INTEGRATED ENERGY SOLUTIONS TOWARDS SUSTAINABLE ISOLATED COMMUNITIES

by

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“*We can’t solve problems by using the same kind of thinking*
we used when we created them.”

Albert Einstein (1879-1955)

I. Resumo

Nos últimos anos têm-se assistido a grandes desenvolvimentos e avanços tecnológicos na área da saúde, bem-estar e, consequentemente, nos níveis de vida da humanidade. O acesso a recursos energéticos, constitui um dos bens essenciais dos países desenvolvidos que o tomam como garantido, mas será importante relembrar que existem quase 1.2 mil milhões de pessoas sem acesso a eletricidade e 2.7 mil milhões fazem uso de biomassa como recurso energético para cozinhar alimentos. O acesso a recursos energéticos modernos e limpos é ainda muito limitado em países em vias de desenvolvimento, especialmente em áreas isoladas.

No âmbito do suporte à melhoria da condição de vida, tem havido um esforço significativo na recolha de informação estatística detalhada sobre o acesso à energia que, apesar de demonstrar a necessidade de implementação de soluções que aumentem esse acesso, não tem tido as consequências esperadas. Algumas das razões apontadas são os custos elevados, os desafios tecnológicos, preocupações ambientais e aceitação social. Na literatura não é citada ou elencada qualquer ferramenta de planeamento/modelização energética que considere um valor mínimo de energia como requisito estipulado quando se consideram diferentes opções de acesso à energia. Não existe também uma definição clara para aquilo que são os requisitos mínimos de energia, apesar de serem efetuados muitos estudos por organizações internacionais, que têm feito um esforço para definir quais os requisitos per capita. Contudo, qualquer uso (correto ou incorreto) de dispositivos que utilizem energia (eficiente ou ineficiente) pode adulterar os resultados de tal forma que a avaliação quanto ao nível de acesso baseada numa análise per capita não será a mais adequada. Os requisitos mínimos são bem mais do que um requisito per capita e requerem uma abordagem abrangente que considere as necessidades de todos os utilizadores finais. Nessa abordagem bottom-up a definição dos requisitos mínimos de energia deverá considerar condições e características locais.

A investigação efetuada neste trabalho endereça os desafios do acesso de energia em áreas de países em vias de desenvolvimento e desenvolve uma metodologia que estabelece os requisitos mínimos de energia e/ou melhora os padrões de vida e de bem-estar. Conceptualmente, são consideradas todas as abordagens mais bem classificadas entretanto definidas, como a avaliação matemática, a ajuda à decisão baseada em análise multicritério, a proposição de opções e os procedimentos de avaliação. Cada passo é suportado por ferramentas e subsequentes requisitos de entrada. O foco inicial foi colocado na definição de requisitos mínimos de energia, recorrendo a um modelo bottom-up construído que considera o número de habitantes e casas, a eficiência dos dispositivos e o número de horas de operação feito através de um fator-x.

De forma a aplicar o modelo completo e todas as ferramentas subsequentes, foi selecionada uma comunidade hipotética em Bihar, Índia. Foram considerados como entrada dados provenientes de casos de estudo reais, sendo feita a avaliação da situação corrente. Simultaneamente, os requisitos mínimos de energia foram redefinidos de acordo com a metodologia proposta. Com base na disponibilidade de recursos locais e no uso de técnicas de apoio à decisão baseado em análise multicritério, foram criadas cinco opções, que consideram o uso de tecnologias baseadas em renováveis, combustíveis fósseis, ou tecnologias intermédias. Para a seleção da opção mais adequada do ponto de vista de tecnologia de geração, todas as alternativas foram avaliadas economicamente, com base no custo total do sistema resultante de uma avaliação inicial da utilização para cada função. A identificação das soluções globais é efetuada recorrendo a uma análise multicritério (MCDA), sendo posteriormente novamente avaliadas num processo multriatributo que dá origem à solução final.

A comparação de um conjunto abrangente de opções de custo e uma análise de sensibilidade, permitiu concluir que a opção baseada em renovável com geração PV-diesel é a solução preferencial para a o sistema de geração neste tipo de comunidades.

Esta investigação enfatiza a complexidade do planeamento do acesso à energia dadas as especificidades locais, os inputs para a tomada de decisão e a diversidade de dispositivos de uso final bem como as tecnologias de geração. Um conjunto de opções viáveis que cumprem os requisitos mínimos definidos é sugerido, permitindo melhorar a saúde e o nível de conforto dos utilizadores. Assim, torna-se possível, considerando as preferências definidas para uma localização específica e a disponibilidade de recursos locais, identificar a solução mais apropriada.

Palavras-chave: acesso à energia, planejamento energético, MCDA, requisitos mínimos de energia, comunidades isoladas

II. Abstract

The rapid technological advancements and developments have led to noticeable improvements in health, well-being and living standard over the years. In most parts of the developed world we take the almost unlimited access to energy for granted. Yet, there are almost 1.2 billion people without access to electricity and 2.7 billion that rely on biomass as their primary cooking fuel. Especially in isolated areas of developing countries access to modern and clean energy fuels is still very limited.

While statistical information about the access to energy was gathered thoroughly, the implementation of solutions to increase access is halting. The reasons are diverse and include high costs, technical challenges, environmental concerns but also social acceptance. Within the literature no energy planning/modelling tool was identified that considers a defined minimum energy requirement when proposing options to increase energy access. Also, no common understanding of the minimum energy requirements was found. Major studies and international organizations have made an attempt to define the per capita requirements. However, any overuse/underuse or misuse of a single inefficient/efficient device blurs the results so that a proper judgement about the actual access level should not be solely based on a per capita evaluation. The minimum requirements are much more than a per capita requirement and necessitate an overarching approach that considers the needs across all end-uses and sectors. For that a bottom-up approach in the definition of the minimum energy requirements is encouraged to take into account local conditions and characteristics.

This research takes on the challenges of energy access in isolated areas of developing countries and provides a methodological concept to reach the minimum energy requirements and/or improve living standards and well-being alike. Within the concept all major approaches were defined, such as the mathematical assessment, multi-criteria decision aid, proposing of options and evaluation procedures. Each step is then underlined through tools and, where needed, subsequent input requirements. The initial focus was placed on the definition of the minimum energy requirements. For that a bottom-up model was build that takes into account the number of habitants and households, device efficiency and expected average hours of operation through the introduction of a x-factor.

In order to apply the entire model and all succeeding tools a hypothetical community in Bihar, India, was selected. Following the data input from real world case studies, the assessment of the current situation was made. Simultaneously, the minimum energy requirements were re-defined according to the proposed methodology. Based on the local resource availability and the application of multi-criteria decision aid five options were built. They consider the use of renewable-based, fossil fuel-based or intermediate technologies. For a final selection of the most appropriate option and supply technology, all options were assessed through monetary assessment, a full range of possibilities based on total system cost and MCDA as well as a second MCDA to evaluate the overall option. Sensitivity analysis is applied to all option appraisals.

The comparison of results identified the option with renewable-based end-use devices and a PV-diesel driven electricity generating system as the most preferred solution.

This research emphasizes on the complexities of planning for energy access while taking into account the local specifications, decision maker inputs and a diversity of end-use devices and supply technologies. A set of feasible options is suggested that reach the minimum requirements and thus improve health and living comfort. According to the preferences defined for a specific location and its local resource availability, the most appropriate solution can be identified.

Keywords: energy access, energy planning, MCDA, minimum energy requirements, isolated communities

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Golnar *Porto, May 2018*

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VI. List of Abbreviations

List of abbreviations in written text

AC	Ambient cooling
Adv	Advanced
AH	Ambient heating
AHP	Analytical hierarchy process
CDD	Cooling Degree Days
DHW	Domestic hot water
DSS	Decision support system
Ec	Economic
EDI	Energy Development Index
ELECTRE	Elimination and choice translation reality
En.	Environmental
ESMAP	Energy Sector Management Assistance Program
EUFIC	European Food Information Council
FP	Food preservation
GCEP	Global Climate and Energy Project
GIS	Geographic Information System
HDD	Heating Degree Days
ICT	Information and communications technology
IEA	International Energy Agency
INR	Indian Rupees
Int	Intermediate
koe	Kilogram of oil equivalent
kWh	Kilo-Watt-Hour
MACBETH	Measuring Attractiveness by a Categorical Based Evaluation Technique
MADM	Multi-Attribute Decision-Making
MAVT	Multi Attribute Value Theory
MCDA	Multi-criteria decision aid
MDGs	Millennium development goals
MEPI	Multidimensional Energy Poverty Index
MER	Minimum energy requirements
OECD	Organization for Economic Co-operation and Development
Pas	Passive

PROMETHEE	Preference ranking organization method for enrichment evaluation
Re	Resource
Ref	Reference
RES	Renewable energy sources
SAW	Simple additive weighting
So	Social
T	Temperature
Tc	Technical
TEI	Total energy inconvenience
TEIT	Total energy inconvenience threshold
TOPSIS	Technique for order preference by similarity to identical solution
UE	Useful energy
UN	United Nations
UNDP	United Nations Development Programme
VIKOR	Compromise ranking method
WHO	World Health Organization
WP	Water pumping
WPM	Weighted product method

List of abbreviations for formulas in mathematical approach (section 3.3)

a	Annual
AH	Ambient heating
A^j	Additional devices for end-use j
Cap	Capita
D	Device
DC_n	Cost of device n
DC_n^a	Annual cost of device n
E	Electrically driven
Eff	Efficiency
$fixO\&M_{E_m}$	Fixed operation and maintenance cost of devices that run on electricity
i	Number of sectors
IC_m	Investment cost of electrical generation system
$IC_{E_m}^a$	Annual investment cost of devices that are electrically driven
j	Number of end-uses
L^j	Lack in number of devices for end-use j
LT_n	Lifetime of device n
LT_m	Lifetime of electricity generating system m
n	Number of devices
N	Number of devices per household or service sector
NE	Not electrically driven
$N_{D_n}^j$	Number of devices in use D_n for one end-use j
$N_{D_n}^{Req^j}$	Number of devices D_n according to minimum requirements of end-use Req^j
m	Number of electricity generating systems
MER_{ref}	Minimum energy requirements according to literature
$O\&M_{NE_n}$	Operation and maintenance cost of devices that do not require electricity
P	Power
Req	Requirements
S	Share of devices with multiple uses
T	Duration
TC	Total cost
TC_{D_n}	Annual total cost of device n
TWE_{AH}^i	Total wasted energy of ambient heating AH by sector i
UE_{CAP}	Useful energy consumption per capita

UE_{D_n}	Useful energy by device n
UE_A^j	Additional useful energy requirements for end-use j
UE_L^j	Lack of useful energy requirements for end-use j
UE_{Req}^j	Useful energy requirements for end-use j according to definition
UE_T	Total useful energy
$varO\&M_{E_m}$	Variable operation and maintenance cost of devices that run on electricity
WE	Wasted energy

List of abbreviations for formulas in multi-criteria decision aid (section 4.4)

a	Alternative
A	Discrete and finite set of alternatives
c	Criteria
C	Set of criteria
l	Number of alternatives
k	Number of criteria
max	Maximum
min	Minimum
m_k	Unnormalized weight of criteria k
v	Value function
$v_k(a_{lk})$	Value function score of attribute alternative l and criteria k
w_k	Weight of criteria k
Z	Rational numbers

1. Introduction

1.1. Context

While back in 539 B.C. Cyrus the Great, founder of the Achaemenid Empire, conquered the city of Babylon without encountering any resistance, it is his next action that he is remembered for. After freeing all slaves, he declared all people as equal in race and religion. On that day, he established the first charter of human rights in the world – the Cyrus Cylinder (Olmstead, 1948). It took until 1516 when Sir Thomas More resumed this matter. In his book "Utopia" he defined an ideal society where humans live in perfection, satisfaction, happiness, security and fulfillment – basically a paradise on earth (Davis, 1983).

Today, in the 21st century, we are still confronted with the concerns of human rights and equality. The principal thoughts of Cyrus and More are still omnipresent. Many leading international organizations are built upon the principles of human rights and equality and strive for an ideal society. For instance, the United Nations was formed mainly from a security perspective and to "*foster global peace, prosperity and justice*" (United Nations, 2017). However, over time the goals have diversified successively. Within the Millennium Goals measures to increase quality of life and equality among human kind are defined. Accordingly, the access to goods and services such as energy shall be improved and developed to "*better meet human needs and the requirements of economic transformations*" (United Nations, 2015).

Energy in a human´s life is an intrinsic issue. Throughout history the needs have been in close proportion and relation to the capacities of man use of energy. Over time human kind built tools and machines to increase the use of energy in daily life (Figure 1-1). While energy was used by mankind for millennia at a small ratio of the energy used today, the inventions of steam and four stroke engines at the end of the XVIII and middle of XIX century gave birth to the Industrial Era and its explosive consumption of fossil fuels, which ultimately led to the society of today (Fundação Manuel António da Mota, 2013). Since then rapid economic developments in major parts of the world ended up triggering a new reality that could have not been anticipated.

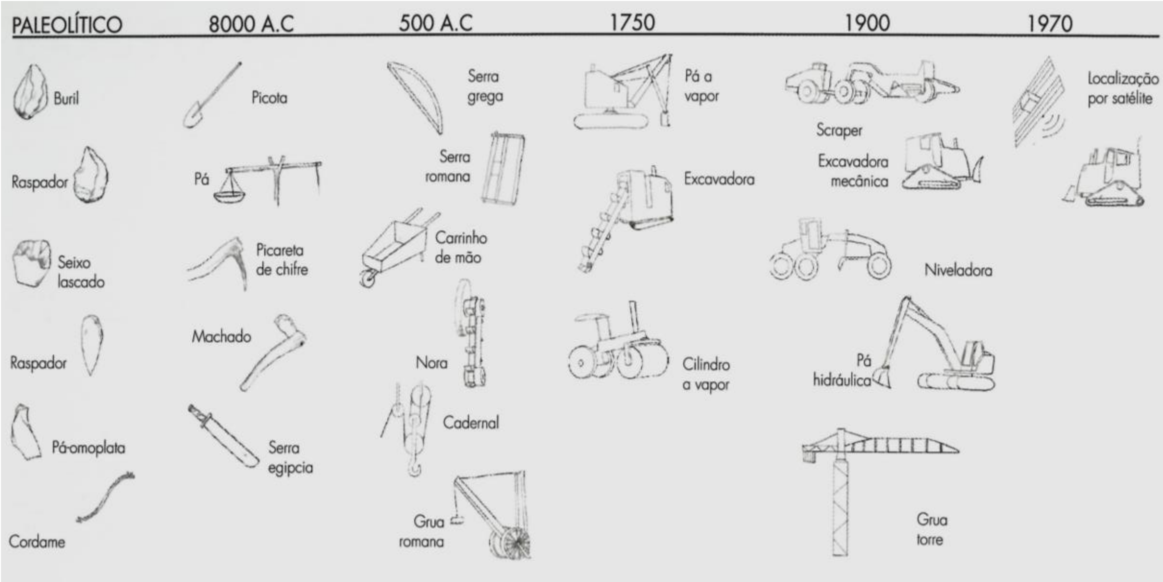

Figure 1-1: Use of machine in human kind history (Fundação Manuel António da Mota, 2013)

While the industrialization was built on heavy machinery, engines and centralized energy generation in developed areas, recent developments, especially in this millennium, have brought forward decentralized generation alternatives such as micro and small-scale technologies that can be applied in remote or isolated areas and with low or limited financial capabilities. Indeed, development is moving towards an increased use of abundant local resources, since renewable energy sources in their diverse forms are available almost everywhere. Through different concepts and technological devices, it is nowadays reasonable to satisfy all energy needs locally.

Yet, it is a major challenge in many 3rd world countries to provide energy to supply the basic human needs. By nature, every human being should have access to an adequate level of energy to fulfill its everyday needs. This includes cooking, food preparation, space heating, space cooling, water heating, refrigeration, lighting and some electrical usage for entertainment, comfort, health and education.

Although we consider access[1] to energy for granted, it is mainly in the developed world where consumption is much higher than necessary. Despite substantial efficiency improvements over the last few decades, both on the demand and supply side, global energy needs are still rising. Indeed, human activities, both, in quantity and quality have started to interfere with the planet's overall conditions. The Earth Overshoot Day, basically the day of the year when "*we will have used more from nature than our planet can renew in the whole year*", is reached earlier every year (Earth Overshoot Day, 2017). That is to say, the sustainability of the planet is under

[1] Access to modern energy resources means access to minimum electricity for housing, small businesses, public services such as health center, school and public lighting, safe homes, sustainable sources for cooking, productive economic activities and mechanical energy for agriculture (OECD/IEA, 2010).

alert even though about 1/5 of today's population does not have access to basic energy supply and relies on wood and dung to manage their daily survival.

The use of new and modern technologies had and has an important role on the accelerated development and increased energy access, but also raised and raises some new challenges based on leap frogging: Sometimes "*too much too soon*" can prevent a successful implementation or adaptation to major technological advancements (Ghosh, Shukla, Garg, & Venkata Ramana, 2002).

"*Energy is [a] critical enabler*" and catalyzer for any sustainable development (OECD/IEA, 2011) and livelihoods (Biggs, et al., 2015). Yet, energy is only one part of the nexus between water, food, energy and livelihoods. From an environmental security viewpoint energy is used for harvesting, processing and transportation on the food side as well as for filtering, desalination and waste water treatment on the water side. Contrarywise, hydropower, tidal power or cooling processes provide energy from water and biofuels or biopower can be considered as energy from food. The linkage of environment and livelihoods is then completed through the sustainable interaction of human demand and natural supply.

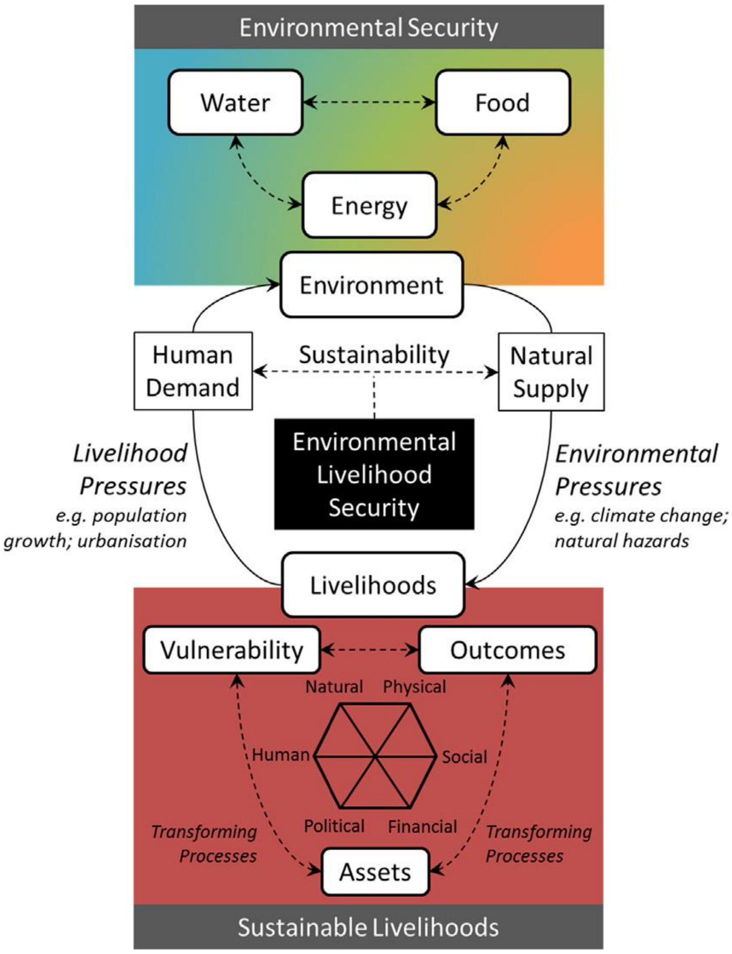

Figure 1-2: Nexus of energy and sustainable livelihoods adapted from (Biggs, et al., 2015)

The concept of sustainability embraces the issues outlined above. In the 1987 Brundtland report sustainable development is defined as: "*the satisfaction of [meeting the] present requirements without compromising the ability of future generations to meet their own needs*" (WCED, 1987). Therefore, sustainability directly imposes the introduction of climate change mitigation strategies, where environmental, economic and social aspects need to be included (IAMP, 2013). According to Cherni, "*Sustainable means not just that something can be maintain[ed] but that it is replicable in diverse geographical and social situations*" (Cherni J. , et al., 2004). For this research the most appropriate definition of sustainability may be: "*sustainable energy [is] a living harmony between the equitable availability of energy services to all people and the preservation of the earth for future generations*" (Tester, Drake, Driscoll, Golay, & Peters, 2005). Thereby, the provision of modern energy services is the foundation for sustainable development (Bazilian M. , et al., 2010).

"*At the heart of development and the nation´s security will be the availability of electric power*" (Oskarsson, 2012) and modern fuels. There is a strong relationship between the per capita electricity and energy consumption and human development. Despite accounting for two third of the world's population, developing countries only consume around half of the world´s primary energy (Ahuja & Tatsutani, 2009). The average per-capita consumption of non-OECD countries is only around 30% of that in OECD countries (Oxford Energy, 2016).[2] Moreover, 16% of the world's population still does not have access to electricity and 37% of all people mainly in developing countries rely on traditional wood and dung for heating and cooking (World Access to Modern Energy, 2015).

The increase of access to energy for services is a critical component for the quality of life since it affects physiological, safety and self-actualization matters (O'Connor, 2010). "*To be clear, [energy] access and poverty are related but distinct concepts and normally, access is just one of several elements of fuel poverty or a precondition for measuring energy poverty*" (He & Reiner, 2014). Nevertheless, poverty and lack of knowledge in the use of energy services are common reasons for the misuse of energy sources and technologies, which in turn also lead to major health, communication, education and comfort issues. For example, the inappropriate use of cooking fuels releases particles and toxins that cause indoor air pollution and subsequently result in respiratory or chronic pulmonary diseases (Duflo, Greenstone, & Hanna, 2008),

[2] The OECD is an intergovernmental organization for economic co-operation and development which was founded in 1961 and currently has 37 member states. Its members are committed to democracy and market economy to stimulate economic progress and world trade.

(Schare & Smith, 1995). Similar accounts for the hazards from using kerosene lamps (Bruce, Perez-Padilla, & Albalak, 2000), (Smith, et al., 2000).

In the end, it must be clear that health, education, comfort and communication all co-benefit from the provision of access to clean energy, namely electricity and modern fuels, and are vital to achieve a higher standard of living and sustainable livelihoods (Cherni & Hill, 2009).

1.2. Motivation

It is part of the United Nation's Millennium Development Goals to reduce poverty in rural areas in developing countries. Thereby, access to energy is a fundamental human right for all and needs to be considered a means to an end (AGECC, 2010), (He & Reiner, 2014), where improvements in energy access can be associated with the electrification of end-use services as well as the substitution of traditional biomass (Silva & Nakata, 2009). This is especially important to decrease the high pressure on natural resources, mainly the overexploitation of biomass resources in developing countries (Neudoerffer & Malhotra, 2001), but also to improve indoor air quality, and thus, health conditions in buildings (AGECC, 2010). The inefficient use of solid fuels indoors may cause very significant indoor pollution and serious impacts on health. Diseases due to pollution were responsible for around 9 million premature deaths in 2015 (Landrigan, et al., 2018). In fact, research of the IEA in 2010 highlights that the number of premature deaths caused by indoor pollutants was higher than tuberculosis and malaria together (IEA, 2010). Women and children are the major concern, since they spend most of their time in close proximity to the source of pollution while making and keeping the fire (Global Energy Assessment, 2012). With already minor enhancements to reduce pollutants substantial health improvements can be expected.

