	**Threats**
• More than 40 years of experience • There is a need from farmer' perspective • Increased yields and incomes for farmers • Highly suitable for vegetables, and there is a growing demand for vegetables in India	• Rebound effect (more efficient water use, so increase in water consumption) • There is a lack of information and knowledge among farmers.

8.6 Conclusions from SWOT analysis

Looking at the SWOT analysis for various low carbon energy solutions, it can be concluded that there is no best solution and all options have different characteristics. SPV pumps can generate electricity for domestic purposes, can be mounted on a trailer and are well established in India, but are expensive and complex. Wind turbines have a more simple design, are cheaper, but India has less area suitable for wind energy and windmill pumps can only be used for pumping water. Hybrid system are the most reliable renewable energy technology for water output and can also be used for domestic purposes, but are new, expensive and complex. Energy conservation is less complex, cheaper and can also increase yields. However, it will only reduce CO_2 emissions, instead of avoiding them, and is only applicable for farmers who already own a pump set.

All five energy solutions have the potential to significantly decrease carbon emissions in India, but should not be seen as separate possibilities. Combinations of low carbon energy solutions can further increase the utilization potential. The combination of renewable energy technologies with improving energy efficiency and drip irrigation seems promising. During field visits it was found that farmers who adopted SPV pumps were complaining about the water output and capacity of pumps working on renewable energy technologies. This was an important reason for farmers living around the farmers that adopted SPV pumps to keep their old pump working on diesel or electricity and were not willing to switch to renewable energy technologies. When farmers increase the efficiency of their pump set, for example by removing unnecessary bends in pipes or substitute old GI (iron) pipes by low friction PVC pipes, water output with a SPV pump, windmill or hybrid system may become sufficient. Drip irrigation systems can cause a decrease in water requirements for irrigation and the water output of pumps working on renewable energy technologies may become sufficient as well.

But, in order to successfully diffuse low carbon energy solutions, farmers should be aware of the possibilities for modern irrigation technologies. It turned out that traditions have a dominant role in decision making processes and farmers do not see the need or possibilities to change their irrigation behaviour at this moment, since they use their land in the same way as their parents did. To raise more awareness among farmers and improve access to new technologies, local people should be trained and educated. They are aware of current irrigation practices, what problems could arise with the implementation of new technologies and how to affect prominent persons in small villages. This enables them to give more specific advice about the possibilities of drip irrigation en renewable energy technologies. Furthermore, they can help farmers in maintaining their machinery and equipment, which will prevent a decrease in energy efficiency.

Which low carbon energy solutions are best at a specific location in India differs. Currently, from farmer's perspective, low carbon energy solutions are financially most attractive when applied in combination with diesel pumps or when new pumps on solar or wind energy replace diesel pumps. Most diesel pump sets are found in the north-eastern part of India (Shah, 2009). The radiation potential in North-eastern parts of India is high, while the wind potential is moderate, so it makes sense to replace diesel pumps by SPV or hybrid system in those areas. For coastal and other windy areas in India, it is preferable to stimulate the adaption of windmill pumps. As there are currently many electric pumps at those parts of India, it is important to reduce the subsidy for electricity for farmers, resulting in more financially attractive windmill pumps. In areas with small amounts of radiation and low average wind speeds, as in the upper north and eastern parts of the country, it is necessary to improve energy efficiency of existing pump sets. Projects similar to the ones that are currently executed by the BEE and EESL seem to have much impact and potential and should be adopted by other states, especially in the Northern and Eastern states.

9. Implementation mechanisms

As the suitable low carbon energy solutions and their barriers are identified, it is important to have knowledge about implementation mechanisms that are able to accelerate the diffusion of low carbon energy solutions. In general, there are two types of approaches, namely regulatory approaches, including standard and labelling programs, and economic approaches, such as providing micro credit or carbon financing. From the economic analysis can be concluded that initial costs can be an important barrier of introducing clean technologies and therefore the focus of implementation mechanisms will be on economic approaches. First, the subsidy mechanism in India is investigated. Second, the role of Clean Development Mechanism (CDM) and micro finance is investigated.

9.1 Subsidies

In India, subsidies for farmers are used to improve the accessibility of required inputs, such as electricity and fertilizers, and to encourage the adoption of clean technologies, such as SPV pumps or windmill pumps. The sustainability and effectiveness of electricity subsidies have become subject to increasing criticism during the past decade in India. Money spent on electricity subsidies for farmers exceeds expenditures on health or education (Birner et al, 2007). The advantage of this subsidy is that small and marginal farmers are able to irrigate their land and are stimulated to irrigate more than they would do if electricity prices were higher. This increases yields and food production, which enables India to be self-sufficient in food production. The disadvantages include that State Electricity Boards (SEBs) operate at an annual loss and that SEBs are discouraged to invest in rural electricity infrastructure (Worldbank, 2001; Birner et al, 2007). This results in poor quality supply of electricity to farmers. Furthermore, due to low prices for electricity, farmers have few incentives to switch to renewable energy technologies or to improve efficiency of pump sets.

More than fifteen years ago, Indian states have made an official commitment to reduce the electricity subsidies to agriculture. But, in spite of that, the number of states that supply electricity free of charge to farmers is still increasing (Birner et al, 2007). It is assumed that in the long term, an increase in electricity prices is beneficial for farmers, because it is likely that this results in an improvement of quality of electricity supply to agriculture.

Incomes of farmers would increase if quality of power supply were improved, which could be financed through higher tariffs (Worldbank, 2001). But even in states that are successful in reforming the energy sector and have raised tariffs, farmers' organizations claim that the quality of electricity supply to agriculture has not improved (Birner et al, 2007).

Although the need for reforms is recognized for many years, there is a lack in success of past reforms. Farmers represent a large share of the Indian population and announcements made by a ruling party to reform power subsidy can decrease their popularity significantly. Opposition parties use this as a weapon to bring down a government, which results in continuous subsidy for farmers (Shah et al, 2004). Reform options to successfully solve the financial problems related to the electricity subsidies to agriculture and the low quality of electricity supply include decentralization of groundwater management and electricity supply and monitoring of electricity quality by citizen groups (Birner et al, 2007). Furthermore, increasing prices for electricity are inevitable, but this should happen at a slow rate and subsidies specifically designed for marginal and small farmers could help them in the beginning.

In India, there are also subsidies to promote the use of renewable energy technologies for irrigation and micro irrigation technologies. These subsidies are available at both central and state level. The advantages of subsidies for new, more efficient technologies is that adoption decisions are more sensitive to upfront costs than long term benefits (Blok et al, 2004). New technologies are becoming more attractive by decreasing these high upfront costs. However, the disadvantages of these subsidies include high subsidies and administration costs for governments. Furthermore, subsidies can be argued to be inefficient as they can involve free riders[32]. And subsidies can miss their target group, which was experienced during field visits[33].