Worldwide there are many regional and national action plans to increase energy access mainly through networks. For instance, electricity network expansions and access to natural gas have increased manifolds in South Asia. However, the inaccessibility to modern fuel and electricity in isolated communities still remains a major impediment for any development in these communities. Isolated communities are defined based on their geographical and socio-economic characteristics: high geographic dispersion, withdrawal from inhabited areas, weak road and communication infrastructure, complicated and often environmentally valuable orography, low density of consumption, low and unstable seasonal income, low growth prospects and economic organization, difficult access to supply and technical services, limited services for health and education, limited clean drinking water, poor sanitation, abandonment of the authorities responsible for the provision of services, etc. (Cañedo-Arguelles, 2011).

In India alone there are around 10 million people living in isolated communities. More than 50.000 hamlets[3] and communities have no access to electricity or modern fuels and another 100.000 hamlets and communities only have access to modern fuels (Chandran-Wadia, Deorah, Nair, & Lath, 2015). What most of these communities have in common are the low-income status and the high lack of literacy. The non-availability of conventional energy sources and the very high fuel prices (Wuyan, Zerriffi, & Jihua, 2008) force even the richest inhabitants to immigrate or use traditional energy systems (Mirza & Kemp, 2009).

The motivation of this research is to follow the "*energy for all*" leitmotiv and define energy solutions for isolated communities (IEA, 2011), specifically those that face the unfeasibility of grid connections and are in poor financial conditions. In South Asia, Africa and South America there is a considerable need to increase energy access and reduce the scarcities on modern fuels, especially as the number of rural agglomerations is high (Figure 1-3) (World Access to Modern Energy, 2015). To exemplify it can be stated that in rural India alone still 72 million households (380 million people) have no access to electricity and rely on traditional biomass or subsidized kerosene (Urban F. , 2009). While the limited access to electricity has direct impact on healthcare, education and communication, the use of traditional cooking and heating fuels leads to (indoor air) pollution and major health issues.

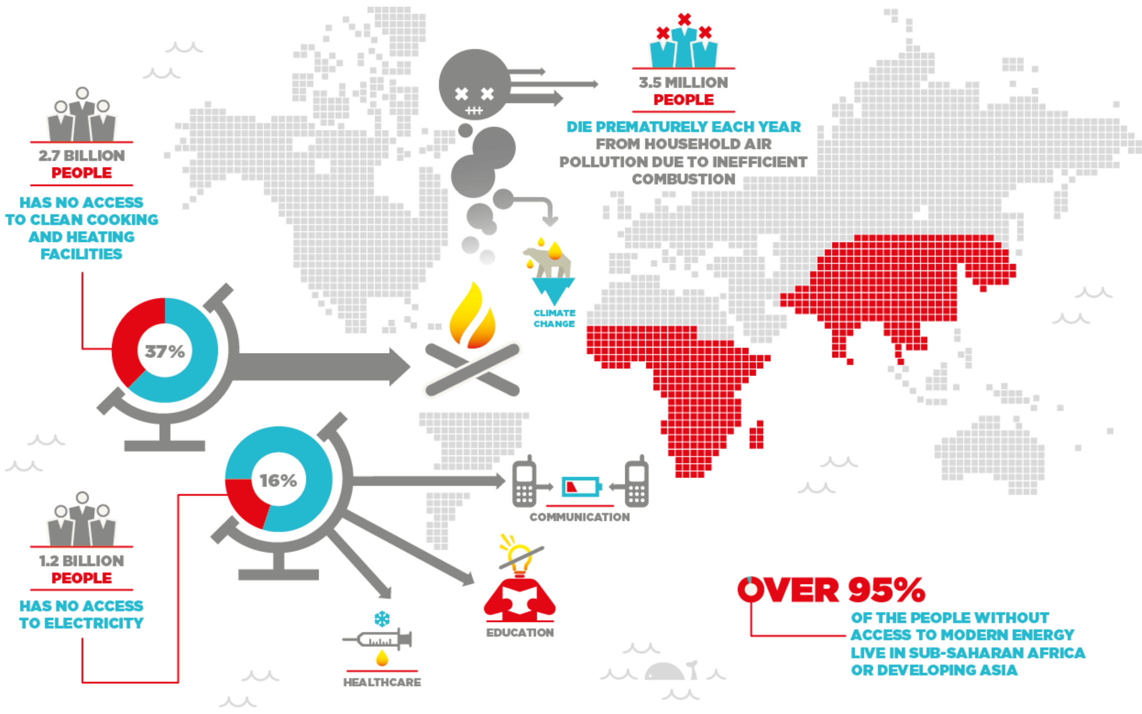

Figure 1-3: Problems associated to lack of energy access (World Access to Modern Energy, 2015)

[3] By definition a hamlet is a human settlement which is smaller than a village and usually without a church.

As reaction to the ongoing challenges faced in India´s (electric) energy sector, there has been a growing shift to off-grid and distributed electricity solutions in non-electrified areas. The International Energy Agency estimates that more than 70% of the rural population worldwide could get access through off-grid solutions and that 65% of those would be micro grids (OECD/IEA, 2011).

As the gamut between energy, health and poverty reduction is close, the inspiration for this research is to reach another step forward in enhancing the role of energy provision, which is the major obstacle of poverty alleviation. Besides, quality of life shall be increased steadily with the appropriate use of technologies (Bazilian M. , et al., 2012). This research provides strategic support on how to increase the level of energy access towards or even above the minimum requirements across all end-uses and sectors. Based on the local conditions and resource availability, reliable and sustainable solutions will be proposed and financially compared.

Hence, improvements in access to energy will provide higher living comfort, better lighting, more machine power to increase output, but also freedom of some daily tasks that restrict comfort and health (e.g. gathering resources), among others (Cherni & Hill, 2009). Twomlow et al. explain the indispensibility of energy provision to the household's survival such as secure food production and cooking facilities, but also upgrading sanitation and lighting in social arrangements like schools or health centers (Twomlow, O´Neill, Sims, Ellis-Jones, & Jafry, 2002).

The United Nations (UN) has established sustainable goals for universal access to modern energy services, global improvement of energy efficiency and increase of renewable energy in the global energy mix (United Nation Foundation, 2013). Recent data from the International Energy Agency and the World Bank shows that between 2010 and 2012 222 million people (2/3 of the United States population) gained access to electricity and 125 million people (approximately the population of Japan) gained access to clean and modern cooking fuels. Just in 2012 alone energy intensity could be reduced by 1.7% and the contribution of renewable energy sources could be increased by 4% (Japans annual energy use). Although these numbers show a promising trend, it is necessary to assess the global targets that shall be achieved by 2030. In fact, reliable and affordable electricity is still a problem for 1.2 billion people, not to mention the 2.7 billion people that still do not have access to clean and modern fuels. In terms of energy efficiency, it is foreseen that energy intensity must decline at least 50% faster than the current trend and the generation of renewable energy should be increased twice as fast. In order to achieve the set targets investments in sustainable energy solutions must be tripled (International Energy Agency (IEA) and the World Bank, 2015). All this can only happen with more accurate policies and strategies at local, regional, national and international level. While there are ambitious strategic plans for the improvement of already modernized energy systems in developed countries, emphasis still must be placed on developing countries, in particular areas which are clearly below the minimum energy requirements and/or in isolated areas. Therefore, specific energy plans are essential to take into account the local and natural conditions in these areas.

According to UNDP and World Health Organization, the major findings of energy access situation in developing countries (UNDP and World Health Organization, 2009) are as follows:

- Although the level of energy access varies significantly amongst developing countries, there is a noticeably lower access in poorer developing countries
- Modern fuels and improved stoves are out of reach for most people in rural areas
- 99% of the 2 million annual deaths from pneumonia, chronic lung disease, and lung cancer are the result of indoor air pollution from cooking with biomass and coal
- Burning of solid fuels has significant impact on global warming effects
- The number of countries with targets and strategies in place to improve access to modern energy and reduce energy poverty is very limited
- Developing countries are far behind in achieving the Millennium Development Goals
- Continuous effort is essential to improve the statistical information related to energy access
- Substantial effort to expand modern energy access for cooking and mechanical power is especially needed in rural and isolated communities

1.3. Research Problem

Making decisions and finding an implementation strategy to respond to the energy needs of millions of humans in the middle of nowhere in remote areas in the exacerbated world of technology development and economic uncertainty is a difficult and complex task. Decision support is essential to cluster problems into layers that can be analyzed so that potential and adequate solutions can be provided.

As there is a close connection between decisions and actions for energy processes at all levels, particularly the local level, wrong decisions and solutions can cause crucial challenges like a misleading understanding of outputs and/or outcomes.[4] In energy planning decision makers are confronted with many alternatives, mainly in terms of energy resources and technologies.

[4] While outputs broadly describe the efficiency achieved from inputs, outcomes are characterized by the effectiveness of objectives.

In order to provide decision support for an adequate energy mix or for the selection of technologies and end-use devices, concerns related to resource availability, costs and ease of use, but also sustainability in general, have to be considered in an interdisciplinary approach. Thereby planning should not only take into account technical, economic and environmental aspects, but also the point of view of the end-user, who in the end has to adapt to and use the new devices and technologies (Borofsky, 2015).

Regardless of the many planning policies at national or regional level, often there are no major policies established for local or isolated areas. Also, these areas often lack financial support and an adaption of existing national/regional plans cannot take into account the local conditions, thus diminishing the expected outcomes noticeably. Ramachandra already highlighted the deprivation of solutions at regional and local level, by emphasizing the need of decentralization and community involvement for effective outcomes (Ramachandra, 2009). The same research also reveals the lack of computational tools available for energy solutions that can correspond to the conditions in isolated communities.

These communities, with limited or poor access to modern energy, are also limited in the number of habitants. Commonly, communities consist of a few hundred inhabitants that are confronted with lack of financial and technical support to develop a grid and modern fuel network. According to Practical Action, which developed an energy access ecosystem framework, there are three aspects (capacity, policy and finance) that are essential when evaluating the performance of the energy system (Practical Action, 2012). Yet, it may be argued that further social, cultural, technical and environmental aspects have to be considered, so that the ecosystem can be assessed from a sustainability point of view.

Despite being insufficient and causing indoor air pollution and diseases, most energy requirements in undeveloped isolated areas still rely on traditional bioenergy. However, in recent years a successive increase in the implementation of renewable energy electrification projects could be noticed. While most projects may be effective, they are neither sufficient nor sustainable in the long-term (Terrados, Almonacid, & Hontoria, 2007).

Another challenge for isolated communities is how to use locally available resources with advanced, intermediate[5] or portable technologies. The appropriate selection necessitates a

[5] Appropriate or intermediate technologies are an ideological movement resulting from the work of Dr. Schumacher. They generally represent a technologic choice of an application of small scale, decentralized, labor intensive, energy efficient, environmentally sound and locally controlled usage. Nowadays these technologies are also very people centered (Peterson, 2008).

plan that starts from the diagnose of the community´s consumption, proposes different options, oversees the implementation of a solution and evaluates its impact.

It can be summarized that the current situation in these isolated communities requires the development of methodologies to support the selection of technologies to be implemented, to incorporate future users in the decision-making process of their empowerment and to consider technical, economic, environmental and social aspects through an interdisciplinary approach. At the same time, a universal bottom-up approach that reflects planning aspects from the demand and supply side, while taking into account local characteristics of resources and habitants, needs to be established.

1.4. Aim of Research and Research Questions

The aim of this research is based on the structure proposed by the logical framework approach, which is a tool for program development via identification, design and management (NORAD, 1997). It is intended to recommend energy planner´s and local decision makers in developing countries to understand the level of energy access and the comparison with minimum energy access requirement and also to identify the most appropriate energy solutions and achieve a higher degree of performance considering local resource and technology availability in order to bring together sustainability, environmental justice and equity in isolated communities. There are 3 dimensions related to this concept. First, areas with unequal income distribution, no qualified political rights and weaker civil liberties have lower environmental and energy quality. Second, environmental and energy problems bear down disproportionately upon the poor, since the majority of these isolated communities face poverty. Third, sustainable development only will be reasonable if social needs, welfare and economic opportunities are integrally connected to environmental and technical concerns (Boyce, 2003). Consequently, with the proposed integrated water and energy solution it is expected to enable isolated communities to improve health, education, entertainment and communication, comfort and self-esteem and women empowerment.

To create a conceptual decision method, it is intended to identify and structure the objectives that are essential to obtain thoughtful and valuable scientific outcomes. According to Bock it may be divided in (Bock, 2009):

1) Analysis: describes the problem, defines performance criteria, investigates related work and states the objectives;
2) Hypothesis: specifies the solution, sets goals, defines factors, postulates performance metrics;

3) Synthesis: implements a solution, designs and conducts experiments and obtains results;
4) Validation: computes performance, prepares documentation and draws conclusions.

There are many objectives that are directly or indirectly relevant to sustainable livelihoods. Hence the 'objectives' network is presented in Figure 1-4. In this research it is intended to focus on increasing local development and improve energy access, while decreasing health issues caused by the misapplication of energy systems.

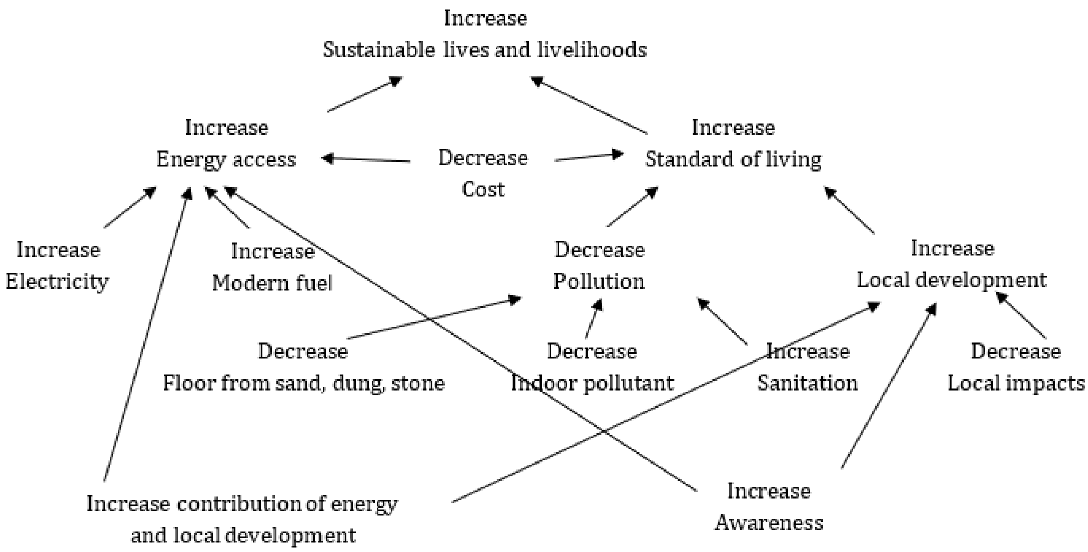

Figure 1-4: Identifying the values and strategies through an 'objectives' network

The proposed concept is considering a medium-term time frame of 10-20 years and the following energy "services": electricity, heat and mechanical power. The resources and technologies that are taken into consideration include solar, hydro, wind, bioenergy, others, some intermediate technologies as well as imported fuels. Since a connection to the main grid is most of the time economically unattractive, if not even unfeasible, the scale of potential solutions is limited to small and medium stand-alone systems, and micro or mini-grid solution that fulfill the electricity requirements of the entire community. Besides, upfront costs of these solutions are major boundaries and therefore it is necessary to identify alternatives to cover the energy deficit till the financial difficulties can be overcome. In the researches of Vuuren et al. and Haydt et al. it is emphasized that to develop any solutions or plans fundamental, well-defined objectives and attributes should be identified in the first place (Vuuren, Nakicenovic, Riahi, Brew-Hammond, & Nilsoon, 2012), (Haydt, Leal, & Pina, 2011).

The research questions raised and addressed in this thesis are:

1) What is the current situation of energy access in isolated communities?
2) How to provide minimum energy access to cover basic living conditions?

3) How to balance technological alternatives of adjusted dimensions given the economic capacity and how to identify local needs where future network energy services are impossible for isolated communities?

Due to the variety of aspects to be considered within such an overarching and interdisciplinary concept, the following aspects are omitted: geopolitical influence, transportation and study of the conflicts that might arise between local/regional and national energy planning approaches. The value proposition for successfully providing energy services in the Developing World is to achieve more performance from fewer resources but for more people ("More for Less for More") (Benson, Sassoon, & Hung, 2013). By developing a suite of distributed energy technologies that can leap-frog the current generation, accelerated access to low emission energy services can be provided without the need to build costly energy infrastructure as in the developed world, in much the same way that cell phones revolutionized the telecommunications market. This request is an opportunity to explore creative but credible ideas that could be applied across the energy system, including clean cooking fuels, distributed electricity generation and energy storage, and non-fossil-based heating and cooling. The global climate and energy project (GCEP) outlines a program of research that, if successful, could enable the development of an energy technology, process or system for developing countries that meets basic energy needs or provides energy access (Benson, Sassoon, & Hung, 2013).

Poverty and lack of energy access remain two important undeniable issues for the majority of the South Asian society. The link between access to energy, specifically electricity, and improvements in quality of life is well-supported by the literature (Gaye, 2007), (Khandker, 2012). In fact, in relatively poor areas "*it can be expected that climate change will not become a priority, when the population suffers from poverty, lack of literacy, bad health care and high rates of unemployment and income issues*" (de Oliveira Fernandes, et al., 2011). As a consequence of the low literacy rate and high poverty most inhabitants of these areas have to use whatever resources and conversion devices are available. Aspects of sustainability or the exposure to (indoor air) pollution for themselves or the environment are usually not taken into account.

1.5. Outline of Work

Quite regularly the occurrence of a decision problem is opposed with the identification of alternatives. Keeney emphasizes on the initial definition of values, since the recognition and enunciation of values is fundamental for the creation of better alternatives and the identification of decision opportunities. To that extent it is vital to specify values to be reached within the solution (Keeney, 1992). After that the results can be examined in order to assess the effectiveness. Within this research the validation of the proposed methodological concept will be based on a pre-defined hypothetical community in India.

In this context the research methodology sets out to:

- Outline the energy access problem in isolated areas;
- Identify the type of solutions that responds to the problem (optimization solutions or pre-specified alternatives that can generate solutions);
- Determine local intermediate and renewable energy technologies as alternatives and study the combinations of them;
- Outline the problems of local decision makers in terms of choosing appropriate resources and technologies in the energy mix of isolated community to correspond to the local needs;
- Support decision makers in their decision-making process and in achieving the specific objectives;
- Review existing energy models and energy planning tools, criteria and aspects to identify the requirements that should be considered in the proposed framework;
- Identify decision analysis methods;
- Evaluate the potential of using dispersed energy solutions based on locally available resources considering multi-criteria decision aid;
- Establish a concept and framework, both, through a systematic and mathematical approach;
- Design a decision support method that assesses all relevant solutions to cover the energy requirements of isolated communities; and
- Apply the concept to case study.

After this introduction in Chapter 1, the literature review is presented in Chapter 2. Thereafter the proposed methodological approach is explained in Chapter 3. Within Chapter 4 all tools are explained in details, so that they can be applied to the hypothetical community in Chapter 5. This work closes with the conclusions and potential for future work in Chapter 6.

It is expected that this research benefits all stakeholders of such isolated communities, since substantial improvements in the daily life and comfort are foreseen.

2. State of the art

While the world´s population in foreseen to further increase, the number of people without energy access has decreased from 2 billion in 2002 to 1,1 billion in 2010 (International Energy Agency (IEA) and the World Bank, 2015). Yet, energy access remains a major global challenge mainly in poor and/or rural areas[6].

The inequality of access to energy is quite substantial. While in some countries the average annual consumption per capita is above 10,000 koe, others use less than 500 koe per year (The World Bank, 2017).[7] The vast majority of human beings with limited or even without access are living in South Asia, (central) Africa and Latin America.

Since developed countries use energy at the highest level (electricity and clean modern fuels) (de Oliveira Fernandes, de Almeida, & Cardoso, 1998), these countries are inappropriate to be role models when implementing energy access strategies and/or policies. Quite frequently such implementation measures have failed, because end-users are overwhelmed by the level of advanced technologies and cannot easily adapt to the same. In fact, (very) advanced technologies are often too complicated to be used by someone with no prior technical experience. Likewise, the interest to learn about and to maintain these new technologies is oftentimes rapidly decreasing. Subsequently, new technologies are misused, not used efficiently or the end-user easily loses its curiosity in them. All these challenges need to be kept in mind, when introducing new technologies in areas with limited or no educational background and support.

Energy transitions are usually long-term structural changes in the energy system that bear in mind natural/local boundaries between the differs type of actors involved and limitations along with the method, quality and quantity of use (Koehrsen, 2017).

The 'Trias Energica' concept of Lysen presents a three-step strategy within the context of an urban design to reduce energy use, introduce renewables and use fossil fuels efficiently (Lysen,

[6] In 1950, 70% of the world's population lived in rural areas, but in 2014 this number had fallen to 46%. In Asia and Africa 52% and 60% of the population were still living rural areas in 2014 (United Nations, Department of Economic and Social Affairs, Population Division , 2014).

[7] These numbers refer to the total primary energy supply and include all input to produce fuel and electricity for end-users. In absolute terms, the actual average consumption is isolated communities is much lower, since there is no or very limited use of transportation, industrial uses and public uses. If only the domestic sector is taken into account than the consumption might only be a fraction of the national average.

1996). However, if the concept is applied at local level then there are benefits from the resource perspective since independence can be increased and fuel imports can be decreased. Hitherto, the concept also has some challenges in its execution: financial support, social barriers of acceptance, environmental barriers such as erosion and the way of land use, and technical barriers such as low and fluctuating output of the main variable renewable energy technologies (PV, wind) that require backup and/or storage. Despite the challenges the concept provides an immediate solution with much lower impacts compared to pure fossil fuel solutions. Thus, it becomes a reliable and valuable option to be used at local level. Local energy transitions bear great potential for many areas with a scarcity of energy access to achieve a higher standard of living and comfort, but and to safeguard energy resources and human's health. Energy transition can be planned and managed through various methods and methodologies. Therefore, it is of great interest to study the use of energy models and energy planning methods to explore the local energy system under various aspects.

Within rural isolated communities the main energy users are generally households, followed by some essential public centers, such as schools or health centers. Plus, there are usually a few small businesses which require energy for water pumping (irrigation), reap and ventilation systems for livestock, etc. Quite frequently, enhanced energy services are the ones that will increase earning alternatives via new business opportunities by improving the existing activities or by reducing the time spent by women and children to gather resources or keep the system operating (Practical Action, 2010). Thus, time and human resources will be used more efficiently.

Within the literature review the status quo of energy access, energy demand, possible supply technologies and end-use devices as well as energy planning strategies and multi-criteria decision aid for isolated communities will be assessed. Focus will be placed on isolated communities in South Asia, particularly India.

2.1. Status Quo of energy access

The current status of energy access in South Asia is summarized in Table 2-1, where an overview of the total rural population, the energy access level, the access to electricity and to modern fuels as well as the annual average energy and electricity consumptions are shown. In addition, an adjusted energy consumption value is defined based on the fact that in most countries a major part of energy is used for transport and industry. Hence, these two sectors had to be subtracted from the average value to have a better approximation of the actual consumption of residents in rural communities.

Table 2-1: Energy access situation in South Asia

Country	Total Rural Population 2016 [%]	% of rural areas with access to			Annual Average Electricity Consumption	Annual Average Energy Consumption	Annual Adjusted Energy Consumption[1]
		Electricity [%]	Modern fuel [%]	Water[2] [%]	kWh/capita (koe/capita)	kWh/capita (koe/capita)	kWh/capita (koe/capita)
Afghanistan	73%	88%	17%	47%	N/A	1050 (90)	305 (26)
Bangladesh	65%	51%	10%	87%	310 (27)	2438 (210)	707 (61)
Bhutan	61%	96%	68%	100%	N/A	23810 (2047)	6904 (594)
India	67%	70%	34%	93%	806 (69)	6601 (568)	1914 (165)
Maldives	53%	100%	99%	98%	N/A	3980 (342)	1154 (99)
Nepal	81%	82%	26%	92%	139 (12)	10814 (930)	3136 (270)
Pakistan	61%	96%	45%	90%	471 (40)	5687 (489)	1649 (142)
Sri-Lanka	82%	91%	19%	95%	531 (46)	5578 (480)	1618 (139)

[1] The adjusted value presents the total energy consumption subtracted by transport (22%) and industry (49%) which account for 71%. Consequently, the adjusted value is the energy demand for residential, service and agricultural services. The breakdown is based on the case of India and has been applied to all other countries.
[2] Water access refers to the possibilities of having access to improved sources

(The World Bank, 2017), (Oskarsson, 2012), (OECD/IEA, 2011), (INFORSE, 2013)

Despite the fact that access to electricity, modern fuels and improved water sources is steadily increasing, the above figures only present national average values. In absolute terms a considerable share of the rural population is still struggling to meet its daily energy needs and only uses a fraction of the average values. Energy access is also subject to the availability of local supply resources to fulfill the electricity, heat and fuel requirements.

From a demographic point of view, these rural isolated areas frequently have a high population growth rate. Young and old generations live together in one household. The living standard ranges from very low to low, since the limited income prevents any efficient economic development. Small businesses and agriculture are the main services and industries. The topography of most villages varies considerably from one location to another and the villages are separated by vast unpopulated areas. Though, in some cases, for instance in India, 5-15 villages are grouped together as so-called Panchayat (Kishore, 2013), (Public Administration, 2013). Many isolated areas are in the middle of forests or mountains. They are located several kilometers from the nearest network or in rough terrain. Nouni et al. studied power generators and concluded that for small villages with a distance of more than 5 km from the grid, decentralized electricity supply options are financially more attractive (Nouni, Mullick, & Kandpal, 2008). Moreover, these isolated communities have low or limited access to communication tools and to the "outside world".

Depending on the characteristics of a regular level of life, life expectation, topography, demography, etc., the energy requirements vary noticeably. Because income is low, locals are confronted by two major energetic obstacles: 1) fuel limitation and 2) alternatives to replace inefficient and pollutant conversion and/or end-use devices. Thus, the "*transition from traditional to modern energy use and household electrification*" is a key factor in shaping the future energy demand (Ruijven, et al., 2011).

The major challenge with defining modern energy access is best described through the International Energy Agency. While "*there is no internationally-accepted and internationally-adopted definition of modern energy access*, […] *significant commonality exists across definitions*" (International Energy Agency, 2015):[8]

- Household access to a minimum level of electricity
- Household access to safer and more sustainable (i.e. minimum harmful effects on health and the environment as possible) cooking and heating fuels and stoves
- Access to modern energy that enables productive economic activity, e.g. mechanical power for agriculture, textile and other industries
- Access to modern energy for public services, e.g. electricity for health facilities, schools and street lighting

It is known that the requirements of habitants may change from one community to another; and also, from one country or one climate to another. Yet, it is common for the poorer level society that most of the households spend one third or even half of their monetary income and time for energy services (Practical Action, 2010). Energy related tasks, such as the gathering of wood and dung, but also water as well as the preparation and maintenance of the fireplace are the major tasks for women and children. The high involvement of children in the daily tasks along with the limited possibilities of lighting after day light hours prevents most children from having any time or possibility for education. The daily survival is the primary objective for all family members–(Trading Economics, 2013). A study conducted by Haughton and Khandke reveals that the majority of participants live in poverty with less than $1 - $2 per day (0.7-1.4 € in 2009) (Haughton & Khandker, 2009). Because of the extreme monetary limitations many people still use informal economies, whereby work is provided in exchange for other goods and services. The effects of these informal economies are barely recorded, thus causing poor quality of monetary and energy data (Ruijven, et al., 2011).

In addition to the crucial elements of economic and social development, various other related issues have to be considered. They are usually referred to as quality of supply and take into account elements such as technical availability, adequacy, reliability, convenience, safety, affordability, actual use of end-use devices and possible generation supply technologies (ESMAP, 2014), (ESMAP, 2015).

[8] Access to water is not part of the defined commonalities

An exemplary framework to define energy access for all (sub-) sectors is illustrated in Figure 2-1 (Practical Action, 2013).[9] Thereby, it is clustered in access to cooking fuels, electricity and mechanical power. While the levels between 1 and 3 can be considered as minimum access level, levels 4 and 5 already provide some minor forms of comfort and convenience.

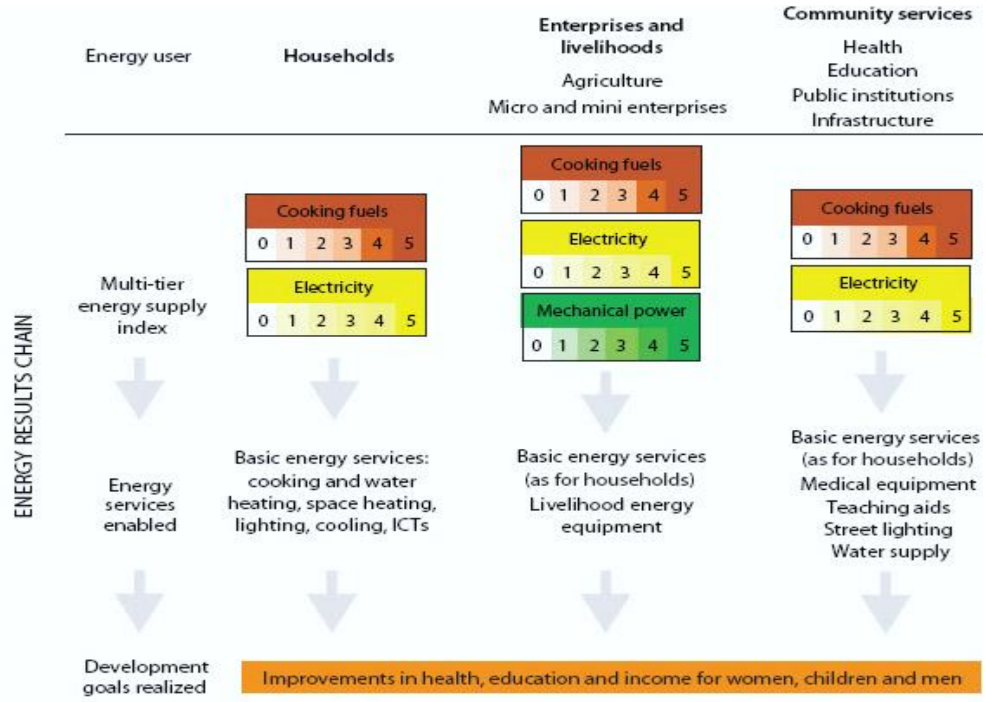

Figure 2-1: Framework for defining and measuring access to energy (Practical Action, 2013)

It is important to note that energy access should not be increased immediately from 0 to 5. A step-wise increase is much preferred, since “*too much too soon*” can prevent a successful implementation of new or better devices. It has been demonstrated that plans and/or strategies that were originally designed for developed countries and then adapted to regions with no or very limited energy access, often did not perform as expected or even failed completely (Ghosh, Shukla, Garg, & Venkata Ramana, 2002).

Due to the currently low levels of energy access, local decision makers require crucial assistance to get acquainted with the minimum electric and thermal energy needs across all end-uses, the local resource availability, the diversity of potential energy solutions but also the technology development cycle of conversion devices and its main driving forces (Metz, 2007).

[9] Cooking fuels: 1: collecting wood or dung and using a three-stone fire; 2: Collecting wood and using an improved stove; 3: Buying wood and using an improved stove; 4: Buying charcoal and using an improved stove; 5: Using modern, clean-burning fuel and stove combination. Electricity: 1: No access to electricity at all; 2: Access to third party battery charging only; 3: Own low voltage DC access for home appliances; 4: 240 V AC connection but poor quality and variable supply; 5: Reliable 240 V AC connection available for all uses. Mechanical Power: 1: No access to mechanical power. Hand power only with basic tools; 2: Mechanical advantage devices available to magnify human/animal effort; 3: Powered (renewable or fossil) mechanical devices available for some tasks; 4: Powered (renewable or fossil) mechanical devices available for most tasks; 5: Mainly purchasing mechanically processed services.

2.2. Minimum energy requirements

The minimum energy requirements (MER) provide an overview of how much energy a human being should have access to on a daily/annual basis to meet its basic requirements. There are various approaches on how to define the MER. Studies reviewed span across 3 decades, whereas varying considerations in terms of energy versus electricity and individuals versus households have been included. They all tried to define appropriate levels of energy access, where the primary level should refer to the MER that satisfy immediate social needs such as cooking, drinking water, lighting, street lighting and also cater for economic growth and provide survival matter. Hence, the focus of this research is placed on analysis the primer stage of energy access, which is also knows as minimum energy access.

- Goldemberg was one of the first to construe a daily limit of energy use. In the late 80s a daily use of 500-600 W/capita was defined (around 180-220 kWh per year), (Goldemberg, Johansson, Reddy, & Williams, 1985), (Goldemberg, Johnsson, Reddy, & Williams, 1987), (Goldemberg, 1990).
- A more detailed analysis was undertaken around the Millennium by a task force of the G8 and indicates that most rural villages were below the minimum level of energy access; in particular electricity access. The G8 country report (Table 2-2) defines the minimum electricity need for households – considering 5 habitants – with 2-6 kWh/month (24- 72 kWh/year; 2.1-6.2 koe/y). In addition, public services and productivity activity were considered with 1-2 kWh/month (12-24 kWh/year; 1-2.1 koe/y) and 0-20 kWh/month (0-240 kWh/year; 0-21 koe/y) respectively (G8, 2001).

Table 2-2: Typical energy service requirements in the form of electricity for off-grid populations in developing countires (G8, 2001)

Development Need		Typical Energy Services for Off-grid Households	Electricity Demand kWh/month per household
Household energy need	Lighting	5 hours/day at 20 W for a household	2-6
	Radio/Music	5 hours per day at 5 W per household	
	Communication	2 hours per day at 10 W per household	
	Portable Water	Electric pump providing the community with 5 liters per day per capita	
Medical Services		2.5 kWh/day for basic services in a rural clinic with 100 households	0.5-1
Education		2.5 kWh/day for lighting, water pumping, copying, computer, copier, TV, Video, radio, etc. in a school for 100 households	0.5-1
Productive (income generating uses)		5 kWh/day for equipment used by workers from 10 households	0-20
Total			3-30

- The same study also looked at energy service specifications for poverty alleviation, where energy needs for basic and quality energy services were defined. The major difference between both services is the addition of TV and refrigeration for the quality service, which alone account for a doubling of the annual needs. While for basic energy services the annual needs are defined with 51 kWh per year and capita, the quality energy service should be around 103 kWh per year and capita (G8, 2001).
- In 2005 the Government of India defined the lifeline rate with 365 kWh/year (31.38 koe) (Government of India, 2005).
- Modi et al. defined minimum energy needs with around 580 kWh (49.87 koe) per capita per year (10 koe for electricity and 40 koe for cooking) (Modi, McDade, Lallement, & Saghir, 2005).
- In the 2011 World Energy Outlook energy access for rural areas was defined with 250 kWh per year and with 500 kWh per year in urban areas (21.5 and 43 koe) (OECD/IEA, 2011).
- The annual energy (fuel, heat and electricity) consumption per capita map[10] lists all South Asian countries as follows: Afghanistan and Nepal with less than 1,466 kWh (126 koe); Bangladesh between 1,466-2,640 kWh (126-227 koe); India, Sri-Lanka and Pakistan between 2,933-7,390 kWh (252.2-635.42 koe); and Bhutan between 22,000-43,700 kWh (1,891-3,758 koe) (BURN, 2013).
- As presented by AGECC, incremental energy access levels contain basic human needs, productive uses and modern society needs (Figure 2-2) (AGECC, 2010). Thereby, the equivalent of 1,200 kWh per capita per year (103 koe/y) is proposed.

Level 1 **Basic human needs**	**Level 2** **Productive uses**	**Level 3** **Modern society needs**
Electricity for lighting, health, education, communication and community services (50-100 kWh per person per year) **Modern fuels and technologies for cooking and heating (**50-100 koe of modern fuel or improved biomass cook stove)	**Electricity, modern fuels and other energy services** to improve productivity e.g. -Agriculture: water pumping for irrigation, fertilizer, mechanized tilling - Commercial: agricultural processing. Cottage industry - Transport: fuel	**Modern energy services** for many more domestic appliances, increased requirements for cooling and heating (space and water), private transportation (electricity usage is around 2000 kWh per person per year)

Figure 2-2: Incremental levels of access to energy services (AGECC, 2010)

- Sanchez suggests 120 kWh of electricity and 35 kg of LPG per capita per year considering improved cook stoves in the system (Sanchez, 2010).
- Sovacool defined the energy ladder towards level of services and access for basic needs per person (50-100 kWh/year = 4.30-8.6 koe) and for productive uses (500-1,000 kWh/ year = 43-86 koe) (Sovacool, et al., 2012).

[10] Does not include Maldives

- In the Progress Toward Sustainable Energy 2015 report multitier matrices for household electricity (Table 2-3) and household cooking (Table 2-4) are presented. With an increasing level and with progressively higher attributes, each tier marks the ability of the energy accessed to serve more energy applications (International Energy Agency (IEA) and the World Bank, 2015). Such a planning approach by tiers is particularly interesting for energy planners in isolated/rural areas (ESMAP, 2015).

Table 2-3: Multi-tier matrix for access to household electricity supply (ESMAP, 2015)

ATTRIBUTES		TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
1. Capacity	**Power**		Very Low Power Min 3 W	Low Power Min 50 W	Medium Power Min 200 W	High Power Min 800 W	Very High Power Min 2 kW
	AND Daily Capacity		Min 12 Wh	Min 200 Wh	Min 1.0 kWh	Min 3.4 kWh	Min 8.2 kWh
	OR Services		Lighting of 1000 lmhrs per day and phone charging	Electrical lighting, air circulation, television, and phone charging are possible			
2. Duration	**Hours per day**		Min 4 hrs.	Min 4 hrs.	Min 8 hrs.	Min 16 hrs.	Min 23 hrs.
	Hours per evening		Min 1 hrs.	Min 2 hrs.	Min 3hrs	Min 4 hrs.	Min 4 hrs.
3. Reliability						Max 14 disruptions per week	Max 3 disruptions per week of total duration <2 hours
4. Quality						Voltage problems do not affect the use of desired appliances	
5. Affordability					Cost of a standard consumption package of 365 kWh per annum is less than 5% of household income		
6. Legality						Bill is paid to the utility, prepaid card seller, or authorized representative	
7. Health and Safety						Absence of past accidents and perception of high risk in the future	

Note: CO = carbon monoxide; ISO = International Organization for Standardization; IWA = International Workshop Agreement on Cookstoves; PM = particulate matter; lmhrs = lumen hours

- Potential improvements for the multitier matrix for access to household electricity supply have also been investigated through an empirical analysis of household electricity access in rural Bangladesh, whereas the metric stresses the need for a refinement of the attribute algorithm (Groh, Pachauri, & Narasimha, 2016).

Table 2-4: Multitier matrix for access to household cooking solutions (ESMAP, 2015)

ATTRIBUTES		LEVEL 0	LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
1. Indoor Air Quality	**PM 2.5 (μg/m³)**		[To be specified by a competent agency such as WHO based on health risks]			<35 (WHO, IT-1]	<10 (WHO guideline]
	CO (mg/m³)					<7 (WHO guideline)	<7 (WHO guideline)
2.Cook stove Efficiency (Not to be applied if cooking solution is also used for space heating)			Primary solution meets tier 1 efficiency requirements	Primary solution meets tier 2 efficiency requirements	Primary solution meets tier 3 efficiency requirements	Primary solution meets tier 4 efficiency requirements	
			[To be specified by the competent agency consist with local cooking conditions]				
3. Convenience	Stove preparation tie (min/meal)			<7	<3	<1.5	<0.5
	Fuel acquisition and preparation time (hrs./wk.)			<15	<10	<5	<2
4. Safety of Primary	IWA safety tiers			Primary solution meets (provisional) ISO Tier 2	Primary solution meets (provisional) ISO Tier 3	Primary solution meets (provisional) ISO Tier 4	
	OR Past accidents (Burns and un-intended fires)					No accidents over the past year that required professional medical attention	
5. Affordability						Levelized cost of cooking solution (including cook stove and fuel) <5% of household income	
6. Quality of Primary Fuel: variation in heat rate due to fuel quality that affects ease of cooking						No major effect	
7. Availability of Primary Fuel						Primary fuel is readily available for at least 80% of the year	Primary fuel is readily available throughout the year

Note: CO = carbon monoxide; ISO = International Organization for Standardization; IWA = International Workshop Agreement on Cookstoves; PM = particulate matter.

The review of studies dealing with minimum energy requirements shows various similarities, but also major contrasts. Yet, there is a trend towards higher minimum requirements over time. While some studies purely focus on electricity, others consider the entire energy spectrum and include heating fuels and mechanical power. This is particularly important since only the combined use of all energy forms can cover the essential requirements to improve health, comfort, environmental and social aspects. Recent studies have brought forward concepts to gradually increase consumption. This is especially valuable to ease the adaptation of local inhabitants with improved/intermediate or even advanced technologies.

2.3. Sectorial demand and end-use requirements

In addition to the minimum energy access, which is generally expressed in an annual per capita value, it is equally important to identify all end-uses and requirements by sector (Bellanca & Garside, 2013), (Neves, Leal, & Lourenco, 2015). As a matter of fact, minimum energy access may already be achieved in various rural communities by using (very) inefficient devices. This however does not guarantee good conditions for a human's health, comfort or convenience. In contrary, very inefficient devices, such as for cooking, may cause severe indoor air pollution and health problems.

At local level the energy requirements and the level of access to fulfill all services are directly relevant to the end-user devices. The energy requirements are a crucial and important input parameter (Pachauri, Mueller, Kemmler, & Spreng, 2004) that needs to be matched with locally available supply sources (de Oliveira Fernandes, et al., 2011). For that reason, it is encouraging to have a heterogeneous energy use across all households and community services (Ruijven, et al., 2011). According to Joshi et al. the main end-uses in isolated South Asian areas are cooking and irrigation, followed by electricity for lighting and water pumping (Joshi, 1992). Table 2-5 summarizes the different end-uses by sectors that are expected to be covered within a minimum energy access calculation.

Table 2-5: Energy end-uses by sector

End-use/sector	Households	Service - education	Service - health center	Service - community center	Small businesses	Street lighting	Agriculture
Cooking	✓						
Domestic hot water	✓	✓	✓				
Ambient heating	✓	✓	✓				
Ambient cooling	✓	✓	✓				
Refrigeration	✓		✓				
Lighting	✓	✓	✓	✓	✓	✓	
ICT	✓	✓	✓	✓	✓		
Water pumping	✓	✓	✓	✓			✓
Mechanical power							✓

Depending on the sector there are different end-use requirements. At the proposed village community level sectors can be clustered in households, community activities (education, health center, communication center and street lighting) and productivity activities (small businesses and agriculture). There are generally 9 end-use services: cooking, domestic hot water, ambient heating, ambient cooling, refrigeration, lighting, ICT (is sub-divided in radio, telecommunication, TV, computer, copy machines, modem and satellite dish as well as other small electrical devices), water pumping and mechanical power. Other end-uses, mainly for comfort and hygiene (e.g. sewage system or sanitary facilities) are not considered at this stage. Households are usually the biggest energy consumers within isolated communities. According to Narula et al. the dominant end-use is cooking. At the same time space heating and cooling are barely applicable (Narula, Nagai, & Pauchari, 2012).

The following paragraphs analyze the different end-uses in more detail to provide further information about the expected minimum requirements.

Energy for cooking in remote areas still dominates energy consumption (35-45% of the total energy demand) (Pachauri, 2007). Bravo et al. quantify the household's average energy need for cooking and lighting in tropical areas such as South Asia with around 0.92 koe per capita per day (Bravo, Mendoza, Legisa, Suárez, & Zyngierman, 1983). Goldemberg´s interpretation estimates around 1.07 koe per capita per day (Goldemberg, 1990). A third interpretation by Khandkar et al. foresees 0.64 koe per household per day (Khandkar, Barnes, & Samad, 2010). Within the households the share of cooking is as high as 80+% (Purohit, Kumar, Rana, & Kandpal, 2002).Most cooking appliances use traditional fuels that have no monetary cost for the user; they are neither concerned about health affects nor comfort (Ramji, Soni, Sehjpal, Das, & Singh, 2012). The shares of fuels for cooking, for instance in India, are given as: firewood (59%), dung (20%), agricultural resides (14%), kerosene and LPG (5.2%) and other (1.8%) (TERI, 1993). The technologies in use are very simple and mostly require no appropriate preparation of resources. Efficiencies are commonly around 10-15% (Jetter, et al., 2012). Consequently, there are many other combustion fuels along with more efficient and cleaner devices that could substitute the current devices (i.e. via support mechanisms and incentives). This would not only reduce (indoor) air pollution (Parikh, 2011), but also prevent a further deforestation in these areas (Foell, Pachauri, Spreng, & Zerriffi, 2011), (Joon, Chandra, & Bhattacharya, 2009). It has been stated by the World Health Organization that *"energy-efficient biomass and gas cook stoves can help avert a large proportion of chronic obstructive pulmonary disease (COPD) in poor countries"* (WHO, 2011). Moreover, the WHO report highlights that from solid fuel caused indoor pollutants are associated to the death of around 662,000 people per year in South Asia (Legros, Havet, Bruce, & Bonjour, 2009), (Mehta & Shahpar, 2004).

Energy for illumination is the main concern of households without electricity. Lighting would be required for a variety of purposes, but especially to extent working hours beyond the availability of day light. Simultaneously, it would give the younger generation a chance to study. Since during the day most households cannot omit the workforce of the youngest generation and women, having light at night might be their only chance for any proper education or having their own small business for additional income. Yet, illumination, if available, is often provided by kerosene lights and candles. Besides the costs for kerosene, this form of lighting is very dangerous and hazardous. In addition, the brightness of light – the lumen – is very low and therefore not sufficient for reading purposes (Khan & Abas, 2011). According to Practical Action the minimum standard for lighting should be at least 300 lumens at household level, which is equal to a typical incandescent bulb of 25 W (Practical Action, 2012). There are various high-efficient solutions available, such as solar – LED lighting or biogas lamps (Jones, Du, Gentry, Gur, & Mills, 2005) that can cover the lighting requirements with a lower power and also reduce the dangers of kerosene and candle light.