9.2 Micro credit

As mentioned before, access to credit is of great importance for the diffusion of new technologies. In rural areas of India, there is a lack of access to credit for many farmers. Poor farmers are affected by lack of access to and inadequate provision of financial services. Despite the high amount of regional rural banks (RRBs), the formal banking sector has a limited impact on microfinance or lending to the poor (Krishna, 2012). This is unfortunate, because microfinance can improve the accessibility of credit for farmers and therefore reduce poverty. Microfinance in rural areas of India can be advantageous at both

[32] In this context, free riders are defined as farmers who make use of the subsidy, but would have undertaken the subsidised action anyway - and without any delay (Blok et al, 2004)

[33] During field visits, we visited six farmers who had adopted SPV pumps in 2003 using subsidies. These subsidies were intended for farmers that would use SPV pumps for irrigation. However, one of the farmers installed many batteries and used the array for charging these batteries. Electricity generated by the array was used for domestic purposes, as electricity for domestic purposes is more expensive. A similar observation was made at another farmer, which sold the array to his brother. His brother was using the electricity generated by this array for his private hospital. Both visits were excellent examples how subsidies can be mistargeted.

ends. It provides farmers with small amounts of money without any collateral security, while banks can easily earn money, as the repayment rate of loan is as high as 95% and even more (Pokhriyal and Ghildiyal, 2011). The most famous form of microfinance in India is in the form of Self-Help Groups (SHGs), although over the last years MicroFinance Institutions (MFIs) have grown rapidly as well.

A SHG is a group of individuals who combine their money and savings into a fund. From this fund they can borrow money when needed. This group is linked to a bank where they have a group account. After six to twelve months, the bank begins to lend to the group, not the individuals, without collateral. The idea behind this concept is that the peer pressure within this group will cause strict repayments of these loans (Krishna, 2012). The SHG consists of a group between five and twenty persons, preferably all from different families. The leader and deputy leader, as well as the amount of deposit required by each member to join the SHG, are determined by group members. Once all members have made their deposit the group can open a savings bank account. All savings are on a regular basis collected by one of the members and deposited in the bank account. SHGs are often started by a certain group of people and not extended over time. This is because it can be expensive to add new members and new members have to be accepted by all existing members, which can be a difficult process. It is often easier to start a new SHG than joining a pre-existing one. SHGs loans are largely used for children's health and education, home improvements, repaying old debts and buying agriculture inputs (Srinivasan, 2010).

SHGs are there in three forms. The first option is that the bank is aiding the process of SHGs and will lend the money to the SHG directly. The second option is that a NGO will form the SHG, but the bank will lend the money to the SHG. This form is used under most programs. The third option is that the NGO will form the SHG and will also act as an intermediary for lending by the banks.

Loans are then given out to individual members from out these funds. So the first loans are completely paid by the group savings. These loans, called 'inter-loans', have a short repayment period, usually between 3 and 6 months. After this, the bank will consider making a loan to the SHG. Usually the maximum loan is a multiple 4:1 of the total funds. Thus, a 10 member SHG with individual monthly deposit level of Rs. 20, completing a six-month successful inter-loaning, accumulates total savings of Rs. 1,200, from which a part may be lent out to individual members. The maximum bank load would be 4,800 Rupees (Debroy and Khan, 2004).

The main advantage of Self Help Groups lies in their joint liability and consequent peer monitoring of member borrowers. But SHGs are not successful in all parts of India. In some Northern and Southern parts of India there are difficult regional, political and economic conditions that have slowed down the movement of the SHG program. Banks should put more attentive efforts for the promotion of this program. Furthermore, the amount of loans should be high enough so that it can be used for important investments (Pokhriyal and Ghildiyal, 2011). If these concerns are taken into account, this concept could be extended and specialized for agricultural purposes. Farmers could join themselves and start a group in which they start saving money. In order to make investments in new technologies, deposit levels should be much higher as in the example given above, around Rs. 400 per month. This is below 10 percent of average monthly income of farmers interviewed during field work and is still significantly below incomes of marginal and small landholders interviewed during field work. Therefore it is assumed that this will not cause any problems. The bank loan could be used for technologies that increases yield and decreases operational costs, such as micro irrigation or renewable energy technologies. All farmers are responsible for the investment made and are therefore motivated to maintain the equipment properly.

Next to SHG-bank linkage programs, there are MFIs that provide small amounts of credit to the poor. In the 1990s, MFIs operated as non-profits, but transferred their operations into for-profit nonbank finance companies (NBFCs)[34]. MFIs are mainly supported by commercial and state-owned banks, although there has been a trend over the last few years that MFIs are also capitalized by specialized microfinance investment vehicles and private equity funds (CGAP, 2010). There is a significant transformation from an open microfinance market, which is dominated by NGO and other donor-financed institutions, towards a competitive market. In March 2010, over 59.6 million people were provided with a cumulative loan of more than 272 billion rupees with the SHG-bank linkage program, while MFIs reported a total clientele of 26.7 million people with outstanding loans of more than 183 billion rupees. From 2006 to 2010, SHGs grew with more than 70 percent, while the amount of MFI borrowers with outstanding accounts grew with more than 165 percent. The estimations are that MFIs will exceed the SHG-bank linkage program within a few years (Srivinana, 2010). Another difference between SHG members and MFI customers is the average loan size. In the year 2009-2010, SHG members had an average loan of Rs. 4,570, while MFI customers had an average loan of Rs. 6,060 (Srivinana, 2010).

The increasing number of SHGs and especially MFIs has a positive effect on the accessibility to credit for farmers in rural areas of India, but should be strictly regulated. Otherwise it can collapse, as it did in

[34] According to the Reserve Bank of India, a NBFC is a '*company registered under the Companies Act, 1956 and is engaged in the business of loans and advances, acquisition of shares/stock/bonds/debentures/securities issued by Government or local authority or other securities of like marketable nature, leasing, hire-purchase, insurance business, chit business* ***but does not include*** *any institution whose principal business is that of agriculture activity, industrial activity, sale/purchase/construction of immovable property*' (RBI, 2012). Therefore, MFIs are operating almost similar to commercial banks.

Andhra Pradesh. This state has a long history of SHGs, with more 17.1 million clients state-wide. But in the late 1990s, some of India's first MFIs got their start in Andhra Pradesh as well. These MFIs were the first in India to attract large investments from both microfinance investment vehicles and private equity funds. These financial injections caused incentives for continued levels of high growth (CGAP, 2010; Srivinana, 2010). This resulted in that some MFIs generated uncommonly high return on assets and they confirmed the image of commercial institutions. The presence of both well-funded state-backed SHG-bank linkage programs and many MFIs resulted in a rapid growth of outstanding credit in Andhra Pradesh. The average debt outstanding per household in Andhra Pradesh is almost ten times as high as national average (Srivinana, 2010). At this moment, there is much rivalry between MFIs and SHG models for serving poor villages. This rivalry caused that clients started to have multiple loans at different institutions and use new loans to repay old loans. Some reports linked the increasing number of suicides in the state with MFI practices and state governments strengthen legislation. This affected the way MFIs operated and loans collections for MFIs dropped dramatically. MFIs have difficulties to refinance their loans or to raise new equity and are in conflict with the state government about current policies (CGAP, 2010; Srivinana, 2010).