Figure 2-3: Use of Kerosene lamp and traditional dual cause indoor pollutant (Santos Perez, 2015)

Energy for information and communication technologies (ICT) includes a wide range of appliances such as TV, Radio, Computer, internet and telephones (Marker, McNamara, & Wallace, 2002). Typically, after lighting the next electricity need is for entertainment and communication (Pachauri, Urge-Vorsatz, & LaBelle, 2012). Based on this fact the energy consumption for TV and radio devices varies significantly[11]. There is no specific power defined

[11] The energy consumption is determined by 4 factors: on mode power, standby mode power, off power, share of time the equipment spends in each of the modes.

in the literature. Though, some studies list the demand requirements of radios with around 5 Watt, and that of televisions with 50-100 Watt (Varman, Mahlia, & Masjuki, 2006). As most users in isolated areas will buy second or even 'third hand' devices, the efficiencies of these devices are probably even lower than what the label of the devices indicates. Apart from radios, which are often powered by battery, and television which is only affordable by richer families or the community as a whole, there is a strong desire of low-income families, mainly men, to use mobile phones (International Development Association, 2009) (GSMA, 2010). Simple mobile phones usually have a power of not more than 10 W.

Energy for space heating is not a priority issue of habitants to be solved. In fact, most households in the mountainous areas of Asia use 70–80% of primary energy directly for cooking and 20–25% directly for space heating (Practical Action, 2010). However, as cooking systems are very inefficient, 60% of the energy for cooking contributes to heating, thus leaving only 40% for cooking itself (Hulscher, 1997). Moreover, it has been stated by the WHO that *"Insufficient natural ventilation is associated with higher risk of airborne disease transmission, dampness and accumulation of indoor pollutants that are risk factors for allergies and asthma"* (WHO, 2011). For space cooling, especially in the warmer South Asian regions, only natural and passive cooling systems are used. These include shading, but also the construction of houses with natural air flows. In other words, additional energy devices are uncommon to achieve cooler temperatures. The architecture of houses is simple and small - basically in hamlet style (Narula, Nagai, & Pauchari, 2012). In terms of construction, most of the individual houses in isolated communities are made of simple, natural and locally available materials, such as wood, bamboo, mud, clay, self-made bricks etc., without concerning the use of a passive design (Mrema, Gumbe, Chepete, & Aqullo, 2011) (Mathur & Goel, 2000). Nonetheless, Practical Action defines the required daytime indoor temperature in the range of 12-30 degree Celsius (Practical Action, 2010). Subsequently, higher or lower temperatures should be accounted for through the necessity of cooling and heating days.

Energy for cooling appliances or refrigeration, i.e. preservation of food or medicine, are barely available for houses, medical centers, schools, etc. According to (GSMA, 2010), 830 million people in developing regions are undernourished. One of the main reasons is the lack of food preservation facilities. However, low capacity refrigerators (100 W), but also intermediate technologies in the form of pot-in-pot or zeer pot devices could change this situation considerably.

Energy for water pumping is one of the most important prerequisites for any rural development to guarantee water supply for humans, livestock, irrigation and the community in overall. In most cases the energy requirements for using water are fulfilled with man and animal power. If the water cannot be covered from surface reservoirs, mechanical power is required to pump water from a well or underground reservoir. In such cases intermediate technologies such as vane-flapping turbines represent a great and easily deployable option. In the end, it is of utmost importance to have access to clean and sufficient water and also adopt conditions to purify, distribute, pump, desalinate and elevate water in the village. At the household level it is expected to have around 5 liters of water per capita per day (G8, 2001).

The energy demand for community activities is rather small. Indeed, most communities do not have many public services. The most common services are usually a school, a medical center, a religious center or a social community center where people can gather throughout the day or in the evenings. Consequently, the energy requirements are generally characterized by electricity for lighting, refrigeration (medicine) and ICT. In contrary to the household level these electrical end-uses are more essential, especially as these services are required by the whole community. In a study undertaken by USAID the energy demand for a primary school with 100 students was assessed with 5 kWh/day (1,825 kWh/year) (157 koe/year) respectively. For health centers similar demand requirements are expected for an according community size, while community centers require noticeably less (USAID, 2002). In addition to the public services there is usually some small demand for public (street) illumination.

Energy needs for productivity activities are subject to the local conditions of a village and the availability of farmland, livestock and agricultural activities (FAO, 2009), (GIZ, 2011). Productivity activities might include graining, grinding or crushing. Each of these processes can either use mechanical power (humans or animals) or energy in the form of a diesel-powered system. Lastly, small local businesses require energy; especially lighting and ICT. Lighting would be of particular interest as opening hours of stores could be extended – and so could income.

The review on energy demand requirements by end-use and sector highlights the difficulties in defining appropriate levels for minimum energy access. It is a challenge by itself to associate demand requirements for each end-use, since there are several factors that need to be taken into account.

- Conflict between devices to be used. This is especially a challenge for cooking, water heating and space heating, since many devices (e.g. open food fire) may be used for more than one of the three end-uses.

- There are many different end-use devices. They all differ significantly in their demand requirements because of the varying efficiencies and the way they are used.
- In addition to the efficiency it is also of concern how long end-use devices are actually being used. The time of use is a crucial element in the definition of minimum requirements, since an over-use may fulfill the minimum requirements but waste a lot of valuable resources.
- "*Cultural practices, climatic conditions, social customs, subjective wants, and so on*" have all a major influence on the energy, which additionally also vary by country and region (He & Reiner, 2014).

Yet, there is neither a standard definition for the efficiency devices should have nor an indication for the standard hours of daily use. Since the energy for services and end-use devices is related to one another, discrepancies in the definition of the minimum energy requirements occur throughout the literature. While for households the requirements can be expressed on a per capita basis, for community and productivity activities a justification of minimum energy access values becomes more demanding. Subsequently, the methodological framework in Chapter 3 will take into consideration various aspects of minimum energy requirements by end-use and sector.

2.4. Potential supply technologies and end-use devices

The understanding and perception of the term technology has changed radically since the mid-20th century. Nowadays, almost all technology concepts used until then are considered as traditional. They were then complemented and/or replaced by intermediate technologies in the 1960's. The succeeding current technologies and concepts are referred to as appropriate or advanced ones and also include most renewable energy solutions. This clustering of technologies is particularly interesting since the immediate use of renewable energy solutions is proposed frequently to cover the electrical needs in isolated communities. Yet, the highest consumption occurs for thermal purposes.

While most South Asian governments defined a target for electricity access (e.g. India: 56% in 2006 and 67% in 2009), they did not define a target for modern fuel access (Bhattacharyya, 2006). Moreover, evaluations of various studies indicate market failures for using renewables (Cherni J. , et al., 2007), (Kruger, 2007) due to several reasons: i.e. lack of maintenance and spare parts (no local people were trained for maintenance); misallocation of investments, leading to inappropriate infrastructure (Van Beeck, 2003); inappropriate size of the system based on the resource potential; lack of knowledge of decision makers for near future grid connection (Dorji, Urmee, & Jennings, 2012); divergence of interests between different actors involved; perception of quality of life; lack of infrastructure service and knowledge about the technology capacity; or the inappropriateness of successfully applying the concept of solution to other places (Morgenstern, 2002). Bhattacharyya presents the unlikeliness of solving the energy access problem when considering electrification only, due to low penetration levels of electricity in the energy mix of the poor communities (Bhattacharyya, 2006). Besides, the Prayas Energy Group raises concerns related to the reliability of supply (Prayas Energy Group, 2011).

Despite all Trappey et al. emphasize that renewable energy solutions can be successfully adopted, when they are proposed with sufficient educational, technical and financial support (Trappey, Trappey, Lin, & Chang, 2012).

Consequently, exploring energy solutions for isolated communities in developing countries still is very thought-provoking. This is in particular due to the paucity of data and the variety of external factors that are linked with the energy system. Some organizations and research institutes such as ESMAP and Practical Actions are already on track of a concept for total energy access of an isolated ecosystem (Practical Action, 2012). However, it is essential to bear in mind the characteristics of end-use devices across all end-uses and sectors when selecting possible supply technologies.

In order to give an overview of the different useful energy services and devices as well as the resources they are commonly supplied with in isolated communities, it can be referred to Table 2-6. Households and community activities are grouped together and the most important resources for productivity activities are also summarized.

Table 2-6: Current resource of end-use devices by service and sector

Currently used supply resources	**Useful energy service**	**Households and community activities**	**Productivity activities**
		End-use device	
Wood, dung, coal, paraffin, agriculture waste	Cooking	Open fire Stove	N/A
Kerosene, candle wax	Illumination	Lantern	
Electricity from diesel	ICT	Mainly radio, phone or TV	
Wood, passive	Space heating / cooling	Natural building design; open fire	
Passive, Isolation	Food preservation	Pot in pot	N/A
Diesel, human and animal power	Mechanical processes	Grinding, Chopping	Motors
Diesel, human and animal power	Water requirement	Pulling water from well	Pump

According to the literature review the most popular end-use devices are the ones with low efficiency rates that also cause an overall low quality of life (Reddy, 2003), (Hiremath, Shikha,

& Ravindranath, 2007). The most common supply resources locally available for heating systems are wood and dung as well as some imported diesel and kerosene. In some cases, local hydro resources are also being used (UNDP and World Health Organization, 2009). Most other renewable energy resources are abundant but not yet explored (WEC, 2000). The literature review on supply alternatives also indicates a considerable lack of energy solutions and planning at community and block level (administrative division of some South Asian countries) (Hiremath, Shikha, & Ravindranath, 2007).

It is important to emphasize that at the community level the difference between energy sources and energy carriers is hard to distinguish, since the connection between the primary resource, final energy and end-use is not as clear as in a regular energy network. Figure 2-4 presents the dynamic interplay between energy sources, energy carriers and energy end-uses. Along the energy supply chain, it is necessary that sources and carriers are accessible, available and locally accepted (IPCC, 2007).

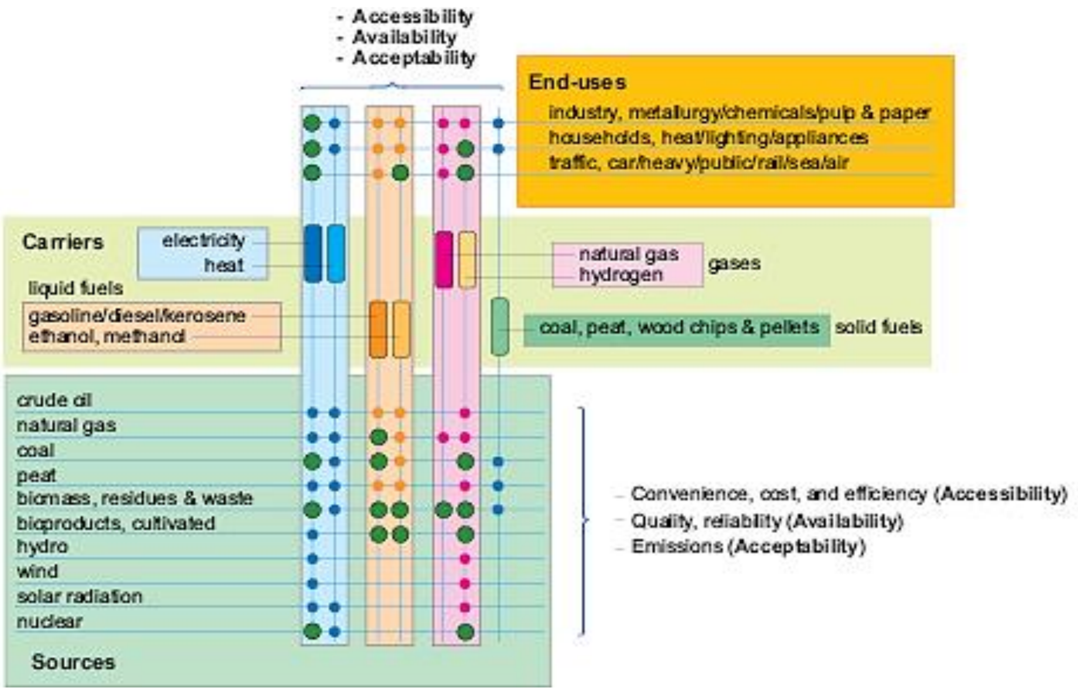

Figure 2-4: Dynamic interplay between energy sources, energy carriers and energy end-uses (IPCC, 2007)

In order to cover the various end-uses, the following sections explore different supply possibilities for isolated communities. Thereby, it is divided in, intermediate and improved technologies, decentralized energy systems which can be either distributed or dispersed generation systems (stand alone or off-grid system).

1) Intermediate and improved technologies

Intermediate and improved technologies were an initiative to provide solutions that facilitate the use of energy from the Stone Age. In 1960 Ernst Friedrich Schumacher introduced the concept of intermediate technologies which held the ability to be developed and maintained locally and represent an appropriate solution when it is expensive to make use of larger-scale energy technologies. Indeed, intermediate technologies are more affordable and can be more localized. These types of technologies reduce the dependency on fossil fuel imports and mineral resources, they are clean and do not pollute or poison the environment, they consider people over profit, and they are low- to medium cost as well as labor-intensive (Wicklein, 1998), (Varma, 2003). Lastly, these technologies shift the energy capability from traditional (low) towards intermediate access. Table 2-7 provides an overview of the most common intermediate and improved technologies by end-use.

Table 2-7: Selected intermediate and improved technologies by service

End-use service	Intermediate/improved technologies
Lighting	High efficiency lamps
Cooking	Improved cook stove with chimney, Angi, Udairaj, Laxmi, chulha
Drying	Solar fish dryer
Cooling reserve	Pot-in pot evaporative, Zeer pot, LPG, diesel refrigerator
Ventilation	Fan, passive use via structure of building
Production activity	Organic waste-fishpond green house, Co-products of sugar cane composting, brick press, lever oil press, ram press (D-Lab: Development, 2009)
Water pumping	Vane-flapping wind converter, Choti bijli (Diesel genset) (Palit & Chaurey, 2011) Vertical axis sail wind converter, flap valve pump, solar pump
Irrigation	Treadle pump
Desalination	Solar desalination
Purification water	Solar water Distillator, Sari cloth filter (D-Lab: Development, 2009)
Multi-functional platform	Mechanical and electrical energy generator from diesel or biodiesel (GENI, 2016)

Improved cook stoves (usually have a 40% efficiency (Practical Action, 2010)) are devices to replace traditional technologies such as open fire[12] (Figure 2-5) (Mwalenga, 2012). Solar cookers can also be well-planned options. Replacing the old system will cause a reduction of the time required for fuel gathering and enlarge efficiency, comfortability and better indoor air quality (MacCarty, 2010) (GEA, 2012).

For a better acceptance of habitants Dutta found that decision making processes for cooking and other services are divided between women and men. Men decide the location, and anything that deals with monetary factors (Dutta, 1997). Women decide on the type of devices and non-monetary matters such as fuels and food (Shanker, Onyura, & and Alderman, 2015). If the resource is by product from agriculture collection or requires transportation men will also participate. Hence, there is much evidence about the failure in projects when changing the cooking system in South Asia because of not considering adoption and acceptance (Jeuland, 2012) besides the participation of rural habitants and communities (Anderson & Doig, 2000), (Malhotra, Neudoerffer, & Dutta, 2004). When changing the behavior to consume modern fuels,

[12] Open fire is and has been used for multiple purposes: flame of fire for lighting and entertainment; heat for cooking, space heating, drying food and material; smoke to prevent mosquitoes, etc.

it is indispensable to consider the external biophysical environment, external socio-economic environment with internal effects on households (Van der Kroon, Brouwer, & van Beukering, 2013). The broadly varying energy requirements for cooking with different devices is analyzed by Sanchez (Sanchez, 2010)[13].

Figure 2-5: Types of cook stove technologies (Mwalenga, 2012)

[13] Minimum cooking requirements presented by Practical Action: To have at least 1kg wood fuel/0,3 kg charcoal/0,04 LPG or 0,2 kerosene or ethanol per capita per day, time for access to fuel should be less than 30 minutes per households per day, particulate matter consideration to be annually less than $(PM)<10\mu g/m^3$ in households (Sanchez, 2010).

Improved illumination devices replace fluorescent lamps with compact fluorescent lamps and eventually light-emitting diodes (LEDs). Jones et al. compared the performance and cost of non-grid connected illumination options and looked into alternatives to fuel-based lighting in rural China. Many poor households use kerosene-based lanterns or candles that have extremely low efficiency and luminosity and also are much more expensive compared to the same amount of light provided from electricity or solar lantern (Jones, Du, Gentry, Gur, & Mills, 2005). Plus, kerosene causes severe indoor air pollution (Muller & Diab, 2003). In order to present the magnitude of using efficient lighting it may be referred to Deshmukh et al. who claims that by managing efficient lighting services for 70 million households in India the annual kerosene consumption can be reduced by 3,600 million liters (Deshmukh, Gambhir, & Sant, 2010).

Improved cooling services for nourishment and medicine might be covered with three types of technologies: passive cooling systems, increased efficiency and mechanical compression. Passive cooling systems generate a temperature between 10-25°C. The benefit of this solution is the omission of fuel or electricity as well as its low cost (i.e. Zeer pot). An increased efficiency and comfort level can be achieved via sorption refrigerators that generate cooling services from gas or kerosene. Lastly, modern technologies use mechanical compression to generate temperatures below 10°C. Therefore, electricity is required. The concept can be used for medicine, vaccine, nourishments, blood storage, business use such as dairy products, retail trades for fresh meat or fruits, etc. (EUFIC (European Food Information Council), 2016).

2) Decentralized energy systems

Decentralized generation systems are usually installed at or near the point of use. This reduces capital investments – mainly for networks – but also transmission losses. Decentralized generation systems can be either distributed or dispersed depending on the scale and connection to the network. The drivers for the use of decentralized systems are usually the lower cost of electricity, the geographical factors such as the existence of transmission congestion, savings on outage cost, among others. In the case of isolated communities these concerns are of minor interest (Balaji, 2004). While there may be potential to have local resource availability and to implement decentralized generation systems, they are unlikely to be connected to the network. Subsequently, these considerations are not within the scope of this research.

In 2013 Navigant Research estimated a total global microgrid capacity of 3,793 MW (Navigant Research, 2013). Though only 20% of this capacity is believed to correspond to remote systems, where microgrids are typically of (very) small capacity. However, Schnizter et al.

suggest that this percentage may be higher if the breakdown was in terms of number of systems (Schnitzer, et al., 2014).

As such, stand-alone (off-grid) systems offer added value to supply the energy requirements in isolated communities. Hitherto, studies dealing with the optimum energy mix with locally available resources are scarce (Hiremath, Kumar, Balachandra, & Ravindranath, 2011), (Narula, Nagai, & Pauchari, 2012). While in cases with smooth demand patterns small individual stand-alone systems can be proper alternatives, in cases with concentrated demand and more commercial loads larger scale stand-alone systems (basically micro grids) would be the better choice (ESMAP, 2011). Vivian's research tries to summarize notable microgrid projects and developers (Vivian, 2016). An overview of common stand-alone (off-grid) supply systems at community level is then put together in Table 2-8.

Table 2-8: Selected stand-alone (off-grid) supply systems applied at community level

Resource	Electricity generation	Thermal generation
Solar	Micro grid PV	Solar thermal
Wind	Small wind turbines (SWT)	
Biomass	Biogas digester system	Biogas digester system
	Biogas from Husk Power	Biogas from Husk Power
	Biomass gasification	Biomass gasification
Diesel	Micro generators	
Gas	Micro generators	Micro generators
Hydro	Macro & Pico Hydro	
Hybrid	Electricity hybrid system	Thermal Hybrid system
	Electricity- Thermal hybrid	

For the selection of possible supply technologies many factors have to be considered: e.g. income level of consumer, ease of maintenance, social acceptance or technology adoption and adaptation to climate change (Kemmler, 2006). Nouni et al. and Ruijven et al. compared many techno-economic renewable technologies (Nouni, Mullick, & Kandpal, 2005), (Ruijven, et al., 2011). They studied different pilot cases of PV projects in India and found that the levelized unit cost of electricity for appliances of 1-25 kWp varies between 28.31 and 59.16 INR/kWh[14] (0.5-1.0 €/kWh). This means that without financial incentives solutions for users will not be attractive. The annual electrical power output of 1 kWp typically varies between 1,075-1,600 kWh depending on the location. In terms of annual delivered electrical power, remote locations in the West and North of India are more attractive than most other areas (Nouni, Mullick, & Kandpal, 2006a). For micro-hydro projects in remote areas Nouni et al. assessed the cost range with 2,670 to 5,010 $/kW (2.120-3.980 €/kW)[15]. The capital costs show some economy of scale mainly for capacities between 10-100 kW. Though, the financial viability of micro-hydro

[14] In 2006 the exchange rate for 1 Euro was around 56 Indian Rupees (https://www.statista.com/statistics/412830/euro-to-indian-rupee-average-annual-exchange-rate/).
[15] The US$-Euro exchange rate in 2006 was $1,26 is equal to 1 €. (https://www.statista.com/statistics/412794/euro-to-u-s-dollar-annual-average-exchange-rate/)

projects is critically dependent on the plants load factor (Nouni, Mullick, & Kandpal, 2005) (Nouni, Mullick, & Kandpal, 2006b). Small wind generator projects can be financially attractive, but only when they are supported by at least 20% of the capital cost. For such projects the levelized unit cost of electricity varies between 4.67 and 83.03 INR/kWh (0.08-1.48 €/kWh), while the evaluated capacity range was between 3.2-50 kW. The considered annual mean wind speed was 5-10 m/s and the annual electrical power output for a 1 kWp project was assessed with 765-1,770 kWh (Nouni, Mullick, & Kandpal, 2007a).

Monitoring and Reporting Regulation from the European Commission define *"Biomass means the biodegradable fraction of products, waste and residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the bio degradable fraction of industrial and municipal waste; it includes bio liquids and biofuels"* (European Commission, 2012). The production of biomass in rural areas is dependent on the resource availability. In the study of Nouni et al. the techno-economic aspects of biomass gasifiers for remote areas in India are evaluated (Nouni, Mullick, & Kandpal, 2007b). Levelized costs are expected in the range of 13.14 to 24.49 INR/kWh (0.23-0.44 €/kWh). However, with lower loads the generation price increases significantly. Lastly, the study found that in certain cases it might be more attractive to operate two systems of lower capacity rather than one with a large capacity.

Biogas is an anaerobic biological process. The gas that is generated is a mixture of methane, carbon dioxide, and partially oxygen, and nitrogen. The most popular biogas plant which is installed in rural areas is the fixed dome plant type. A biogas plant of 2-4 m^3 can supply a household with 4-6 members with sufficient gas for cooking and lighting. The life time of the biogas plants is up to 15 years. For such a project the cost per m^3 is about 2.500-4.833 INR[16] (37-71 €) (Riek, Ruker, Schall, & Uhlig, 2012).

Another calculation was made for comparing the financial attractiveness between a grid extension and implementing an off-grid system (micro-hydro, dual fuel biomass gasifiers system, small wind electric generators and photovoltaic) in remote areas of India (~20 households; peak load of 5 kW and load factor of 0.2). Micro-hydro systems for hilly areas were identified as best choice. Dual fuel biomass gasifiers came second for up to 75 households and small wind and PV will be the last options for areas of 20 or less households (Nouni, Mullick, & Kandpal, 2008), (Nouni, Mullick, & Kandpal, 2009).

[16] In 2012 the exchange rate for 1 Euro was around 68 Indian Rupees (https://www.statista.com/statistics/412830/euro-to-indian-rupee-average-annual-exchange-rate/).

The above studies have highlighted the value of having an off-grid system rather than a grid extension. However, if there is not enough financial support for an off-grid system, intermediate technology and micro or pico systems from renewables or conventional energies should be considered. In the end, the objective must be the achievement of sustainable plans, where a diversity of aspects, including technical feasibility, social acceptance, environmental impact, etc. are considered.

Based on the demand and the geographic availability of resources, there are many possible options for small off-grid systems (up to a few 100 kW) based on renewable sources. In Table 2-9 a selection of the technologies that can be applied at community level is presented (Alliance for Rural Electrification, 2011).

Table 2-9: Selected off-grid renewable energy technologies applied at community level (Alliance for Rural Electrification, 2011)

	Electricity	Thermal	Production activities
Solar	Portable devices (Solar Tuki) Pico PV system (PPS) Classical solar home sys. (SHS) Solar residential sys. (SRS) Productive sys.	Passive system Thermal collectors Concentrated solar thermal Solar Cooker Solar Refrigeration	Solar Gur production Soap, Candle production, Boiling production Distillation use
Wind	Small wind turbines (SWT)	Passive use	See intermediate technologies
Biomass	Biogas from Husk Power Biomass gasification	Biogas digester Sys. Biolite home stove	
Hydro	Mini & Pico Hydro		Milling, Pressing, Cutting, Spinning, Flouring.
Geothermal		Ground source heat pump	
Hybrid	Electricity-electricity system	Thermal-Thermal system	

A more detailed review by Paleta et al. highlights that each renewable energy system has its strengths and weaknesses (Paleta, Pina, & Silva, 2012). USAID analyzed the changes from an economic point of view; mainly the operational cost that will be altered through the size of the system (USAID, 2002). Consequently, it is necessary for any energy solution to assess the technical size of each supply option that wants to correspond to the partial/overall demand. Nonetheless, for a sustainable solution it is necessary to assess all aspects (including environmental and social ones) and not only the techno-economic ones (Paleta, Pina, & Silva, 2012), since frequently off-grid projects have failed for minor reasons for either oversizing of the system which leads to excess expenses and a highly undesirable resource constrained setting or undersizing of the system which leads to customer frustration. In the end, both reasons increase the likelihood of failure for micro-grid projects, so that adequate planning, including the consideration of pico and dispersed systems, becomes essential for a successful deployment. Likewise, the local resource availability, and the influence of decision makers on the same, has to be accounted for, i.e. potential imports of fossil fuels provide a variety of supply alternatives.

2.5. Energy planning and modeling

Energy planning and modeling has undertaken massive changes over the decades. Basically, from the late 80's and early 90's onwards different methods, models and tools have been developed. However, as time passed everything became more complex and newer or advanced features/updates had to be considered or integrated.

The wide spectrum of features that can be considered in energy models is shown in Figure 2-6. The schematic illustrates the relations between different energy model characterizations (Neshat, Amin-Nezari, & Danesh, 2014). While some features need to be clearly separated in models, for instance it must be decided if a normative or descriptive approach is chosen or if the model aims to make predictions, forecasting, exploring or back-casting, other models can include multiple characteristics within a single model, where focus can be placed on all geographical scales or various time horizons. As a matter of fact, the model complexity increases with the number of features considered. Hence, decision makers and energy planners need to have a clear definition of what they actually aim for. There are substantial differences in choosing a bottom-up or top-down approach, but when making plans for a local community, for instance in a remote area, then bottom-up approaches are more suitable since they take into consideration the local conditions. Contrarywise, weather or climate models work better with large scale geographical coverage, unless there are local or regional areas with very distinct and/or uncommon characteristics.

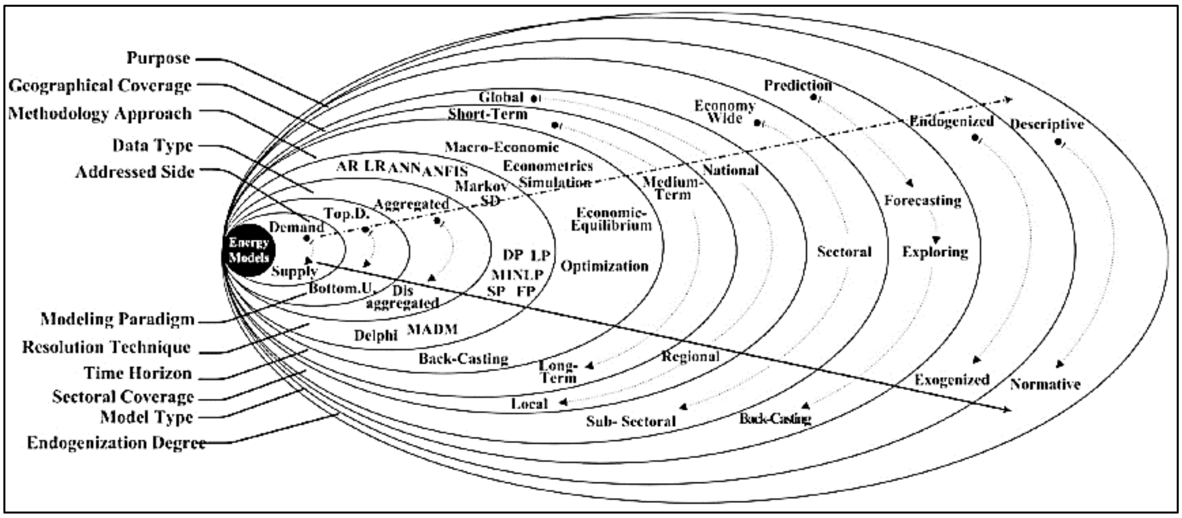

Figure 2-6: Schematic diagram of relations between different ways of energy model characterization (Neshat, Amin-Nezari, & Danesh, 2014)

As the core of this research relies on proposing options to increase energy access, energy planning and modeling tools have been reviewed extensively to assess what type of models and tools are available and consider the research theme (see Appendix 8.1). Tools are divided by category in energy accounting tools, simulation tools, optimization tools, externalities and

environmental impact calculation tools, databases, advanced local energy planning tools and tools under development. Then the name of the tool, the model type, a small description, the goal and scale are analyzed. Lastly, evaluations were made on whether or not the modeling tools include considerations of electrification or energy access.
By the time of this review (2013 and early 2014) more than 170 modeling tools were identified and analyzed. Yet, this only represents a selection. It can be expected that the number is noticeably higher today and that updates and extensions of various modeling tools have been released since then.

The most relevant energy planning and modelling tools for this research have been summarized in Table 2-10. In addition to the analysis undertaken in Appendix 8.1, further emphasis has then been placed on the aspects of energy access and electrification. Therefore, each of the tools has been thoroughly investigated for a better understanding of the tool specifications, data requirements, inputs, expected applicants and modelling paradigm.

Some of the tools offer thought-provoking considerations for energy planning in isolated communities. Yet, none of the tools defines the minimum energy requirements as the goal that should be achieved within the planning process. Besides, there is very limited focus on bottom-up approaches in isolated rural communities of developing countries.

Table 2-10: Selected planning and modeling tools dealing with energy access

Tool	Description
ENACT **(IIASA, 2012)**	The tool aids decision makers to assess future policy choices and to evaluate the effectiveness of meeting the universal energy access goals by 2030. Major application is aimed at policy advise, whereas costs and benefits of policy choices are visualized.
Energy Costing Tool/ MDG Assessment **(UNDP, 2006)**, **(UNDP, 2010)**	The Energy Costing Tool/MDG Assessment tool estimates the amount and type of energy investments needed to meet the MDGs. The tool identifies interventions to expand energy access. Thereby, national based MDG targets can be defined. The tool will analyze if the MDGs can be reached under the current constraints or what would be needed to achieve the MDGs. The tool is aimed at government planners and decision makers to develop strategies that meet the defined targets through a top-down national approach. The Energy Costing Tool and MDG Assessment tool complement one another.
HEAT **(ESMAP, 2010)**	The Hands-on Energy Adaption Toolkit is an online resource; an interactive and analytical framework and support tool. Assesses climate risks and vulnerabilities in a country’s energy sector and provides options for managing, monitoring and evaluating the risks.
HOMER **(HOMER Energy, 2009)**	HOMER optimizes microgrid designs across all sectors, ranging from remote communities or islands to grid-connected areas. In addition to all the economic aspects, the software also takes into account a variety of technical aspects. Development over the years led to the inclusion of further technologies and different storage systems. While the software may be complex, it provides a detailed overview on the matching of demand and supply.
I-PLACE³S **(Czachorski, Silvis, Barkalow, Spiegel, & Coldwell., 2008)**	The Internet-based Planning for Community Energy, Economic and Environmental Sustainability modelling tool calculates the energy use of development scenarios, taking into account the consumption of building types and land uses, distributed generation technologies and energy efficiency measures in buildings. The tool compares energy use and related emissions for scenarios.

Table 2-10 continued

Tool	Description
MARKEL/TIMES **(Loulou, Goldstein, & Noble, 2004)**, **(Howells, Alfstad, Victor, Goldstein, & Remme, 2003)**	Computational energy model that is applied in non-electrified low income rural communities in South Africa. Depicts all energy flows from resource to end-use. It is rich in technical details and evaluates periods of 20 to 100 years includes the entire geographical coverage.
MESSAGE **(Schrattenholzer, 1981)** **(Messner & Schrattenholzer, 2000)**	A modelling framework for medium- to long-term energy system planning, which also includes policy analysis and scenario development. Assesses major energy challenges and identifies socioeconomic and technological response strategies. The specific MESSAGE-access tool evaluates the regional transitions to clean cooking fuels and electrification.
META – Model for Electricity Technology Assessments **(Chubu Electric Power Company, 2012)** ETOAG – Electricity Technology Options Assessment Guide **(Chubu Electric Power Company, 2012)**	Objective is to allow users to evaluate electricity technology options. The META is a dynamic tool, it is interactive and user-modifiable. Timeframes include a base year (for instance 2010) and projections for 2015 and 2020. Planning takes part on a country scale, where over 50 generation technologies, storage systems, transmission technologies and distribution technology are considered. Looks at off-grid, mini-grid and grid-connected technologies for renewable energy generation, thermal power generation and nuclear generation. While the tool has a default input data set, all inputs can be updated by the user. Also includes uncertainty analysis.
REM **(Urban, Benders, & Moll, 2009)**	Develops scenarios for rural electrification for the period 2005–2030 and to assesses the effects on greenhouse gas emissions, primary energy use and costs. It is a bottom-up simulation model and analyses a countries or regions demand and supply.
STATcompiler **(Rutstein & Rojas, 2006)**	Provides demographic and health surveys in a comprised and easily comparable online tool. The data base offers a range of information on different topics which form a valuable input for diverse research studies dealing with social-demographic subjects.
SURE **(Cherni, 2004)**, **(Cherni J. , et al., 2007)**	Explores optimal energy solutions for rural communities, taking into account their resource constraints. Combines technical information, non-technical criteria and participatory inputs. Designed for low income communities. Solutions aim to enhance livelihoods.

Despite the lack of planning tools for energy access, the interactive energy access tool ENACT of the International Institute for Applied Systems Analysis should be highlighted since it assists national decision makers in their strategic policy planning to improve energy access (IIASA, 2012). The tool estimates the amount of cooking that can be based on modern forms of energy in 2030 by taking into account the population and the share of useful cooking energy from kerosene, LPG and electricity. However, the tool is insufficient for decision makers and analysts to present sustainable energy solutions at local or community level since it follows a top-down approach.

The researches that are more in line with the herein proposed work are that of Howells et al. as well as Brent and Kruger. Howells et al. present a solution via a computational energy model (MARKAL/TIMES) that is applied in non-electrified low income rural communities in South Africa (Howells, Alfstad, Victor, Goldstein, & Remme, 2003), (Howells, Alfstad, Cross, Jeftha, & Goldstein, 2002). Some of the main differences that are included in their work are time-of-day load curves, storage devices and demand side management analysis (Brent & Kruger, 2009). Within the RESURL project the SURE tool has been established as multi-criteria decision aid modeling tool to be used for evaluating the performance of off-gird renewable energy alternatives for Sustainable Rural Livelihoods (Cherni J. , et al., 2007). Furthermore, Brent and Kruger integrated the SURE tool with an intermediate technologies framework while considering sustainable livelihoods. By integrating these two frameworks more robust and community-based implementation strategies may be formulated. The integrated model was achieved by applying the Delphi research methodology (Brent & Kruger, 2009). Other types of solutions are to increase energy access via dispersed systems or via intermediate technologies. Apart from Brent and Kruger no integration of renewables and intermediate technologies was found.

Particularly, the extensive review in Appendix 8.1 highlights that most of the modeling tools are focused on simulation and optimization. There has been also growing interest in environmental forecasting tools. For almost all categories there is a broad selection of modeling tools available, where most tools have an economic or techno-economic focus. Social or integrated approaches are rather rare. Likewise, only a small portion of tools deals with electrification(access) and energy access. In terms of application scale, there are tools available of all scales for each category. While there is generally a higher focus on top-down approaches – from a national perspective, there is also reasonable number of tools looking at the local and regional characteristics. Nonetheless, typical bottom-up approaches for planning at community level are very limited.

For a further overview on energy planning tools and additional segmentations and analysis it may also be referred to studies of Connolly et al., Manfren et al. and Pina (Connolly, Lund, Mathiesen, & Leahy, 2010), (Manfren, Caputo, & Costa, 2011), (Alves Pina, 2012). Another extensive characterization of 85 existing tools with focus on strategic planning, technology deployment and transition planning, innovation and R&D as well as international cooperation was undertaken by Amerighi et al. (Amerighi, Ciorba, & Tommasino, 2010).

Unlike planning and modeling tools, within the literature diverse solutions have been proposed to increase energy access from a methodological point of view. The most typical proposal is to consider the probability of extending the power grid and/or gas network. Though, it became clear from the previous sections, that these types of solutions are not yet achievable in many remote areas; mainly due to financial aspects. The second type of solution that is introduced by planners are decentralized renewable energy systems. Other solutions include off-grid energy systems or intermediate and improved technologies (Parshall, Pillai, Mohan, Sanoh, & Modi, 2009).

The alternative with the highest potential for a successful application depends highly on the financial possibilities and local characteristics. If available nearby, then the grid extension might be the easiest in terms of realization. With an increasing reliance on the local community, a successful implementation becomes more challenging, since a multitude of local conditions needs to be considered (e.g. social acceptance, adaptation, etc.).

Consequently, energy planning for remote and/or isolated communities requires a well-defined methodology that takes into account a diversity of aspects, starting from the evaluation and analysis, to the planning and, finally, proposal of options and solutions. For that reason, different methods and subsequently energy planning models may be required (Figure 2-7). Based on the objectives to be reached, energy planners should take into account the methods and planning models that best meet their requirements.

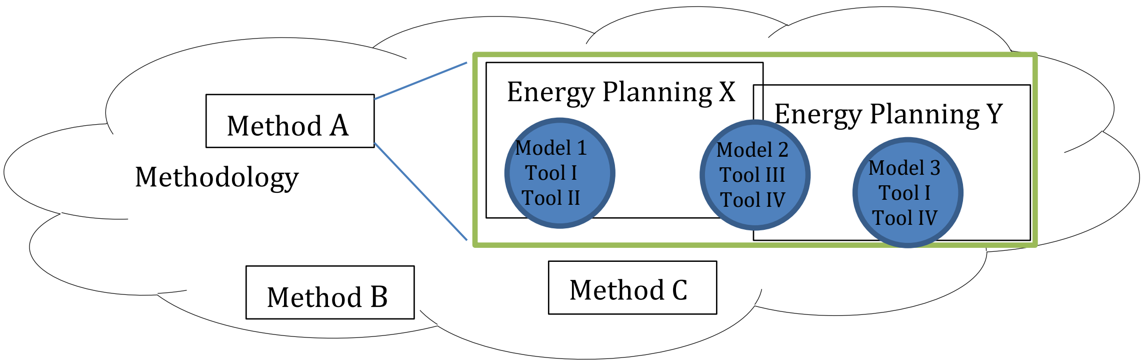

Figure 2-7: Method and energy planning model selection to meet the objectives

In order to consider those local specifications, field experience is compulsory. However, Sovacool notes that between 1999 and 2013 "*[m]ost studies are the result of work under-taken at the bench or desk using computer models and experiments, rather than field research, interviews and surveys*" (Sovacool B. , 2014). Yet, technocratic[17] and communicative planning into a transdisciplinary planning methodology will allow planners in India to incorporate techno-economic, socio-economic, socio-technical, social, political, and regulatory factors that influence rural electrification into a single comprehensive approach (Borofsky, 2015). For that interviews and surveys are highly recommended. The interviewee selection should be driven by the goal of capturing the viewpoints of a wide range of representatives of the various stakeholder groups engaged.

In reaction to the ongoing challenges faced by India's electric power sector, there has been a growing shift in focus (first among entrepreneurs, and now among government officials) to off-grid generation and distribution of electricity in unelectrified areas. In its optimistic *"Energy Access for All"* scenario, the International Energy Agency estimates that 70% of rural people worldwide will get access to electricity through off-grid electrification and 65% of those people

[17] Technocratic refers to a selected group of decision makers which is based on their area of expertise (e.g. scientific knowledge, local responsibilities, etc.)

will gain access via microgrids (WEO 2013). India is home to a substantial proportion of those people.

Critical factors for planning in rural electrifications include: tariff design, tariff collection mechanism, maintenance and contractor performance, theft management, demand growth, load limits, and local training and institution building (Schnitzer, et al., 2014).

2.6. Decision support system

Making decisions contains a variety of factors, constraints and components (UNEP, FAO, 2007), (Zhou, Ang, & Poh, 2006). Therefore, it is beneficial to use a knowledge-based system that might be also computer-based; i.e. Decision Support System (DSS). This will support the analysis of the decision steps in a more structural pathway (Druzdzel & Flynn, 2002). Multi-criteria decision aid (MCDA) methods can be applied within the DSS for problems with diverse aspects (Teghem, Delhaye, & Kunsch, 1989). A decision is defined as the choice of options among a number of alternatives. A decision support system (DSS) is capable of quickly responding and processing a problem and can be controlled by humans through value-focused thinking (Keeney, 1992), whereby decision makers must focus their initial thinking of a given decision situation on the value articulation rather than the identification of alternatives. For assessing the problem and collecting and verifying information, different model-based systems can be chosen (Bohanec, 2001). DSS incorporate both data and models. The system derives an answer by taking inputs from a user, combining it with information in the data store and then running an analytical or logical model on the data.

Even though decision support is a rather young research area, over the past 4 decades a diversity of multi-criteria decision aid techniques has been developed. Methods can be divided in non-compensatory and compensatory methods. The former *"do not allow tradeoffs between attributes"*, whereas the latter "allow tradeoffs" (Sun, Gollnick, Li, & Stumpf, 2014). Non-compensatory methods include conjunctive, maximin, maximax, amongst others. The most common compensatory methods are simple additive weighting (SAW), weighted product method (WPM), analytical hierarchy process (AHP), technique for order preference by similarity to identical solution (TOPSIS), compromise ranking method (VIKOR), preference ranking organization method for enrichment evaluation (PROMETHEE) (Gayatri & Chetan, 2013), elimination and choice translating reality (ELECTRE), multi-attribute value theory (MAVT), goal programming (Sun, Gollnick, Li, & Stumpf, 2014) or MACBETH (Bana e Costa, Ensslin, Corrêa, & Vansnik, 1999). In this research it is expected to develop a spread sheet-based Decision Support System through MAVT using Excel.

For designing any solution comprehensive assessment and defining relevant aspects are essential, especially for sustainable energy solutions for the future (Cherni J. , et al., 2007). As there is not necessarily one unique solution for a problem, MCDA can be used to find the most appropriate solutions.

There are many criteria to take into account when designing sustainable, robust medium and long-term solutions. As the analyzed areas have limited access to the rest of the world, it is reasonable to focus on self-sufficient solutions. The relevance of technology options depends on the context they will be applied to. This also concerns overlapping of and conflicts between end user devices. It has been demonstrated that habitants use, for example, the same stove to cover space heating, cooking, water heating and also lighting. A very comprehensive review of MCDA methods in energy planning was undertaken by Pohekar (Pohekar & Ramachandran, 2004). An integrated approach considering MCDA methods along with Geographic Information System (GIS) tools has been established by (Vagiona & Karanikolas, 2012). A summary of using MCDA for energy planning has been published by the author of this research (Wimmler, Hejazi, de Oliveira Fernandes, Moreira, & Connors, 2015). From the reviews done by Wang et al., Alessandro et al., Greco et al. and Loken it can be concluded that using MCDA for deriving sustainable energy decisions is appropriate and suitable (Wang, Jing, Zhang, & Zhao, 2009), (Alessandro, Michele, & Patrizia, 2014), (Løken, 2007). While there are many MCDA methods applied to energy solutions and planning (International Society on Multiple Criteria Decision Making, 2013), (Politidis, Haralambopoulos, Bruinsma, Vreeker, & Munda, 2005), it is necessary to highlight that many solutions for remote and isolated areas are based on renewable technology solutions (Abu Taha & Daim, 2011). However, the literature review revealed that there is a considerable lack of applying MCDA for integrated energy solutions and energy access at community level.

2.6.1. MCDA for energy solutions in isolated communities

Decision making processes involve a large number of actors with sometimes conflicting objectives (Figure 2-8). “Actors” such as individual households, communities, NGO´s, private investors and administrative authorities can influence the decision-making process directly or indirectly through their values, aspects, conditions and priorities. According to Georgopoulou et al. point of view actors can be classified into 5 main categories: decision makers, interveners (influence decision makers), passive actors (users), shadow actors (indirectly influence the whole decision process; i.e. government support) and intermediaries (increase knowledge and awareness) (Georgopoulou, Lalas, & Papagiannakis, 1997).

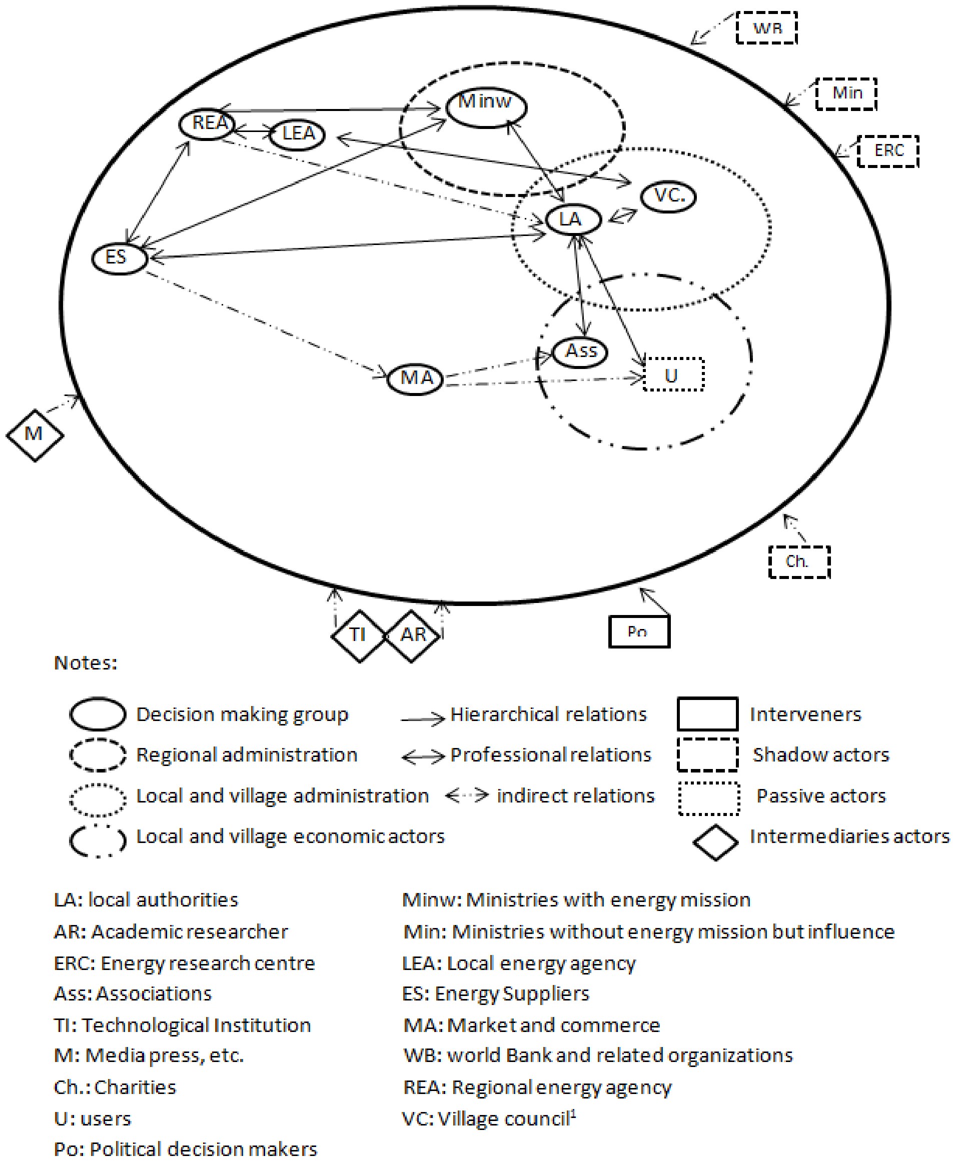

Figure 2-8: Author´s perspective on decision making processes in isolated communities (based on (Georgopoulou, Lalas, & Papagiannakis, 1997)

As many decision-making processes are based on local authorities, it is worth increasing awareness to get the proper support for an energy secure economy system[18] (OECD/IEA, 2011). The research also reveals that there is a difference between rural and urban decisions in terms of the willingness to pay (Bergmann, Colombo & Hanley, 2008), (Bergmann, Hanley & Wright, 2006), (Wiser, 2007). The social, economic, cultural and demographic factors have close relevance to the value of the decision for the energy system (Carlsson & Martinsson, 2008), (Hanley & Nevin, 1999), (Zografakis, et al., 2010).