This situation is an important indicator that the rapid growth of the commercialization of microfinance in India should be regulated. The microcredit movement has proved that poor people can have access to credit and financial services at a large scale. But at this moment there are still many people without access to formal financial services. It should be the priority of MFIs to reach poor people with transparent financial services. The rapid growth of MFIs has caused that high profits became the main goal, with unethical behaviour as a consequence. Microfinance should be profitable, but not profit seeking. MFIs need to demonstrate that they are relevant and capable to deal with problems of poor people. This is done by good administration practices and investing in the development of products that suit the customers.

9.3 Clean Development Mechanism / carbon financing

In order to assist non-annex I countries in achieving sustainable development and assist annex I countries in complying with their quantified emission reduction commitments, the Clean Development Mechanism is defined in article 12 of the Kyoto Protocol (IPCC, 2007b). The idea behind this mechanism is that private companies that are responsible for greenhouse gas emissions can fund projects in developing countries. These projects must reduce greenhouse gasses and meet sustainable development criteria. Furthermore, the emission reductions must be additional, which means that reductions achieved would not have been made without the CDM funding (Lewis, 2010). The projects are rewarded with certified emission reductions (CERs), which are equivalent to one ton of carbon dioxide. Their CERs can be sold to developed countries and they can use them to meet their reduction commitments. More than 200 types of projects are eligible, such as renewable energy and increasing energy efficiency (Lewis, 2010; Jun and Jiaoxu, 2011). More general information about CDM can be found in Appendix E.

In the scope of this research, there are no CDM projects registered for SPV pumps or wind mill pumps, only 2 projects at validation stage for improving energy efficiency in water pumping and 1 project at validation for micro irrigation systems (CDMpipeline.org, 2012). In general, most CDM projects registered are large-scale projects in the energy and waste sector. According to Purohit (2006), CDM projects for the diffusion of SPV pumps in India are not likely to happen, as other sectors are much more attractive for CDM. The lack of small-scale projects, such as SPV pumps, windmill pumps or micro-irrigation projects is due to the high transaction costs involved in the registering and verifying process. The CDM Executive Board must approve stand-alone CDM projects individually, which can be a lot of work in case of many SPV pumps or windmill pumps. There is also a high risk of non-registration, meaning that many projects are rejected, and therefore large-scale projects are more attractive for CDM (Beaurain and Schmidt-Traub, 2010).

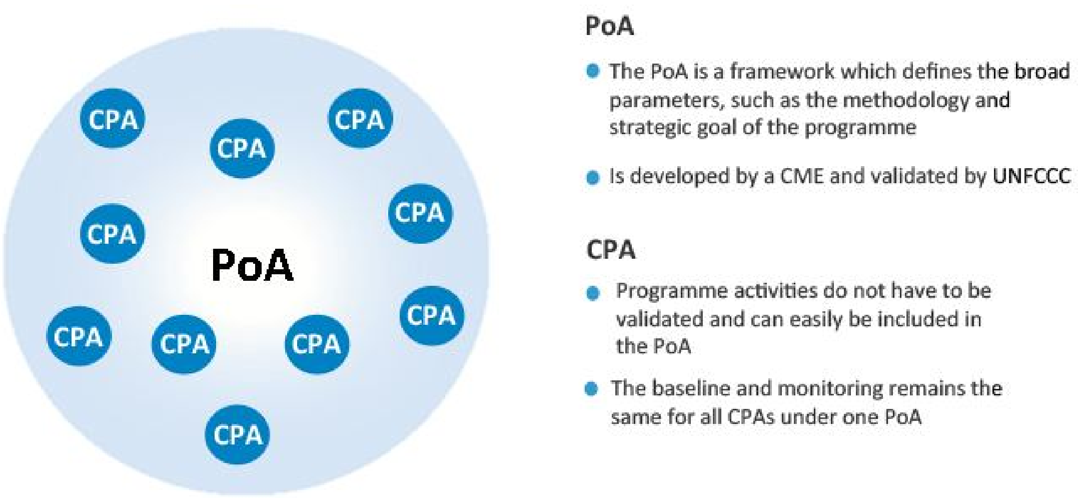
In order to reduce transaction costs involved in registration and verification of CDM projects and to make it more attractive and applicable for small-scale project activities[35], the CDM Executive Board launched the Programme of Activities (PoA) modality. In 2005, it was decided that project activities under a program of activities can be registered as a single CDM project. A PoA can be considered as an umbrella program under which multiple projects can be implemented. A government, agency, NGO or business, referred to as a Coordinating/Managing Entity (CME), develops a PoA. This means that a CME defines broad parameters for project activities, such as a baseline and monitoring methodology. These program activities are referred to as CDM Programme Activities (CPAs). All the characteristics defined in the PoA remain the same for all CPAs incorporated in the program.

The main advantage is that a PoA only needs to be registered and validated once by the CMD Executive Board, after which it can include an unlimited number of CPAs. This will make it much easier and faster

[35] According the UNFCCC, small-scale projects in the case of programmatic CDM are defined as projects which aggregate energy savings does not exceed the equivalent of 60 GWh per year.

to execute CDM projects as CPAs, once a PoA is registered. Many individual and similar activities can be brought together in the framework of PoA, which is illustrated in figure 14.

Figure 20: Graphic representation of programmatic CDM



Other advantages of programmatic CDM compared to CDM include a reduction in time to market for project operators that would like to secure CER revenues. Transaction costs are significantly lower, as CPAs have a streamlined verification and registration process. The lag before CDM income is decreased, as well designed PoA can include CPAs within 2 to 5 months, which will mean that projects are able to generate carbon credit during the first year of operation (Beaurain and Schmidt-Traub, 2010).

The CME can add a CPA at any time of the PoA, as long as the PoA is registered. The CDM Executive Board can only approve the PoA when at least one CPA has been developed. It is required that this first CPA must be validated simultaneously with the PoA. All the following CPAs we be modelled after this first CPA and does not need to be validated individually. As for CDM, the crediting period of a CPA can be fixed at 10 years or a renewable crediting period of 7 years that can be renewed maximum twice. But it is limited to the end date of the PoA, no matter when the CPA was added. The maximum lifetime of a PoA is defined at 28 years. As long as a host letter of approval is provided for each host country, PoAs can be international and are not limited to one country (Beaurain and Schmidt-Traub, 2010; UNEP, 2010).