[18] The financial sources may vary between multilateral organizations, bilateral official development assistance (ODA), developing country governments and private sectors. Based on the cases they use different financing instruments such as grants, equity, loans, insurance, subsidies or guarantees to support energy solutions (OECD/IEA, 2011).

In order to achieve sustainable solutions in research, political support should take into account policy prioritization frameworks that consist of secure energy, avoidance of air pollution, health and also climate change (Haydt, Leal & Dias, 2013), (Vuuren, Nakicenovic, Riahi, Brew-Hammond, & Nilsoon, 2012). It is valuable to study the investment needs for energy solutions in isolated areas and what type of policy mechanisms are available to support the decisions to become sustainable (Johansson, 2012).

The synergies between energy access and energy efficiency policies were revealed in (Urge-Vorsatz & Tirado-Herrero, 2012). Thereby, it became clear that by preventing the implementation of inefficient technologies, energy poverty can also be decreased. Trappey et al. illustrate the importance of supporting renewable energy and efficient technology solutions with policies. They have also tried to identify the local and national benefits from such policies (Trappey, Trappey, Lin, & Chang, 2012). Moreover, energy can be a catalyzer for sustainable livelihoods (Gupta, 2003). To be successful there are many barriers to overcome energy poverty in remote areas. This means that the basic needs of any act are the social structure and institutional framework which sustain any changes in these areas (Cherni & Hill, 2009), (Cherni, 2008), (Bellanca & Garside, 2013). Any solution, either from the upper or lower level, must be accepted by the users. Watts presents the integration of climate change resilience into local to national development thus considering the acceptance of stakeholders (Watts, 2012).

Another issue is related to the energy market, since market functions are frequently double tracked in isolated communities. First, the market structure is relying on the nature of supply which is different from source to source. Without adequate study of the market, any changes in the energy solutions in these areas will be prone to failure. Besides, there are informal market mechanisms to sell agricultural or animal waste to habitants that they do not have land or livestock to use their waste as an energy source (Mirza & Szirmai, 2010). Other challenges include the resource vulnerability or the preparedness of households to accept changes.

For any solution there will be some consequences and benefits that should be considered. Based on the level of the human decision in the process, the models are classified in analytical, simulation, gaming or operational exercise model. Close to real world problems can be conducted by implying more realism and cost and less abstraction and speed. At the same time human decision making must be part of the modeling process (Bradley, Hax, & Magnant, 1977).

The complex interactions in energy systems show the value of using MCDA to decrease the difficulty for decision makers via using qualitative and quantitative criteria in complex problems (Wang, Jing, Zhang, & Zhao, 2009). Roy defined multi-criteria decision aid is "*the activity of a person who, on the basis of models strictly explicit but not necessarily completely* *formalized, assists at obtaining the elements in order to answer the questions set by an inverter during a decision process*" (Roy, 1990). MCDA methods are tools designed to formalize the decision process in order to clarify the decisions and recommend, or simply favor, an alternative or a group of alternatives that reflect the decision makers' preferences. MCDA is based on different theoretical foundations such as optimization "*employ numerical scores to communicate the merit of one option in comparison to others on a single scale*" (Linkov, et al., 2004), goal aspiration "*Goal aspiration, reference level, or threshold models rely on establishing desirable or satisfactory levels of achievement for each criterion*" (Huang, Keisler, & Linkov, 2011), outranking "*compare the performance of two (or more) alternatives at a time, initially in terms of each criterion, to identify the extent to which a preference for one over the other can be asserted*" (Linkov, et al., 2004) or a combination of the beforementioned (Kahraman & Kaya, 2010), (Herva & Roca, 2013). As there are many multi-objective and multi-criteria methods established, decision support systems are meant to provide help in selecting the most appropriate methods for the problem (Teghem, Delhaye, & Kunsch, 1989).

The Department for Communities and Local Government highlights that "*In MCDA consistency of preferences is a virtue, and helps to ensure valid results. The initial assessment of scores often reveals inconsistencies, both within and between criteria. Several iterations may be needed until the key players feel that there is sufficient consistency in their preferences. The modelling process actually helps people to attain that goal; consistency is not required to start*" (Department for communities and local government, 2009). After selecting criteria the research tries to assess the provisional set of criteria and if it fulfils the requirements of: completeness (all main criteria in the value tree should be covered), redundancy (omit criteria that are unnecessary), operationally (each option can be judged against each criterion), double counting (omit giving extra score in the final decision), size (control the number of criteria to prevent extra analytical process and complexity) and time preferences in the process (Department for communities and local government, 2009). Besides the fact that most MCDA methods require the definition of criteria weights, Bouyssou highlighted the value of selecting precise evaluation criteria in MCDA approaches. From his point of view, they should be legible, operational, exhaustive, monotonic and not redundant (Bouyssou, 1990). To choose an appropriate MCDA method for a specific decision-making situation, the framework (Table 2-11) proposed by Guitouni and Martel can be applied (Guitouni & Martel, 1998).

Table 2-11: Requisite steps for MCDA method (Guitouni & Martel, 1998)

Problem Definition	The first step is to define what are important issues to be considered? (For example, in the proposed research it is the lack of energy solution plans that consider renewable and also intermediate technologies). In case one defines the purpose of the MCDA wrong, even an excellent analysis can result is a disastrous problem outcome.
Define decision makers and actors	In this step it is necessary to define who the decision makers are; both, first hand and second hand. Who are the stakeholders? As in many energy planning problems the government can play an important role, it is necessary to get familiar with the governmental structure. It would be helpful knowing control agencies, front line agencies, civil society pressure groups, public agencies, etc., In energy planning it might be appropriate to include the different interest groups in some or all stages of the project so that they can present their perspective on the issue.
Define Options	At this stage it is ideal to look at the advantages and disadvantages of selected options and compare pairs of options. Also, the creation of possible new options, that might be better than the original ones, should be considered. Score all options. Repeat the above steps until a 'requisite' model is obtained.
Define Objectives	Establish the decision context and then define the objective. The main Objective is to promote accessibility to every day facilities for all, to contribute to an efficient economy, and to support sustainable economic growth in appropriate locations, to promote the integration of all forms of energy and land use planning that lead to a better and more efficient energy system.
Define Criteria	There are broad types of measurements for different criteria: Monetary (based on CBA principles), Quantitative (impacts can be quantified) and Qualitative (where impacts cannot be quantified they will be assessed with qualified measurements). It is important to consider how to choose options and also criterion so that the performance can be measured or judged in practice. If there is a chance to define many criteria in the same issue, it is valuable to group the criteria. The main reasons are to clarify for the further research, which other possible criteria that can be used, to help the process and to check that the selected criteria are appropriate, easy to track, and give weight to each criterion.
Process	Define the expected performance of options via the defined criteria (Value function to translate a measure of achievement on the criterion into a value score on the 0-100 scale, liner or non- linear) The second approach to scoring performance on an interval scale is direct rating. This is used when a commonly agreed scale of measurement for the criterion in question does not exist, or where there is neither the time nor the resources to undertake the measurement. Combine the criteria and options in decision process to achieve overall value, examine the result, conduct the sensitivity analysis of the results to changes scores and weights, compromise the recommended solutions via sensitivity analysis to enhance the transparency of the procedure

2.6.2. Energy access indicators and criteria

In order to value the current situation and proposed solution, it is necessary to analyze the outcome, consequences and concerns by assessing the current situation and solution from a sustainable point of view (Ren, Gao, Zhou, & Nakagami, 2009). Therefore, different criteria and indicators should be defined (Afgan & Carvalho, 2008), (Shen, Lin, Li, & Yuan, 2010), (Singh R. , Murty, Gupta, & Dikshit, 2009).

Sustainable energy solutions are complex and seek multi-dimensional goals (Wang, Jing, Zhang, & Zhao, 2009), (Longden, Brammer, Bastin, & Cooper, 2007). For any comparative process it is necessary to use criteria or indicators to diagnose and monitor the process (Steelet, Carmelt, Cross, & Wilcox, 2008), (Neves & Leal, 2010). Bouyssou and also Roy define criterion as "tool" which allows comparing alternatives according to a particular "*significance axis or a point of view*" (Bouyssou, 1990), (Roy, 1985). The review of several criteria is shown in Table 2-12 according to (Wang, Jing, Zhang, & Zhao, 2009) and (Mattiussi, Rosano, & Simeoni, 2014). For better understanding the benefits of MCDA in energy decisions, it is a vital requirement to review the corresponding methods in the multi-criteria stages, such as criteria selection, criteria weighting, evaluation and final aggregation. The criteria are most frequently grouped in technical, social, environmental and economic aspects. Other groups also include resource, policy, energy or sustainability.

Table 2-12: Selected energy planning criteria for energy access

Aspect	Code	Criteria
Environmental	EN.01	Land use
	EN.02	Visual impact
	EN.03	CO_2 emission reduction
	EN.04	Emission Reduction (NO_x, SO_2, Particle)
	EN.05	New Construction needed
	EN.06	Reduction of damage on air quality
	EN.07	Reduction of damage on soil quality
	EN.08	Reduction of damage on Water quality
	EN.09	Biodiversity of flora and fauna
	EN.10	Reduction of impact of batteries
	EN.11	Need of waste disposal
	EN.12	Other
Social	SO.01	Reducing Vulnerability: noise
	SO.02	Reducing Vulnerability: pollutants
	SO.03	Reducing Vulnerability: disease
	SO.04	Social benefit: Markets increasing
	SO.05	Social Benefit: Livelihoods satisfaction
	SO.06	Social Benefit: Livelihood: employment
	SO.07	Social Benefit: Increasing awareness
	SO.08	Social Benefit: Democracy to choose
	SO.09	Social Benefit: support the commercialization
	SO.10	Social acceptability (availability, practicability, profitability)
	SO.11	Social adoptively (NIMBY issue[19])
	SO.12	Social acceptability and suitability of solution
	SO.13	Job Creation, increase local economy
	SO.14	Others
Technical	TC.01	Availability (lack of local technical capacity)
	TC.02	Reliability (continuity and predictability of performance)
	TC.03	Ease of use
	TC.04	Efficiency
	TC.05	Safety
	TC.06	Generation capacity
	TC.07	Lifespan
	TC.08	Technical assistance
	TC.09	Performance (quality control)
	TC.10	Exergy efficiency
	TC.11	Primary energy ratio
	TC.12	Maturity
	TC.13	Feasibility
	TC.14	The duration of preparation phase
	TC.15	The duration of implementation phase
	TC.16	Local technical know how
	TC.17	Exergy
	TC.18	Others

Aspect	Code	Criteria
Economic	EC.1	Investment cost
	EC.2	Fuel Cost
	EC.3	Electricity cost
	EC.4	Service life
	EC.5	Maintenance & operation cost
	EC.6	Net Present value
	EC.7	Payback period
	EC.8	Repayment cost
	EC.9	Refinancing periodic
	EC.10	Low consumer density
	EC.11	Equivalent annual cost
	EC.12	Cost benefit analysis
	EC.13	Internal rate of return
	EC.14	Present worth
	EC.15	Others
Resource of energy	RE.1	Amount of import to area
	RE.2	Potential to fulfill he need
	RE.3	Amount of electricity generate
	RE.4	Amount of heat generate
	RE.5	Proximity
	RE.6	Convenience of access
	RE.7	Availability (seasonal)
	RE.8	Energy market structure
	RE.9	Domain of one resource
	RE.10	Informal market mechanism
	RE.11	Other
Politics and policy	PO.01	Financial support mechanism (availability of fund)
	PO:02	Financial support mechanism (availability of subsidies)
	PO:03	Protection of specific solution
	PO.04	Risk of fail
	PO.05	Illegal Market Impact
	PO.06	Political acceptance
	PO.07	Compatibility with the national energy policy objectives
	PO.08	Effectiveness in society
	PO.09	Educational support mechanism
Sustainability	SU.01	Degree of acceptance
	SU.02	Poverty alleviation
	SU.03	Equity in affordability
	SU.04	Equity in accessibility
	SU.05	Success: efficacy
	SU.06	Effect on development

[19] Not in my backyard

As sustainable energy solutions are facing multiple criteria it is essential knowing the type of factors that should be considered and measured. Social criteria for instance are difficult to measure (Renn, Hampel, & Brukmajster, 2006). Consequently, professionals are obliged to define indicators that are capable of measuring the aspects. Meadows describes "*The role of indicator is to fulfill the social purpose of improving communication*" (Meadows, 1998). Energy measurements have an incorruptible global currency and unlike money do not need any converter (Pachauri & Spreng, 2011).

At the initial assessment stage of a given study/project case, but also after the implementation of proposed options or solutions – either in practical or theoretical terms – it is recommended to apply indicators for evaluation and/or validation purposes. Indicators are a widespread practice in the research development. Over the years a variety of indicators has been also developed to measure the degree of energy poverty in rural households. Yet, no universally excepted standard could be defined (He & Reiner, 2014). Likewise, indicators to measure the level of energy access are scarce. Consequently, a variety of indicators may be applied for evaluation purposes, whereas different expectations and conclusions can be drawn from the different indicators.

In order to distinguish the different types of indicators, some insights were gathered from the literature. Pachauri and Spreng have highlighted the importance to collect indicators that can capture commitment to a particular program to become more achievable (Pachauri & Spreng, 2011). Sometimes one indicator can attend to several attributes and on the other side many indicators are needed for a specific attribute. Based on the energy level, various elements can be determining factors for energy poverty (sustainable indicator, energy indicator, energy access indicator, etc.) (Hailu, 2012). Both, energy access and energy poverty have many dimensions that can be presented by single indicators, a set of individuals or composite indicators. The strengths and weaknesses of selected indicators are summarized in Table 2-13. In the end, it is up to the decision maker to select the indicator that best meets their requirements. Indeed, it needs to be clearly defined what shall be evaluated by means of an indicator. In that regard it is important to note that indicators can only have a meaningful evaluation if all the inputs can be made. If only parts of the indicator values cannot be provided, then results may be easily misleading, not to say incomplete.

The overview shows that all listed indicators for energy access and energy poverty were initiated by leading global organizations. Since in most cases no detailed information about the indicator inputs is presented, the composite indicators cannot be easily applied to isolated communities, where it is commonly a challenge to obtain/gather all the relevant input data. At the same time, a universal understanding of the terms and an ensuing definition could not yet be achieved. Subsequently, it still remains a challenge to define indicators that correspond to the local conditions.

Table 2-13: Types of indicators for energy access and energy poverty

Category	Example	Initiator	Strength	Weakness
Single	International poverty line ($1 a day)	World Bank	Powerful to interpret one specific dimension	Narrow picture of the issue measured Unsuitable for less tangible issue
Set of individuals	Millennium Development Goals (MDG) Energy Indicators for Sustainable development (EISD)	UN IAEA	Requires framework to capture the various elements	Too difficult to achieve data, use of aggregation model is not preventable
Composite	Human Development Index (HDI) Energy for Development Index (EDI)	UNDP IEA	Single numerals calculated from a variable that represents the aggregated value of a dimension Simple additive method (weighted sum) Ease of use	Lack of common unit (that is a reason they need multi criteria tools to overcome issues of incommensurability Can be misleading in terms of policy when the indicators are poorly constructed Inconsistence, methodological flaws and redundancy, Controversial for weighting all criteria
	Multidimensional poverty index Multidimensional energy poverty index(MEPI)*	UNDP	More advanced approach Less intuitive results	More complicated to compute Participatory methods for assigning weights

* MEPI is a metric to measure energy poverty, which allows a better tracking of the energy requirements for end users.

In Appendix 8.2 some of the more complex indicators, such as the energy development index (EDI), the multidimensional energy poverty index (MEPI) and the total energy inconvenience threshold (TEIT), are discussed in more detail. Kemmler and Spreng investigated some single indicators, such as the energy poverty line (Kemmler & Spreng, 2007). Mirza and Szirmi present measures of energy poverty, where they combine energy inconveniences along with energy shortfalls and defined the total energy inconvenience index (TEI) (Mirza & Szirmai, 2010). Pachauri and Spreng have also identified dimensions and indicators that measure energy poverty at international and national level such as affordability and inconvenience (Pachauri & Spreng, 2011). CSD as well as Singh et al. presented indicators for sustainable development along with a framework for indicator production (UNDSD, 2001), (Singh R. , Murty, Gupta, & Dikshit, 2009), (Singh R. , Murty, Gupta, & Dikshit, 2012). Hailu and Bazilian et al. analyzed indicator requirements for energy access (Bazilian M. , et al., 2010), (Hailu, 2012). Since some indicators are not easy to be quantified, qualitative measurement is worthwhile considering.

Within this research an attempt was made to apply an indicator for evaluation purposes after the potential options were proposed. When analyzing the different indicators in detail, the MEPI was identified as the most appropriate one for this research. However, difficulties were encountered in the input measures. Also, no additional information of how to apply the MEPI at small community level, like the ones investigated in this work, could be obtained from the

University of Oxford; the creator of this indicator. For those reasons it was decided to switch to a monetary comparison of the proposed options.

2.7. Gaps identified in literature review

Although it is clear that there is no unique solution to tackle the challenge of universal energy access, within the large quantity of papers, reports and studies reviewed some major gaps have to be highlighted when dealing with this subject. Many leading international organization and institutions have taken on the challenge and try to provide solution for those in need of energy access. Due to time consuming evaluation procedures of newly-developed concepts and methodologies, research results are oftentimes still limited. This is especially the case for real world case studies where the effectiveness of proposed solutions needs to be verified. The major concerns can be summarized as follows:

1) Definitions about the minimum energy requirements vary widely and depending on the view of the authors or organizations as well as the areas and communities for which the concepts are developed for.
2) Oftentimes energy access is limited to the electrical requirements. While some researches highlight the fact that energy access is much more than just electricity, the major needs are indeed for cooking and warm water, both end-uses are quite frequently not covered from electricity. At the same time, access to clean water should be defined as a minimum requirement.
3) In order to improve health and well-being, especially in housing, the currently used wood and dung in combination with traditional technologies need to be replaced. Therefore, it is not necessarily an improvement from those basic forms of carriers and technologies towards renewables and advanced technologies. Instead, considering modern fuels and intermediate technologies to path the transition towards advanced systems and prevent an overwhelming of the inhabitants in isolated communities should be encouraged.
4) Since many communities have resources locally available, an identification of the local supply potential should be performed. This may limit the costly import of fuels and also reduces a community's dependence on imports and fluctuating prices.
5) A definition of the minimum requirements should not always be done on a per capita basis. Because of the nature of various end-use devices, mainly the ones that use fossil fuels, results are easily "blurring" and may lead to false conclusions. Instead, minimum requirements need to be met for each end-use and each sector across the whole community.

6) In addition to the above mentioned, minimum energy requirements for a community cannot only focus on the domestic sector. Education, health, agriculture, public lighting and small businesses are also essential parts for the inhabitants of any community.
7) The technology level has not been accounted when defining the minimum energy requirements. Indeed, the energetic performance of devices (efficiency) for the same end-use shows substantial differences and consumption levels. Especially, when considering devices of different technology levels (traditional, intermediate and advanced) an adjustment of the requirements seems worthwhile.
8) Devices with multiple end-uses, for instance for cooking, domestic hot water and ambient heating should be considered with shares rather than individually or through double counting.
9) Lessons learned from studies undertaken in rural/isolated communities or islands in the developed countries cannot be equally transferred to communities in developing countries. Frequently, top-down approaches are suggested, but they cannot take into account the local conditions and characteristics of the community and its inhabitants.
10) The severe scarcity of energy solutions or plans that concern energy access or energy poverty as an integrated model has to be highlighted.

According to the gaps identified, it can be said that energy transitions to change the energy system in the long-term are a possibility for many isolated/rural communities to increase energy access and reduce energy poverty. Structural changes at the local level will be essential, so that local benefits from the resource perspective (independence) can be achieved. Nevertheless, challenges in the execution of any proposed option depend on financial support, social acceptance, environmental barriers such as land use and technical limitations such as the fluctuating generation from variable renewables and the additionally required storage/back-up. Despite the challenges, energy transitions provide an immediate solution with much lower impacts, as it becomes a reliable and valuable option to be used at local level. Especially, for rural/isolated communities with limited energy access, a higher standard of living and comfort should be within reach, while safeguarding energy resources and human's health.

Because of the limited research in defining solutions and plans for isolated areas while combining different technology types and exploring locally available resources via dispersed generation, this research focusses specifically in this niche of research.

Although the literature review identified a diversity of tools and methods dealing with energy access, no single one was found capable of combining the issues outlined above. In fact, planning needs to start with the current situation and taking into account local conditions of the community, and end with the proposal of possible options and solutions that reduce health concerns and improve comfort of living. Thereby, detailed analysis on the changes across all end-uses and sectors should be followed to understand where a community struggles/shines the most. Hence, a comprehensive methodological approach will be proposed that combines the strengths of existing tools and methods in a useful way for isolated communities that are unlikely to be grid-connected in the foreseeable future, where micro-grids, intermediate technologies and renewable technologies might present the only alternative to reach the minimum requirements.

In order to evaluate the effect of any solution and to compare it against the closeness of achieving the goal, ex-ante and ex-post evaluation methods may be applied. For evaluating the methodology´s and solution´s performance, decision support in the form of multi-criteria decision aid may be a choice. Due to the inconsistency in the types of indicators and the lacking possibilities to determine the level of energy access, this research does not take into account any indicators for evaluation purposes.

3. Proposed methodological approach

After some of the gaps within the literature have been identified, this chapter proposes a methodological approach to improve energy access while meeting the minimum energy requirements in isolated communities of developing countries.[20] Initially, a methodological framework is built to set the groundwork for all further procedures and analysis. Hence, the methodological framework diagnoses the status-quo in terms of (minimum) energy access and proposes solutions to reach or improve energy access through a comprehensive framework.

Since energy planning has to take into consideration demand and supply, both sides have to be analyzed thoroughly. On the demand side this concerns the identification of devices in use, but also potential future devices to increase energy access and enhance living conditions.

On the supply side it is important to implement a system or combination of systems that lead to a successful sustainable solution. Challenges may arise to adequately dimension supply options for communities, bearing in mind local natural conditions and resource availability as well as the management of technologies to assure their continuous use, while protecting the environment and improving health conditions.

Yet, there are three major concerns when dealing with renewable energy technologies: 1) financing, 2) variability of resources and 3) variety and range of systems. Since potential supply solutions are often of very small dimension, it is not the cost itself but the feasibility of projects that cannot pay for themselves as the users, by both or either their small number and low economic capacity, do not have the economic capability to pay for enough energy to justify such investments. The management of variable and diverse resources, which may be a path to facilitate this type of systems/services, is challenging, especially when there is no alternative for back-up and the community has to rely on polluting resources again.[21] Little improvement is given to a community if, for instance, only all electric services are covered from modern technologies and at the same time still premier resources are used for thermal requirements.[22]

[20] Isolated in the sense that these communities are unlikely to be connected to the electrical network in the foreseeable future. Also, there are limited transportation possibilities in and out of the community.

[21] Alternative forms of back-up through either batteries, electric vehicles or even time-of-use shifts of smart devices are not considered in this work. Especially, the decreasing cost for batteries may lead to further options in the upcoming years, whereas a more renewables-based supply can be realized.

[22] Energy related to transportation (including the transport of fossil fuels) and industrial services is not considered within this work due to the small size of the communities under evaluation.

In order to take the above raised concerns into account, emphasis should be particularly placed on successfully adopting conditions for modern (advanced) energy technologies through sufficient educational, technical and financial support (Trappey, Trappey, Lin, & Chang, 2012). Prior careful assessment of the case is recommended, since changes and adjustments of any solution are more difficult to be realized once a decision has been made (Van Beeck, 2003). Besides, it is obligatory for the evaluation and proposal of options within this research.

Within the methodological framework and the according models, the different stages and connections within this work are illustrated (Figure 3-1). Initially, the human needs have to be mapped, whereas Maslow's hierarchy of human needs plays a crucial role in defining the minimum energy requirements. Accordingly, this research provides a data set which includes the minimum energy requirements for each end-use and sector. Considerations are made per capita or household/center. A data set of end-use devices and technologies is provided.[23]

Following the identification of stakeholders and local requirements, the diagnose of the case is proposed. This includes an evaluation of the current devices in use and the amount of energy used within a community. Subsequently, the level of access can be defined and targets can be set.[24] At the same time, the local characteristics have to be gathered to complete the data sets. This information is then assessed through MCDA to identify locally suitable devices and supply technologies (since two times MCDA is applied in this work, the assessment of devices and technologies is termed as MCDA I).[25]

Within the synthesis different options are built, where the herein proposed approach is only one of many possible ways to build options. All options are then assessed from an energetic point of view to define the amount of energy used. Only if convergence with the initially set target is achieved, an option moves into the appraisal stage where different evaluations are performed to propose potential solutions. Despite the monetization of options, a full range of possibilities based on costs and the results of MCDA I is introduced. In order to evaluate the option as a whole, a second MCDA (termed as MCDA II) is performed with a limited number of criteria that reflect the local characteristics. One such criterion may be the total system costs obtained in the monetary assessment.

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[23] The data set can be improved by adding and/or updating more and/or new devices and technologies.

[24] For the purpose of this research the author decided to achieve or improve the minimum energy requirements. Yet, different levels of access with higher or lower targets can be defined (i.e. this may depend on the current situation of the community).

[25] Within MCDA I consideration is placed on the nexus energy and sustainable livelihoods.

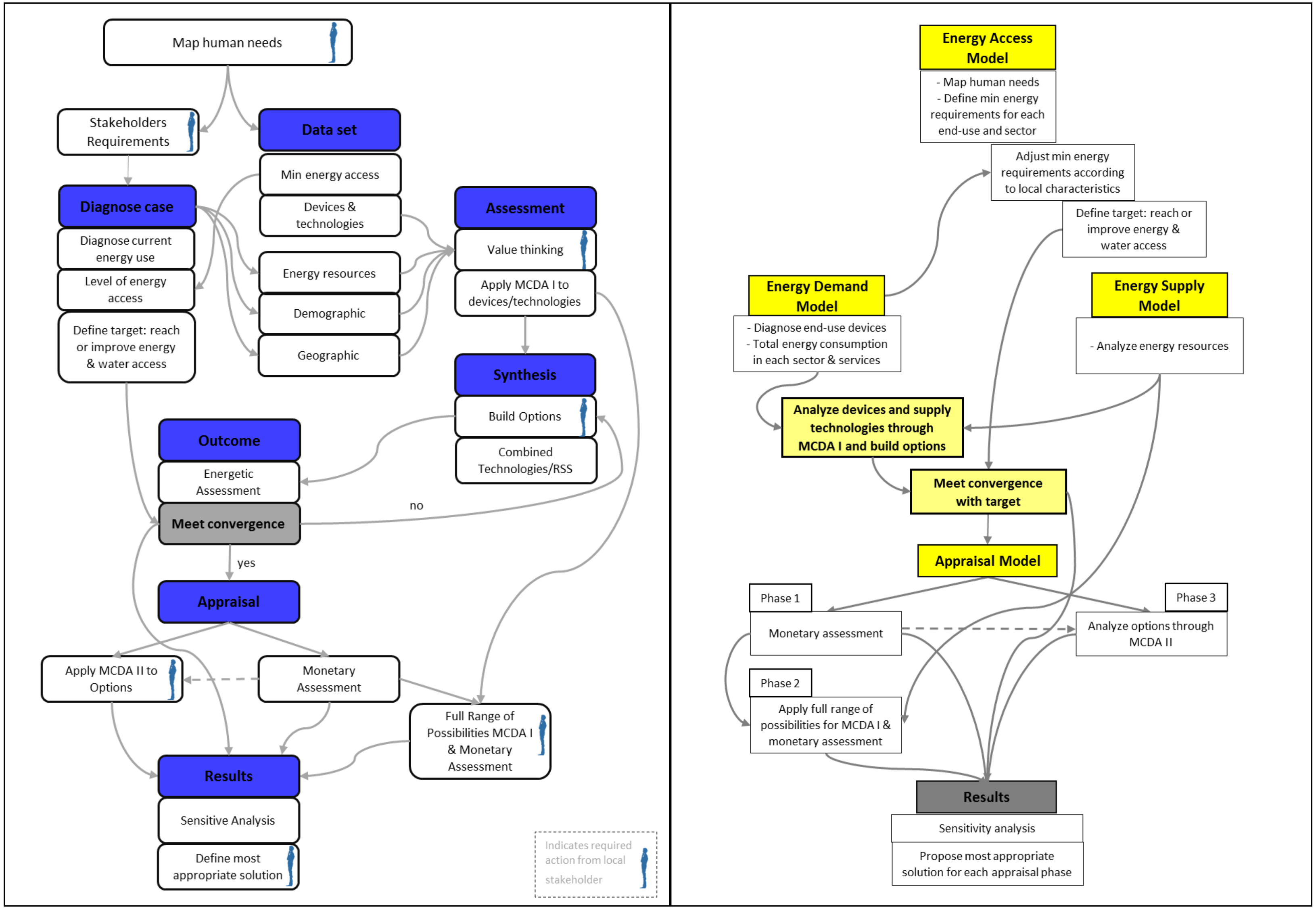

Figure 3-1: Methodological framework (left) and respective models (right)

In order to provide further insights in the effects of input changes on the results sensitivity analysis is applied. The selection of the most appropriate solution then depends on the outcome decision makers value the most.

On the model side there are essentially 4 major packages (right side Figure 3-1). It starts with the energy access model, which contains the data set of the minimum requirements according to the literature and, based on the diagnose of the case, also sets the target to be reached. The energy demand model focusses on the needs within the community, explores current devices and usage, and provides the necessary information to define the target within the energy access model. In combination with the energy supply model, which explores locally available energy sources, the energy demand and supply models also analyze the devices and supply technologies through MCDA to build options. An option moves on to the appraisal model if the option reaches convergence with the defined target. Within the appraisal model 3 phases are distinguished. All provide results through different input requirements and preferences. Following the sensitivity analysis, the most appropriate solution is defined for each appraisal phase. The final selection should be based on the perspective of a local decision maker.

In the succeeding sections the conceptual framework along with the systematic and mathematical approach will be presented and discussed. Consequently, the methods behind the data requirements, the MCDA, building of options and options appraisal are elaborated.

3.1. Conceptual framework

A conceptual framework, representing the overall energy system within the objectives of the energy triangle, is illustrated in Figure 3-2 (World Economic Forum, 2012). The core of this framework is simplified by a community, which could be any isolated village. Hence, it is initially proposed to identify the current energy carriers in use. At the same time, the type and number of devices per household and across the community along with the devices' pattern of use and efficiency should be defined. Then the conditions in and around the community have to be assessed, whereas community demography and topography as well as resource availability are key aspects to focus on. Critical reflection should also be placed upon the availability of land and water, the influence of extreme weather events (i.e. if annual monsoons lead to local floods) or the possibilities of connecting to the outside world. Especially the latter aspect can demonstrate a community's reliance on certain imported energy sources (i.e. kerosene, diesel or paraffin). Additionally, the evaluation of resource conditions requires an assessment of the availability of local resources. Certainly, there would be no interest to assess the possibilities of a wind turbine, if annual wind speed average was very low. Similar accounts for hydro power, which in most cases is scarcely available all around the year and, thus, may compete with other uses such as agricultural activities and drinking water.

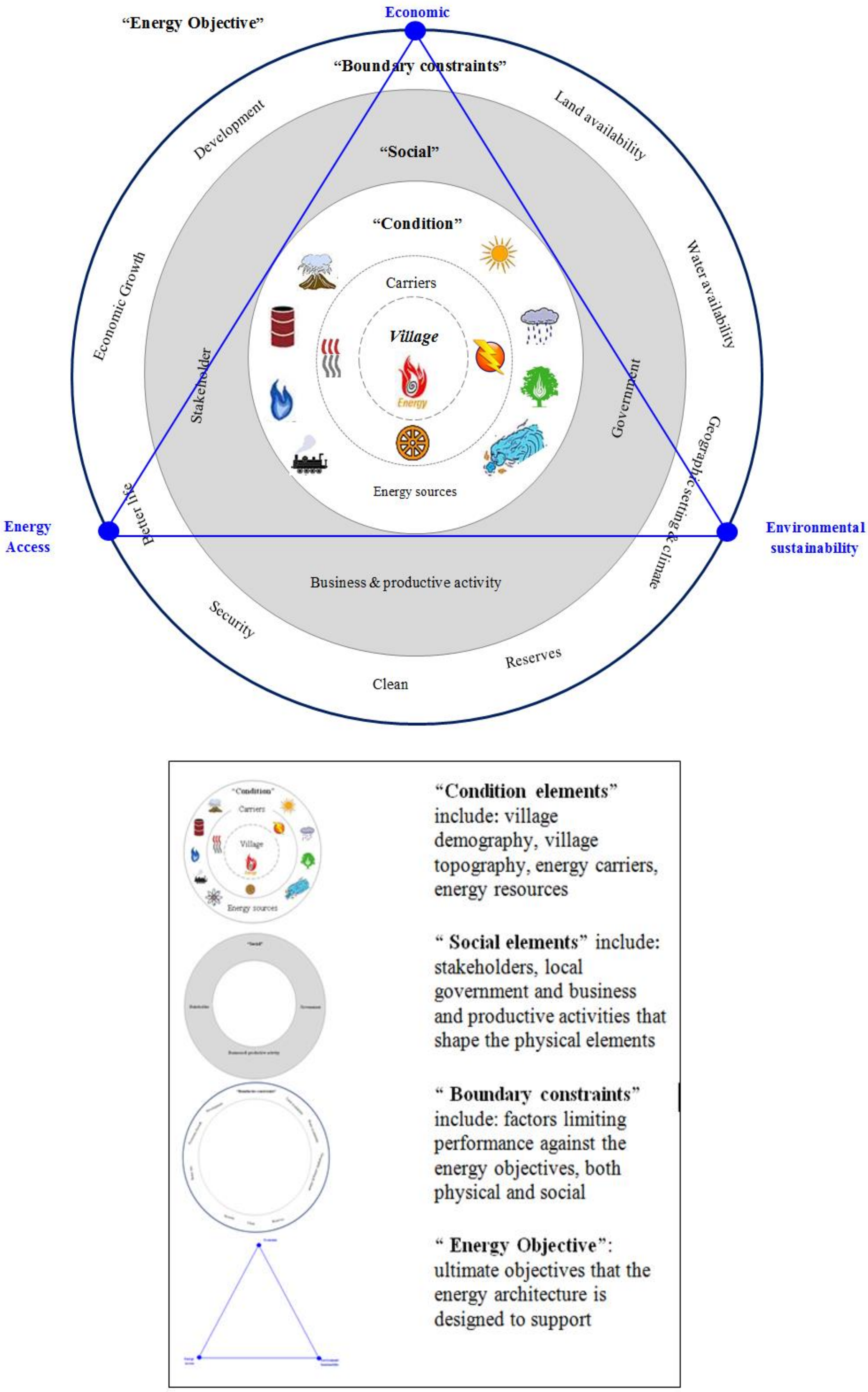

Figure 3-2: Energy conceptual framework (adapted from (World Economic Forum, 2012))

The second phase of the conceptual framework focusses on social elements, which include stakeholders, local government and businesses as well as production activities. All of those elements contribute in shaping the physical conditions of the community. Hence, the acceptability and adaptability of modern energy systems within the community have to be analyzed. Opposition against modern technology or the favoring of a specific technology solution can become considerable obstacles for the implementation of some systems. Consequently, education about and introduction to modern technologies become key factors before any implementation. In addition, local decision makers (e.g. community leaders, local/regional politicians, consultants, investors, etc.) should receive the necessary support when making decisions that affect the long-term future of the community.

The framework continues with a focus on boundary constraints. As such, physical and social elements limiting the performance against the energy objectives have to be assessed. Commonly analyzed constraints should include: land, water, wind, wood, solar radiation, availability of energy reserves, geographic setting and climate, security of supply, economic growth in the community, etc. All of the boundary constraints fall under the umbrella of the energy triangle, where it is intended to provide and increase energy access considering sustainable development in an environmentally sustainable manner.

Along those elaborations the conceptual framework sets the scene when planning to improve energy access in isolated communities. It is clear that not all aspects can be evaluated or assessed. Nevertheless, decision makers can be supported with understanding the complexity of making decisions and how to select energy technologies to supply the respective energy requirements. An overview of the connections within the energy ecosystem at community level, as depicted in Figure 3-3, is recommended, since it provides decision makers an idea about the extent their decisions may have.

Thereby, emphasis is placed on designing solutions that improve the performance of the overall community, rather than a specific household or service. The core of those improvements can be achieved through the use of electrical devices. Electricity is the highest form of energy and can be practically used for all end-uses (de Oliveira Fernandes, de Almeida, & Cardoso, 1998). Despite the challenges of using electricity from variable renewable energy technologies, long-term plans should focus on supply alternatives that are primarily based on clean technologies. Without storage systems in place, back-up in the form of diesel generators may be an adequate alternative to combat renewables-based supply fluctuations. Hence, diesel generators should be considered as transition from the currently pollutant direct use of fossil fuels towards the use of advanced devices and supply systems (including storage alternatives).

Only with a rapid transition of the current systems in place and the diversity of supply alternatives threatening indoor air pollution and health issues can be overcome.

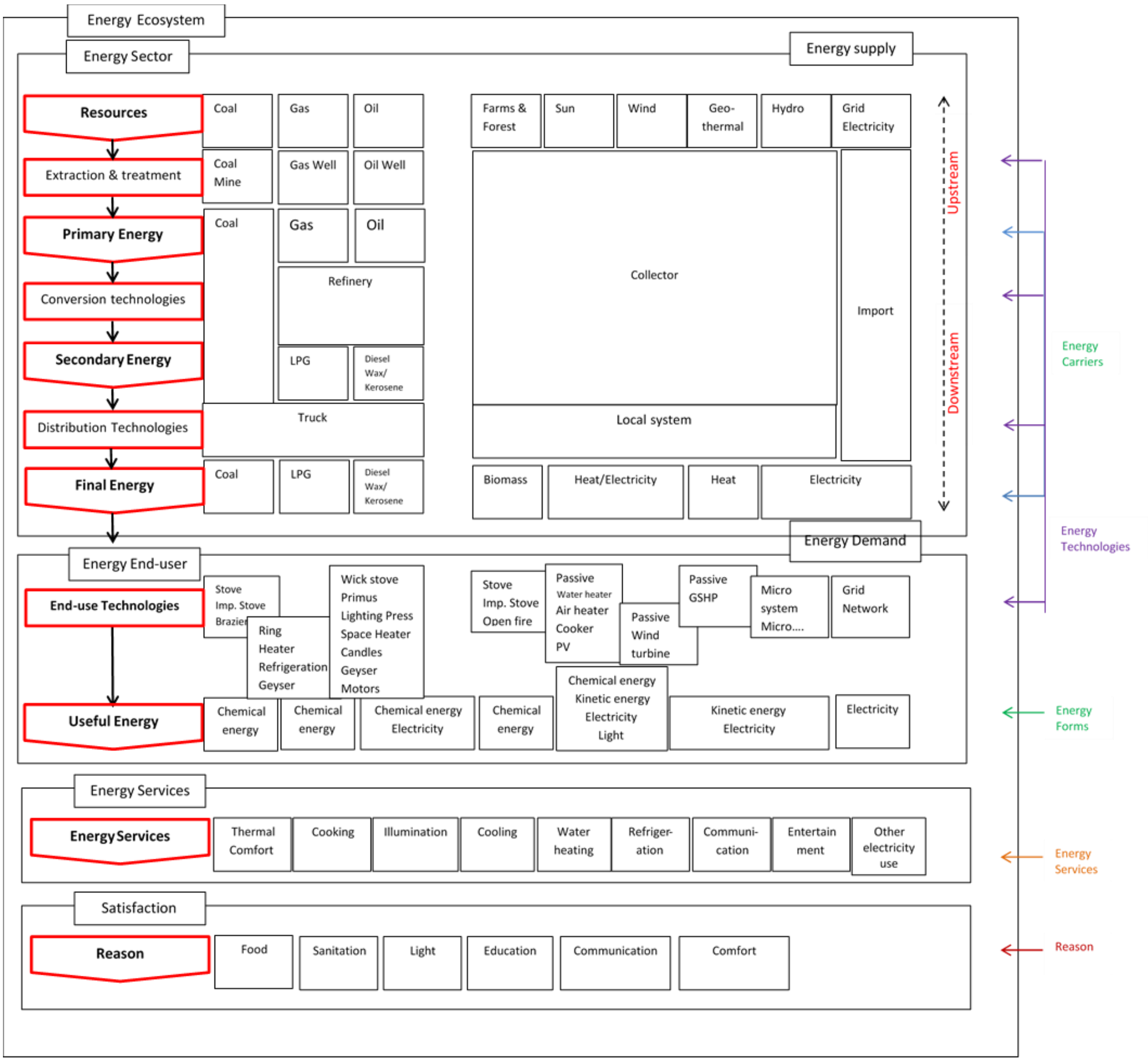

Figure 3-3: Energy ecosystem at community level (adapted from (Afgan, & Carvalho, 2000) and (GEA, 2012))

3.2. Systematic approach

In order to apply the conceptual framework in the case of isolated communities, a systematic integrated approach (Figure 3-4) (Hejazi, Wimmler, de Oliveira Fernandes, Matos, & Connors, 2016) can assist describing each of the different stages of a successful sustainable energy operation.

Stage 1 – Target/Goal: The priority goal is to reach the energy target for the community. It has not been rare in the past to have factories working in isolated areas not contributing to help providing means of more and more qualified energy to the populations living nearby. Consequently, the initial stage must identify the problems and issues associated to the exploration of the energy resources and their services to the people in the area, their housing, community buildings, information, education, etc. and, of course, support for the economy. This includes at all stages the environmental concerns mainly indoor air pollution and its health impacts caused by the current energy resources in use, but also the indiscriminate use of resources leading to the depletion of woodland, fuel scarcity as well as the type and dimension of local resources used (i.e. wood again or water with other competing uses) (World Health Organization, 2000).

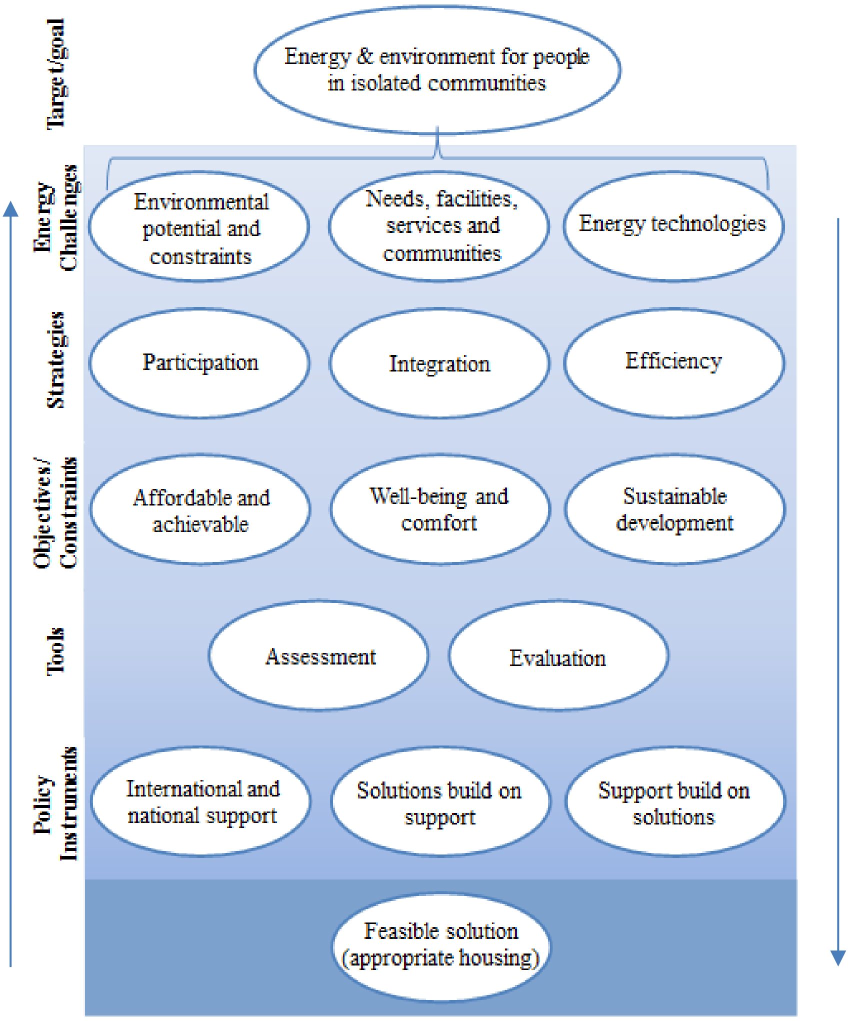

Figure 3-4: Systematic approach for energy access (Hejazi, Wimmler, de Oliveira Fernandes, Matos, & Connors, 2016)

Stage 2 – Energy challenge: The challenges are the environmental context, both outdoors and indoors; the extension and the level of the needs and of the energy resources that will be made available to respond to the former and the technologies that can be afforded. Here the differentiation among the different types of energy services is particularly relevant: lighting, heating, drying, cooling (freezing), mobility, etc. and the corresponding selection of technologies that will allow for providing those services. For instance, passive technologies may represent a first step to fulfill proper indoor comfort conditions before thinking of another type of technology to be used. Yet, the technology has evolved a lot in what regards the understanding of the passive technology potentialities. Even, if through the use of very basic concepts and approaches.