Similar to CDM, every project or CPA must be an addition to actions that would have been executed anyway. So every CPA must demonstrate that the project is not feasible without the money that can be earned by selling CERs. Looking at the low carbon solutions for irrigation, most payback periods are too long to make the technology attractive. In case of wind mills that replace diesel pump sets, payback periods are already considerable and programmatic CDM is not an option. This also the case for most energy efficiency improvements, which have payback periods of a couple of weeks in case of small improvements and up to 2.25 years in case of substitution with a high efficiency motor. However, programmatic CDM can be an attractive option for wind mills substituting electric pump sets and both SPV pumps and hybrid pumps replacing either diesel or electric pumps. Also in the case of drip irrigation, programmatic CDM can play an important role in further diffusion of this technology.

As the first commitment period of the Kyoto Protocol ends at the end of 2012, the future of CDM was uncertain for a long time. But the Cancun Agreement clearly state that 'the project based mechanisms under the Kyoto Protocol will continue to be available to Annex I Parties as means to meet their quantified emission limitations and reduction objectives' (UNFCCC, 2010). However, it seems that there is a slow shift towards Nationally Appropriate Mitigation Actions (NAMAs). Namas were introduced in Bali in 2007 as another important instrument through which developed countries can support developing countries with their mitigation efforts (Tilburg and Röser, 2012). Although there are no clear definitions of NAMAs and their procedures, selection and financing, 50 countries have submitted NAMAs to the UNFCCC at this moment. There is a need to shift from concrete projects (CDM) towards more sectorial approaches, which include strategies and policies. PoAs can be seen as a logic first step in this trend, which will have a positive influence on reducing irrigation carbon emissions.

10. Discussion

This chapter will describe all the uncertainties that came along during this research. The data acquirement was limited due to the scope of this study, so some assumptions have been made. This chapter will highlight the most important issues that may have had an impact on the results of this study. The issues appear classified per chapter.

- Chapter 4: Most findings in chapter 4 are based on the field visits in regions around Moradabad and Saharanpur. Farmer's need for new technologies and the availability of spare parts were investigated by interviews with farmers and villagers. The outcomes of the interviews were often consistent with information found in literature and provided a good overview of farmers' perceptions. However, the interviews were only conducted at two locations. To make a statement on the situation for India as a whole, more field visits in different parts of India are a requirement. Due to time limitations, this was not possible for this research.
- Chapter 5: Firstly, exact prices for SPV pumps, windmill pumps, solar-wind hybrid systems and drip irrigation systems were not known. According to local manufacturers, prices differ per situation and location and therefore only rough estimations of prices can be given. Therefore, initial costs for low carbon energy solutions are mostly taken from literature and corrected by using the Consumer Prices Index. In case of SPV pumps, they are also corrected by the trend in decreasing costs for solar modules and inverters. This causes quite some uncertainties, but it is expected that it would not influence the end results and recommendations. If possible, prices were validated with total costs of specific solar and wind projects given by the MNRE. The calculated prices are used to calculate the payback period and the Unit Cost of Water. Secondly, the payback period also depends on the savings in operational costs. As there are differences in subsidies per state for electricity and diesel, the payback period also differs per location. The same counts for the Unit Cost of Water, which depends on the annual useful energy. The amount of energy available for water pumping depends on the average wind speed or irradiation and is therefore site-specific. The methods to calculate the payback periods and the Unit Cost of Water were chosen to give global estimations for India and should be recalculated for a specific location with more specific data before renewable energy technologies are implemented.
- Chapter 5 and 6: In order to calculate the payback period and CO_2 mitigation potential for renewable energy technologies, the SPV pumps, windmill pumps and solar-wind hybrid pumps are compared with similar sized electric and diesel pumps. Due to varying solar and wind intensity, the useful energy and water output varies. It is therefore difficult to compare existing

electric and diesel pumps with pumps working on solar and wind power. In general, SPV pumps, windmills pumps and hybrid pumps will have a lower rated capacity than the electric and diesel pumps used as comparison, but will be used more hours per day. During field visits, it was found that diesel pumps on average only run for 1 hour per day and electric pumps around 2 hours per day. Pumps working on renewable energy technologies can easily run for 6 to 8 hours per day. It is assumed that the amount of water withdrawn from the source is all cases equal. Therefore, the comparisons between different technologies are assumed to be legitimate, but without actual measurements these assumptions will cause some uncertainties.

- Chapter 6: Windmill pumps used for water pumping have a height between 10 and 20 meters. Recent data for average wind speeds at this height were not available, since most research done is targeted at higher heights for large wind turbines. Therefore, average wind speeds at a height of 80 meters are used in this study, as they are a good indication of high potential wind areas in India. This is combined with a map of the Plant Load Factor, which indicates the actual power available in the wind. The combination of average wind speed at 80 meters height and the plant load factor map gives a good overview of high potential areas for wind energy, but a more detailed map of average wind speeds at a height of 20 meters would be preferred. This causes some uncertainties in indicating high potential areas for windmills and hybrid systems.

  Furthermore, the CO_2 mitigation potential of increasing efficiency of electric pumps is calculated. To give a complete overview of the CO_2 mitigation potential of increasing efficiency of existing pumps, the CO_2 mitigation potential of diesel pumps should be calculated as well. As there is currently no data available about average efficiency of diesel pumps in India, further research is necessary.

11. Conclusion

This research was conducted to find an answer to the question which low carbon energy solutions are suitable for water irrigation in India, and how technical, economic, social, environmental and resource-related factors are influencing the application and implementation. There are two ways to decrease carbon emissions for water irrigation i.e. the use of renewable energy technologies or by energy conservation. In literature is found that the most suitable renewable energy technologies for marginal and smallholders in India are SPV pumps, windmill pumps and solar-wind hybrid systems, which is confirmed by Indian experts. The most suitable energy saving options for irrigation in India are the use of drip irrigation technologies and increasing energy efficiency of existing water pump sets.

It is clear that there is a huge potential for renewable energy technologies and energy savings technologies for irrigation processes in India. However, the penetration of SPV pump and wind-mills, as well as drip irrigation technologies is far below its potential. From literature review can be concluded that demographic, geographic and cultural conditions are often neglected in designing a new technology. The most important conclusions drawn from both literature and experiences during field visits conducted for this research are that the development of renewable energy technologies and drip irrigation is at an advanced stage, but there should be more emphasis on the needs and habits of farmers. It is of great importance that the development is not taken as exogenously, but extensive interaction between developers and end-users is essential. Indian farmers are only willing to adapt low carbon energy solutions when it meets their needs and when all advantages are clear for them. Furthermore, it is necessary for locations where new technologies are implemented to ensure that knowledge and materials are available. This can be achieved by training local people and encourage local dealers and institutions to have sufficient amount of spare parts available. Field work has shown that this is usually not the case at this moment.

Financial barriers identified in this study include high initial costs, unattractive payback periods and a lack of access to formal finance. Due to highly subsidized electricity rates for farmers in many states, operational costs for electric pump sets are low, which result in long payback periods for technologies substituting electric pump sets. Payback periods for substituting diesel pumps are more attractive, as diesel prices are relatively high. From the economic analysis can be concluded that solar-wind hybrid systems have the longest payback period, followed by SPV pumps. Less complex windmill pumps have the most attractive payback period. This means that financial incentives for renewable energy technologies have to be focused on SPV pumps and solar-wind hybrid systems. Low cost measures for increasing energy efficiency, like regular cleaning and replacement of valves and removing unnecessary bends in pipelines have PBPs less than a month and should be implemented immediately. The focus of governments and NGOs related to the adaption of increasing efficiency measurements has to be on the access to knowledge and information about maintenance and efficiency. In case of the combination of diesel pumps with drip irrigation, energy savings can result in attractive PBPs for both shiftable and stationary drip irrigation technologies. From literature and interviews with farmers can be concluded that a large share of marginal and small farmers is willing to make the investment needed for low carbon energy solutions, but there is a lack of access to formal credit. Farmers in rural areas are still largely depending on informal money lending, with unethical practices as consequences.

It depends on the location in India which low carbon energy solution is most suitable. The SWOT analysis has shown that each solution has important strengths and weaknesses. Because of these differentiated strengths it can be concluded that a combination of technologies, where possible, is the best solution for India. The preferable combination of low carbon energy solutions differs per location and depends on many factors, such as annual solar irradiation, average wind speed, type of soil and crop, requirements and habits of farmers etc. However, it is of great importance to start immediately with increasing current efficiency of pumps, especially in areas where renewable energy technologies and drip irrigation have less potential, such as the Northern and Eastern regions of India.

The role of the Indian government includes stimulating the diffusion and adaptation of low carbon energy solutions. One of the mechanisms currently used for renewable energy technologies and drip irrigation are subsidies. It is important to adjust subsidies to the demands of small farmers and to define strict criteria for subsidy applications in order to minimize free riding and the mistargeting of subsidies. Governments and NGOs should actively promote and announce applicable subsidies to eliminate the information barrier. In order to make this financially possible and to increase economic attractiveness of low carbon energy solutions substituting electric pumps, the government should lower electricity subsidies for farmers. The best options should be to switch to metered electricity tariff, which can be partly subsidized to compensate small and marginal landholders. In order to overcome farmers' resistance against metered tariffs, it is important that the metering and collection agent is subject of a tight control system and that farmers that are willing to switch to metered tariff should be compensated, for example by getting free drip irrigation systems.

The accessibility to formal financing is currently improved by increased commercialization of micro credit and the rise of MFIs. This has a positive impact on the situation in rural areas of India, but must be strictly governed, as the example of Andhra Pradesh has shown. If initial costs are too high and payback periods too long for Indian farmers, which is the case for SPV pumps substituting electric pumps, the use of programmatic CDM could be a good solution. The construction of multiple small-scale projects under the framework of one PoA is highly suitable for the diffusion of both water pumps working on renewable energy technologies and drip irrigation systems.

In the end, financial delivery mechanisms, such as subsidies, micro credit and CDM can provide and accelerate the dissemination of low carbon energy solutions. But these options remain limited, as they only focus on financial barriers. In order to successfully implement low carbon energy solutions for irrigation in India, more emphasis on local grass root initiatives is essential. It is important that focus will shift from technology, research and national policy towards the needs of farmers and small-scale projects. For successful decreasing carbon emissions concerned with irrigation, farmers in rural areas have to know where they can gain more knowledge about irrigation and technologies, have access to formal financing resources and spare parts are available in rural areas for them. Local people have to be trained before the implementation of new technologies start and farmers should be aware of the consequences of excessive water and energy consumption. Drip irrigation technologies can lower water requirements and increasing energy efficiency can lower energy requirements, which will result in an increase of the potential of renewable energy technologies. Combining drip irrigation with energy efficient systems, renewable energy technologies and knowledge about farmer's needs and irrigation practices will accelerate the diffusion of low carbon energy solutions for irrigation in India.

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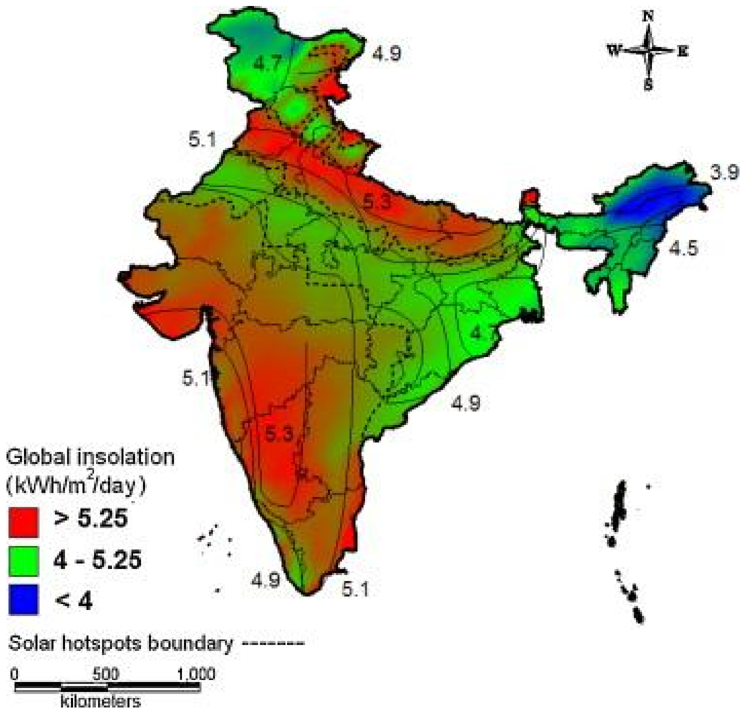
13. Appendices

Appendix A

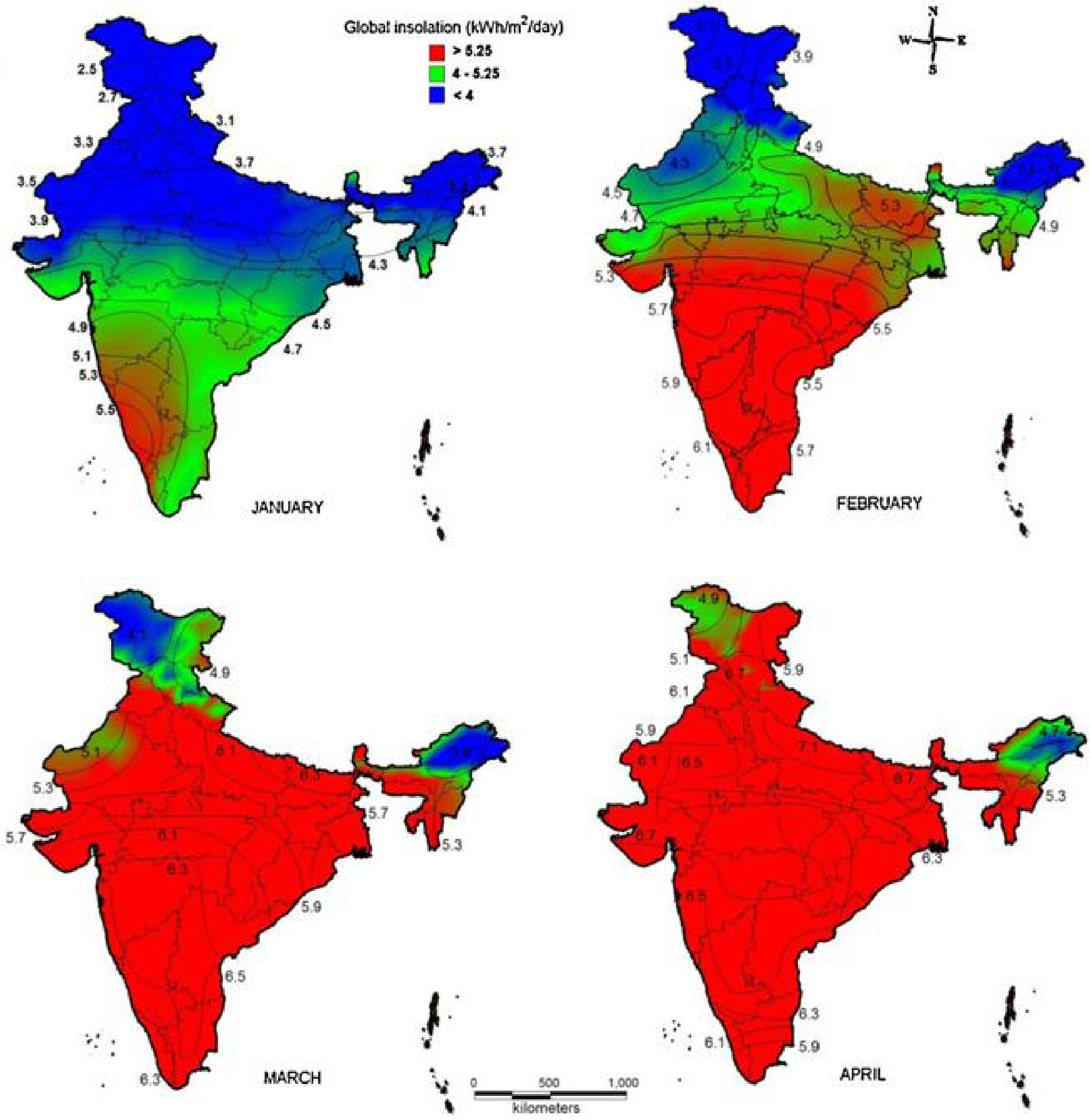
Figure 21: Global insolation map India



(source: Ramachandran et al, 2011)

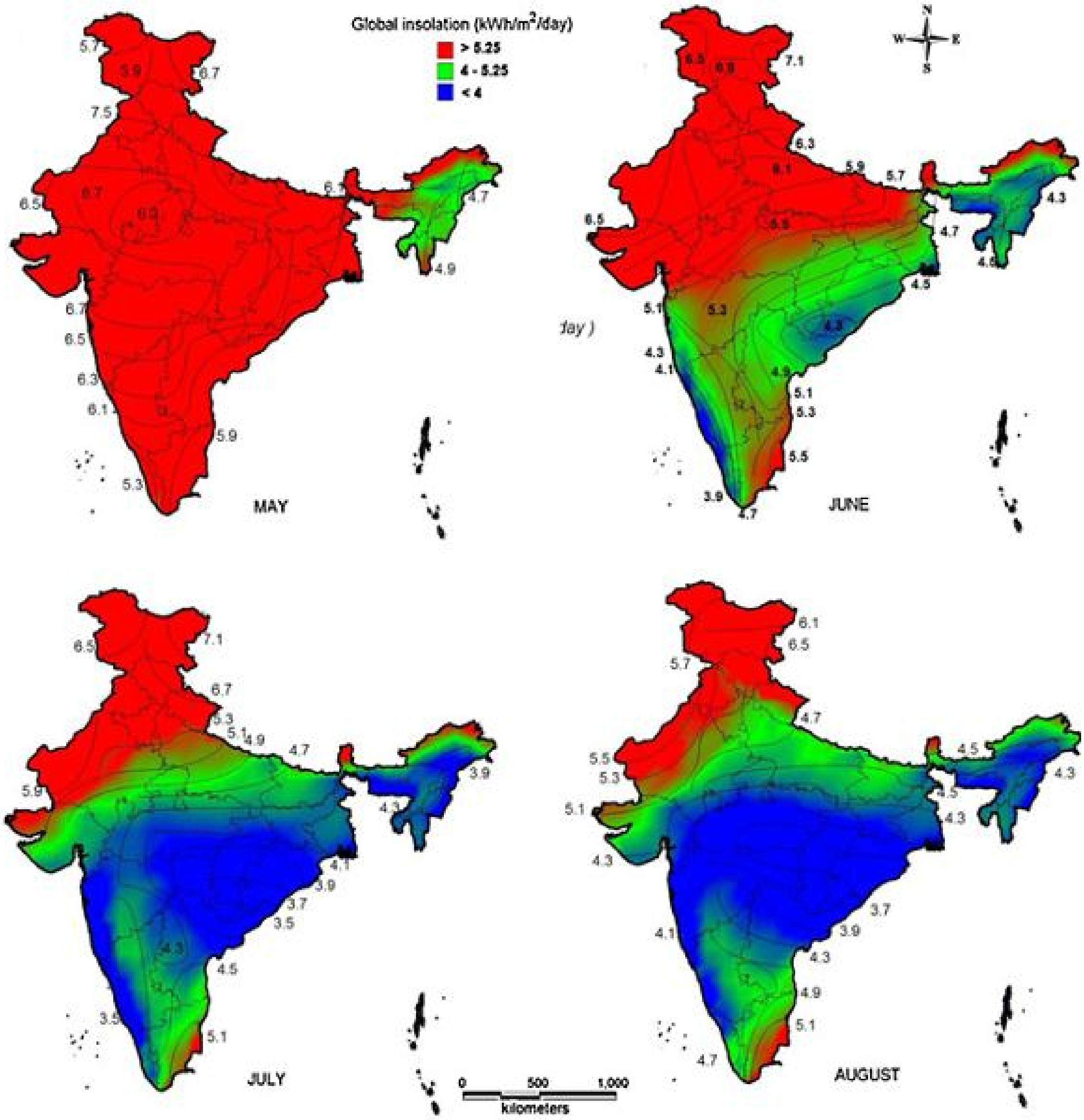
Appendix B

Figure 22: Insolation map India for the months January-April



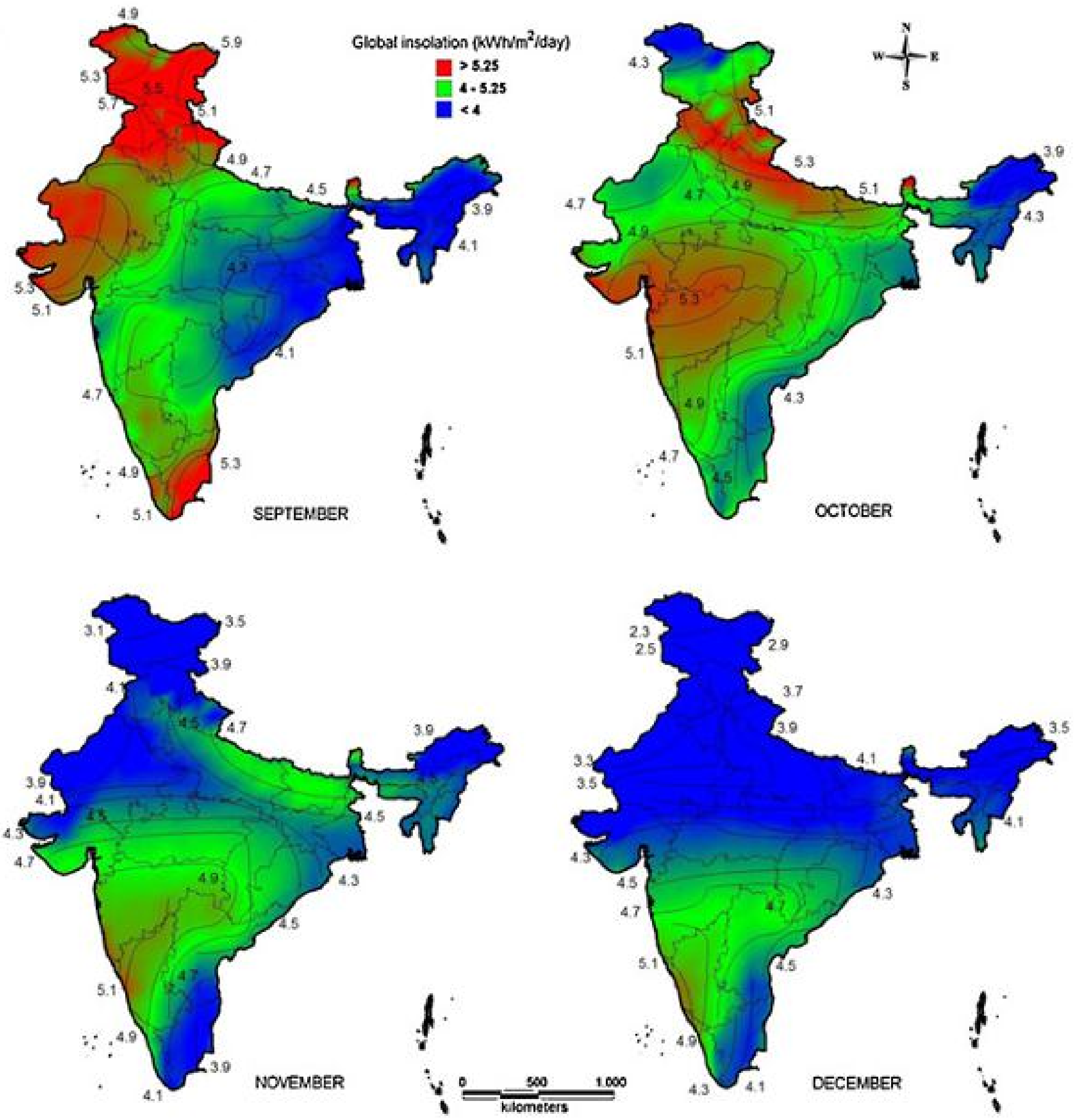
(source: Ramachandran et al, 2011)

Figure 23: Insolation map India for the months May-August



(source: Ramachandran et al, 2011)

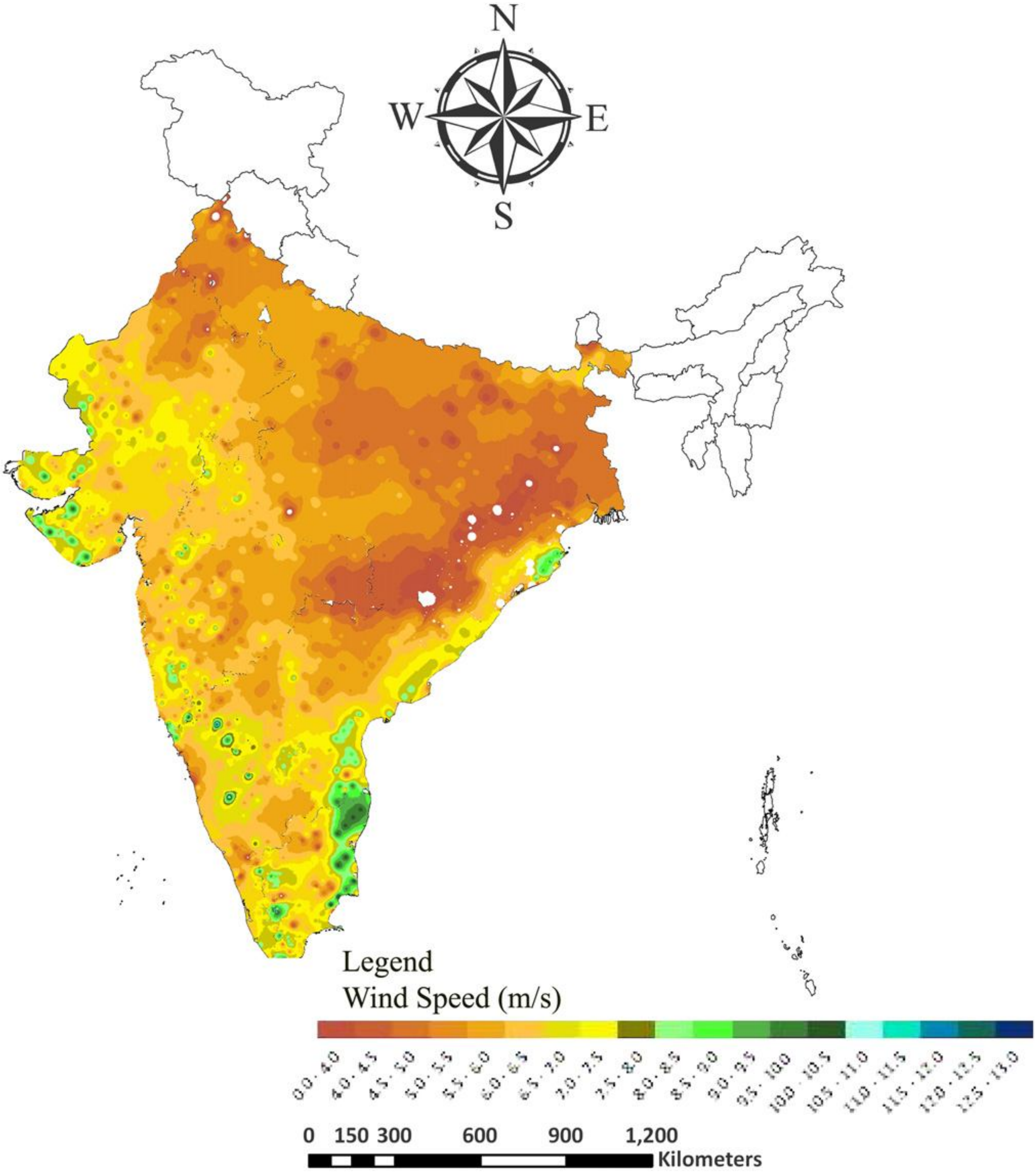
Figure 24: Insolation map India for the months September-December



(source: Ramachandran et al, 2011)

Appendix C

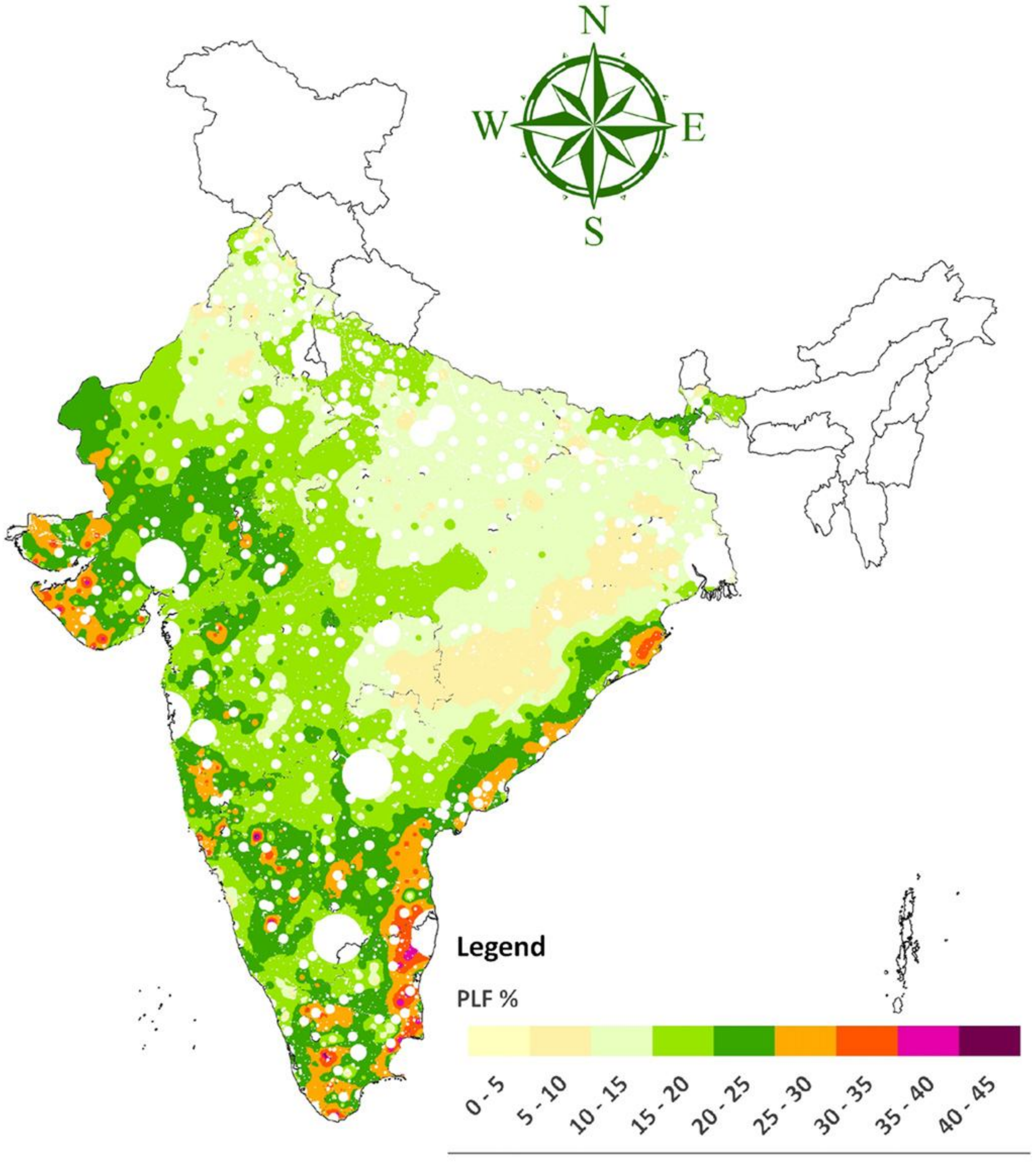
Figure 25: Average wind speed map of India



(source : Hossain et al, 2011)

Appendix D

Figure 26: Plant Load Factor map of India



(source: Hossain et al, 2011)

Appendix E

The CDM allows industrialized countries to continue with their emissions, as long as they pay for reductions in non-annex I countries. It is assumed that it is more expensive for companies to implement emission reductions in their own countries, while at the same time developing countries would gain sustainable benefits. At this time (July, 2012) 8,734 CDM projects are now included in the pipeline, from which 4,296 are registered. Although there are 1,620 CDM projects at this moment (July, 2012) that have got CERs issued, most of them in China and India, there is much debate to what extent CDM contributes to the mitigation of greenhouse gases. There have been many studies conducted to evaluate the degree to which CDM contribute to sustainable development. Most studies conclude that this objective is not met by many registered projects (Olsen and Fenhann, 2008; Alexeew et al, 2010). One of the reasons found is that sustainability comes after cost-efficiency in the eyes of project developers. Another reason is that it is the responsibility of the host country to define and evaluate the sustainability of the project. As host countries are afraid that project developers are prioritizing other countries, they lower the sustainability requirements and evaluation practices (Alexeew et al, 2010).

Furthermore, there is much concern about the 'additionality' of many registered CDM projects. According to the UNFCCC, a CDM project is additional if 'anthropogenic GHG emissions are reduced below those that would have occurred in the absence of registered CDM project activity' (UNFCCC, 2002). As CDM projects allow industrialised countries to emit more GHG than what is established in their Kyoto target, it is of great importance that GHG emissions are reduced in developing countries. In case the project would have taken place anyway, there is no reduction in GHG emissions, but an overall rise in GHG emissions. Additionality will always be a hypothetical concept and it is not possible to say what would have been happened if there were no CDM registration. In the end, it is inevitable that some non-additional projects will be registered. It is therefore of great importance to clearly define a baseline scenario as well as strict monitoring processes.