Additionally, traditional ways of using renewable energy resources rather than modern energy technologies, which could be used elsewhere, have to be highlighted. Such examples include usage of daylight (Balcomb, 1988), drying food in the sun, building or using natural occurring shading, place pollutant cooking stoves outside the house, etc. It is of utmost importance that the pathway to sustainable development does not lead through solely increasing energy access, but to increase the level of comfort in a sufficient, effective and efficient manner. The predominant health issues, as a result of inappropriately using energy resources and modern technology (Fardeheb, 1988) have to be overcome.

Stage 3 – Strategies: should aim at an integrated energy approach. The strategy requires the participation of all stakeholders (mainly end-users), providing them proper information and arguments for their motivation, mobilization and commitment to achieve successful outcomes and increase the energy usage in a more effective and sustainable manner. Besides the social integration there is a need for a coherent integration of different potential energy systems based on criteria of exergy[26] and appealing to storage of the service. All in all, for economic and environmental reasons and to take as much advantage of the integrated system as possible the concern with the energy efficiency must be present at all stages. With proper energy solutions and planning three main correlated benefits will arise for isolated communities: 1) improvement of living level, 2) development of agriculture and 3) saving in wood and agricultural waste that causes less deforestation as well as more equity and health in life (Catania, 1999). Rather than always focusing on the newest and most modern technologies, potential energy solutions should also consider replacing, improving or increasing mitigation procedures.

Stage 4 – Secondary Objectives/Constraints: From the variety of technical, economic, environmental and social aspects the integration process, that considers the combination of aspects, is the preferred one. Economically sustainable solutions require being affordable, realistic, in a timely manner, achievable and with the lowest overall impacts. Thus, three main complementary objectives are to be pursued by a project: affordability bearing in mind

[26] Exergy is the energy that is available to be used. After the system and surroundings reach equilibrium, the exergy is zero. The term was established by Zoran Rant in 1956, but the concept was developed by J. Willard Gibbs in 1873 (Sciubba, 2007).

external support; sustainability in terms of global environment but also in social and economic terms, i.e. not excluding anybody.

Yet, discussions still focus a lot on selecting the renewable energy technology that shall be used to generate electricity. The fact is that the selection process is much more comprehensive as different end-uses require different energy carriers. Adequate decision support to cover all end-use services is obligatory. One of the major drawbacks of an approach driven by one or by a limited number of technologies is the difficulty of overcoming the majority or even all challenges at once. Indeed, it does not seem in the interest of an isolated community to have access to modern energy and thus only cover a few services with those technologies, where many other services still have to be covered from pollutant energy carriers. Therefore, a balanced solution that combines different levels and sizes of technological development is much more beneficial.

Stage 5 – Tools: for the assessment and monitoring shall be used to evaluate and manage the solutions and the system(s). That shall bear in mind the eventual dominant energy users such as residential and communitarian buildings. Since households are the most representative energy use sector within such isolated communities, the further considerations will primarily focus on residential buildings, but also assess the specifications of the remaining sectors.

The dominant energy needs within households imply cooking, hygiene (i.e. hot water), food preservation and storage, communication as well as ambient heating and cooling. However, not all of these services are essentially to be covered from energy technologies. Heating and cooling, for instance, are very much subject to climate and architecture. In fact, adaptive behavior might be a key aspect, especially in terms of sustainable development. While tropical or warmer climates could make use of naturally occurring shading as well as ventilation through the building structure, cooler climates require better levels of building insulation or additional layers of clothing. In both cases, energy is not necessarily a prerequisite. Passive architecture of buildings can significantly contribute to manage ambient heating and cooling requirements, and thus lead to high comfort and well-being within the building without necessitating additional energy resources. Yet, this does not imply a net zero energy building.

Stage 6 – Policy instruments: Search for financial mechanisms and support. Proper design and contextual documentation are crucial. It has not been uncommon to have projects lying down in the shelves of the receiving countries, often elaborated by dedicated institutions to aid or just to finance energy projects for the last 20 years or so. The missing of an integrated approach and the resulting inadequacy to the local context in all those cases then led many projects to never be implemented or be left without any service and maintenance plan. Hence, good projects, well thought, balanced and justified are a sine qua non condition for obtaining appropriate financing. Information on support mechanisms, regulations and policies can be useful complementary instruments for the whole process, especially to avoid gaps or delays in the implementation process or to motivate the use of specific technologies as part of the solution.

This integrated approach appears to open up a compromise between the difficulties of financing infrastructure and the need to respond in an economic, reliable and sustainable manner. Moreover, it is expected that with a more accurate understanding of methods and approaches as well as the progress on available energy technologies and solutions, local decision makers can contribute to increase the energy access to more sustainable vectors not only from a local point of view but also from a global perspective. It is the combination of energy planning with architectural, spatial and economic planning that leads to sustainable development.

3.3. Required input data

Data requirements are always a major obstacle for practical research. Hence, it is mandatory to define all necessary inputs prior to any further assessments and calculations. This research has essentially four major data requisitions: 1) definition of minimum energy requirements, 2) community characteristics and conditions, 3) end-use devices and supply technologies and 4) criteria, attribute values and criteria weights for MCDA.

1) Definition of minimum energy requirements

Within the literature review no universal definition of the minimum energy requirements (MER) could be obtained. Consequently, the primer step of this research is the definition of MER for all end-uses and sectors. For that reason, the daily requirements, both in power and average hours of use, are defined. Since there are multiple energy carriers in place, namely electricity and heat, the requirements need to be brought down to the same denominator. The use of energy in general and electricity in particular needs to be set in relation. Hence, all values within this research can be expressed in either koe or kWh.

In addition to the daily consumption, the number of devices per capita, per household, per (service) sector or the overall community need to be defined. While this depends largely on the number of inhabitants of the community, some minimum requirements are proposed. Additional adjustments based on proportional increases of the number of inhabitants or users (health center or school) are also considered. The minimum definition of community services considers a population of at least 100 inhabitants. Below that number the community might only require domestic uses, water pumping and some agricultural needs.

With the power consumption of the device, the average daily hours of use and the number of devices per end-use and sector, the requirements can be defined accordingly. An aggregation of all end-uses and sectors leads to the minimum energy requirements of the community, which then can also be broken down into a per capita requirement. All MER consider the useful energy available to fulfill the end-use respectively. The definition of all MER by end-use and sector then forms the "MER ref" which will be used for further comparison with the current situation of a community as well as the proposed options.

All useful requirements by end-use are based on the specific consumption of a device. Since there are various devices available to cover each end-use, aspects of efficiency have to be accounted for in the MER. In the literature a lack of consideration of the devices' efficiency could be encountered when defining minimum energy requirements. Therefore, an x-factor has been proposed. All devices in the data set are differentiated according to their efficiency, whereas the energetic performance of intermediate technologies is considered as "standard" value. Devices with a higher efficiency may have lower MER and devices with a lower efficiency have a higher MER. For end-uses with only a limited number of devices, or where only one electrical device is proposed, no further differentiation has been applied, so that all those devices have a x-factor of 1.

2) Community characteristics and conditions

In order to diagnose the current status/performance of any community and propose potential options for the same, an assessment of the local characteristics and conditions is mandatory. According to the conceptual framework, the local site-specific characteristics needs to be defined. This includes general community information such as the number of inhabitants, number of households, availability of service centers, small businesses, etc. Then, energetic performance of devices currently in use and the subsequent energy resources need to be defined; including the number of devices per household/service, average daily hours of use and type of device. From the supply perspective the resource availability has to be assessed, so that the number of potential supply technologies can be narrowed down to the most appropriate ones. Lastly, it is beneficial to collect social, economic and socio-cultural information about the inhabitants of the community, since it is of great importance to propose options that will be adapted by the community, knowing that there is also someone available and capable within the community or contracted from outside to operate and maintain the proposed technologies and devices.

3) Devices and supply technologies

Data input for the devices and supply technologies is key for the energetic and monetary assessment. Therefore, a substantial data set is recommended. With time, further additions may be made to provide further diversity in the devices and/or supply options. Yet, it is essential to only make further additions to the data set if all of the following information, in no particular order, is available: resources used, lifetime, investment cost, operation and maintenance cost, energy consumption (power) and efficiency of appliances. For cooking and heating appliances the thermal efficiency is also required and for lighting devices the lumens available of the device should be provided. Based on the information provided, the devices may then be categorized by energy resource (fossil fuel, renewables and either or both) and technology level (traditional, intermediate, advanced and passive).

4) Criteria, attribute values and criteria weights for MCDA

From the multitude of criteria applied in the literature the most appropriate ones for the evaluation of potential devices and supply technologies should be selected. Criteria can be grouped in technical, environmental, economic, social and energy resource. Further differentiation may also be applicable (including policy, cultural or combinations of the aforementioned). Ideally, a combination of evaluation criteria is chosen to reflect a diversity of aspects and propose integrated sustainable options. The author suggests that the number of selected criteria may vary but should include at least two criteria of the 5 groups presented above. As an upper limit no more than four criteria of the same group should be selected and the difference in the number of criteria per group should not be greater than two. This balanced criteria selection is proposed to consider a diversity of aspects without putting too much emphasis on an individual criterion. It needs to be defined if a criterion is to be maximized or minimized, since this has a major impact on the definition of attribute values. For the final evaluation and to define the most appropriate option for a community another model based on MCDA (called MCDA II) is applied, which focusses on the most important criteria for local decision makers. Based on the literature findings, criteria may include, but are not limited to, costs, resource availability and local acceptance.

Once all criteria are proposed, attribute values can be associated. As the major concern of this research is to exercise the concept and apply it to the model, qualitative data is applied. As a matter of fact, a quantitative data collection of all attribute values would be based on such a variety of references with varying backgrounds and times that a meaningful assessment could not be guaranteed. In fact, it is preferable to have one coherent data set that is based on the same mindset, rather than multiple inputs from conflicting sources. The only quantitative value is the total system cost (in MCDA II), which is obtained from the monetary assessment. Costs are compared with the results of the full range of possibilities within and across each option.

Since the uniform data set may be a demanding task, it ideally considers the input from local decision makers to better reflect upon the local characteristics and conditions. Hence, decision makers should be identified and contacted/interviewed with specifically prepared surveys that intend to explore most of the local specifications (Appendix 8.3) (Borofsky, 2015). Thereby, it is important to emphasize on Keeney's concept of "Value-focused thinking", where decision opportunities can be only reached if the decision maker starts by thinking of what she/he values to achieve a specific decision process (Keeney, 1992). A scoring scale is proposed to differentiate the devices and supply technologies. The scale is divided in: 0 = unsuitable, 3 = partially suitable, 6 = suitable, 9 = extremely suitable. Descriptions are made for each criterion to ease the scoring process.[27] For the evaluation of options, a scoring scale from 0 (worst) to 100 (best) is introduced to better reflect the differences within each option.

Finally, decision makers should also contribute to the weighting process of criteria, where swing weights are proposed for this research. Therefore, the criterion with the highest satisfaction when changing from worst to best needs to be defined. All other criteria swings will then be set in relation to most preferred criterion swing.

Table 3-1: Experts contacted for perspectives on energy access planning

Name of Contact	Organization/ Institution/ Company	Date of contact	Topics/Discussion	Reference
Thomas Princen	University of Michigan	18.02.2012	Sufficiency and sustainable indicators	(Princen, 2012)
Judith Cherni	Imperial College	28.09.2012	Information about sustainable livelihood and SURE tool	(Cherni J. , 2012)
Shonali Pachuri	International Institute for Applied Systems Analysis	25.03.2013	Real challenges in India regarding energy access; information about MESSAGE and ENACT tool	(Pachuri, 2013)
Bridgette Wellington	ICF International	10.04.2013	Introduction to DHS methodology and STATcompiler tool	(Wellington, 2013)
Bilal Mirza	Centre for Policy Studies, COMSATS Institute of Information Technology	23.04.2013	Energy poverty and rural energy markets in South Asia; focus on Pakistan	(Mirza B. , 2013)
Mary Holland	Sustainable Energy Authority of Ireland	26.04.2013	Domestic fuel cost and seasonal system efficiency	(Holland, 2013)
Thiyagarajan Velumail	UNDP re4gional centre	04.09.2013	Energy costs related to MDGs, using a variety of tools	(Velumail, 2013)
Bipulendu Singh	World Bank	05.09.2013	META Tool	(Singh B. , 2013)
Dominguez Bravo	Geographic Information Technologies & Renewable Energy	18.03.2014	IntiGIS tool	(Bravo D. , 2014)

In order to obtain a general overview of decision support methods when dealing with the increase of energy access in isolated areas of developing countries, a selected number of

[27] As this scale considers qualitative scores, each decision maker can judge by their own values.

experts in this field were directly contacted (Table 3-1). Their perspectives and deliberations were considered when defining the criteria and methodology of this work.

3.4. Mathematical approach

The mathematical approach follows the steps described within the conceptual framework. Various researches to encompass and support the model have been taken into account, for instance Van Ruijven et al. who studied the energy use in Indian households (Ruijven, et al., 2011), Vassilis et al. who predicted household energy use in developing countries (Vassilis, van Ruijven, & van Vuuren, 2012) or Mirza et al. who analyzed the proportions of the energy mix in rural communities (Mirza & Szirmai, 2010). In order to evaluate all options, the minimum energy requirements (MER) are analyzed from an energetic and monetary perspective.

In communities that have already reached the minimum energy requirements, further investigation is proposed, since each end-use and sector has to be analyzed. It is expected that even in communities where the per capita requirements are achieved, there is potential for improvements. Based on the devices currently in place for each end-use, more efficient devices may be proposed, so that better living and health conditions can be achieved. The mathematical approach is used for the diagnosis and also the evaluation phase.

3.4.1. Energetic assessment

The energetic mathematical formulation assesses the current situation and proposes solutions in relation to the MER as per definition in the required data input section. All values are expressed in kWh and koe (kg of oil equivalent), where the following conversion is applied:

1 kWh = 0.086 koe

1 koe = 11.63 kWh

Equation 1 assesses the total useful energy needs UE_T across the whole community, which is the sum of the useful energy of each device across all end-uses and sectors:

$$UE_T = \sum_{1}^{I} \sum_{1}^{J} \sum_{1}^{N} UE_{D_{ijn}} \qquad \text{Eq. 1}$$

Where i is the number of sectors (1…I), j is the number of end-uses (1…J) and n is the number of devices (1…N).

Likewise, the useful energy consumption per capita in the community UE_{CAP}, which is the total useful energy divided by the number of persons Cap, will be used to evaluate the current situation as well as solutions in relation to the minimum requirements.

$$UE_{CAP} = \frac{UE_T}{Cap} \qquad \text{Eq. 2}$$

The useful energy for device n (UE_{D_n}) is defined as:

$$UE_{D_n} = P_{D_n} \cdot Eff_{D_n} \cdot N_{D_n} \cdot T_{D_n} \cdot H_{D_n} \cdot S_{D_n} \cdot 365 \qquad \text{Eq. 3}$$

Where P is the power, Eff is the efficiency, N is the number of devices per household or service sector, T is the duration a device is used per day, H is the number of households or buildings per service sector and S is the share for devices with multiple uses; e.g. open wood fire can be used for cooking, domestic hot water and even space heating. The 365 sums up the use over the year.

While the power and efficiency are given within the data sets (see section 4 and 4.1), assumptions regarding the shares of devices with multiple end-uses are made. In fact, all devices that are suitable for cooking and domestic hot water have a share of 80% and 20% respectively. The amount of heat that is actually being lost and could contribute to space heating, has not been considered in the calculation of the minimum requirements. As a matter of fact, the losses through nearly all "Heating" devices are substantially higher than the actual needs for cooking and domestic hot water. This is a matter of inefficiency. Therefore, it has been assumed that the use of these devices provides heat as a by-product and the space heating requirements would be "Automatically" fulfilled. While this is only partially true the bulk of heat is lost or wasted. Yet, if any of these devices for multiple purposes is used, then the heating requirements are considered as fulfilled.

The number of devices per household or service sector is defined in the minimum requirements. If the count of a device is higher than defined in the minimum definitions, then this "Additional" device is considered a means of comfort. Subsequently, it is not accounted in the minimum requirements so that additional devices do not lead to false conclusion when reviewing the total final energy use. Lastly, the number of households or buildings per service sector is defined through the community under evaluation.

It is important to investigate the results of the UE_T, since multiple conclusions can be drawn when comparing the results with the minimum requirements MER_{ref}.

1) If $UE_T > MER_{ref}$

a. The community has already reached a good level of energy access, whereby some habitants use more than the minimum; either through longer duration of use, more devices or inefficient devices
b. This may be a sign of using highly inefficient devices, whereby the use of only a few devices can lead to a noticeably higher energy consumption, and some end-uses are even not yet covered.

2) If $UE_T = MER_{ref}$
a. The community uses devices according to the minimum requirements and most end-uses are covered with appropriate devices
b. Large differences amongst the households and/or sectors occur where some end-uses exceed the minimum requirements and others are not met. Exceeding consumption can be the results of more devices in use, longer duration or inefficiency.

3) If $UE_T < MER_{ref}$
a. The community struggles to meet requirements since various end-uses are still without access.
b. The use of very efficient devices across all end-uses may result in lower energy values. Likewise, the better efficiency allows for a shorter duration of use. This is typically only the case if a community can make use of efficient modern technologies (e.g. electric induction stove or electric geyser).

Consequently, better understanding about the actual conditions of the community can only be obtained through an analysis of the useful energy by device UE_{D_n}in relation to the requirements for that particular end-use. Since discrepancies in terms of duration and number of devices are highlighted and cannot exceed the defined maximum, the overall count per device in relation to the requirements of that end-use provides the most accurate judgment.

In order to better understand the energy use and requirements for each end-use an overview that summarizes the lack of devices and/or the number of additional devices is presented for each service and sector.

A lack in the number of devices for one end-use (L^j) can be identified if the number of devices in use for one end-use ($N_{D_n}^j$) is lower than the expected number of devices according to the minimum requirements for that end-use ($N_{D_n}^{Req^j}$).

$$if \sum_1^N N_{D_n}^j < N_{D_n}^{Req^j} \quad \text{then} \quad N_{D_n}^{Req^j} - \sum_1^N N_{D_n}^j = L^j \qquad \text{Eq. 4}$$

Subsequently, the missing useful energy requirements UE_L^j resulting from the lack of that device(s) is calculated, where UE_{Req}^j is the useful energy requirements for each end-use and sector according to the minimum definition.

$$UE_L^j = L^j \cdot UE_{Req}^j \qquad \text{Eq. 5}$$

If additional devices are used, then the added energy needs are declared as comfort. Additional usage A^j occurs if a household or sector operates more devices than defined in the minimum requirements. Besides, comfort is achieved through the use of advanced technologies. As such, devices that are only used for domestic hot water (electric or LPG geyser, among others) or space heating (Ground source heat pump, electrical heater, among others) are considered.

$$if \sum_1^N N_{D_n}^j > N_{D_n}^{Req^j} \quad then \quad \sum_1^N N_{D_n}^j - N_{D_n}^{Req^j} = A^j \qquad \text{Eq. 6}$$

The additional energy requirements resulting from additional device(s) is calculated as:

$$UE_A^j = A^j \cdot UE_{Req}^j \qquad \text{Eq. 7}$$

In addition to the lack of energy and/or the energy for comfort, wasted energy has been assessed. It is the by-product of all heating devices with multiple end-uses (i.e. devices that can be used for cooking, water heating and ambient heating such as open fire or different stove types), whereby the negative of the thermal efficiency is considered as wasted energy. All wasted energy WE is accounted for ambient heating AH. The share is not considered, since it has no effect on the wasted energy.

$$WE_{AH}^i = \sum_1^N P_{AH_n} \cdot (1 - Eff_{AH_n}) \cdot N_{AH_n} \cdot T_{AH_n} \cdot H_{AH_n} \cdot 365 \qquad \text{Eq. 8}$$

This value is then adjusted by the actual ambient heating requirements UE_{Req}^j. The end-use of ambient heating is considered to be fulfilled despite not using specific heating devices, whereby the sum for each end-use always meets the minimum requirements that are defined. The total wasted energy TWE_{AH}^i by sector is:

$$TWE_{AH}^i = WE_{AH}^i - UE_{Req}^i \qquad \text{Eq. 9}$$

3.4.2. Monetary assessment

In order to compare all proposed options to one another (see chapter 3.7 building options), some common rational needs to be defined. This is done through a monetization of all options, whereby the total cost TC is summed up for the entire community across all sectors, end-uses and devices.

$$\mathrm{TC} = \sum_{1}^{I}\sum_{1}^{J}\sum_{1}^{N} TC_{D_{ijn}} \qquad \text{Eq. 10}$$

i is the number of sectors (1…I), j is the number of end-uses (1…J) and n is the number of devices (1…N). By means of associating costs to all devices and subsequent generation units (for electrical devices) each of the options can be represented through a monetary value. The monetary value has been introduced for a better judgement and more transparency for the decision maker when comparing the options, since the herein selected approach of the MCDA I does not to take into account the whole options portfolio (devices).

As such the annual total cost of device n (TC_{D_n}) will be defined for each potential solution, where DC_n^a is the annual cost of device n, $O\&M_{NE_n}$ is the operation and maintenance cost of devices that are not electrically driven, $IC_{E_m}^a$ is the annual investment cost for devices that are run on electricity, $fixO\&M_{E_m}$ is the fixed operation and maintenance cost of devices that run on electricity and $varO\&M_{E_m}$ is the variable operation and maintenance cost of devices that run on electricity. m is the number of electricity generating systems (1…M), where one system is linked to operate an electrically driven device n.

$$TC_{D_n} = DC_n^a + O\&M_{NE_n} + IC_{E_m}^a + fixO\&M_{E_m} + varO\&M_{E_m} \qquad \text{Eq. 11}$$

All cost components are assessed on an annual basis, whereby

$$DC_n^a = \frac{DC_n}{LT_n} \qquad \text{Eq. 12}$$

And

$$IC_{E_m}^a = \frac{IC_m}{LT_m} \qquad \text{Eq. 13}$$

Take into account the cost of device n (DC_n) over its lifetime (LT_n) and the investment cost of the electricity generating system IC_m over its lifetime (LT_m).

For devices with multiple end-uses the shares of use S_{D_n} are applied to the device cost DC_n^a and operation and maintenance costs $O\&M_{NE_n}$ so that no double counting of costs occurs. For each device the share across the multiple end-uses needs to add up to 100%.

Due to the number of assumptions required, further economic parameters such as the depreciation or interest rate, amongst others, were excluded from further calculations. Besides, time dynamics of demand and supply as well as the daily varying fuel costs have not been accounted. It is not part of this research to assume multiple economic indicators, that provide a rational for further comparison. Subsequently, the total costs for each device and end-use, but even the community itself, only take into account an annual fraction of the investment cost. In the end, the purpose is to practice the concept through this methodological framework.

For the operation and maintenance cost of non-electrical devices and electrical devices as well as the variable cost of electrical generation devices data from the literature has been gathered. In case no data could be found, assumptions were made on the rationale of the literature.

3.5. Multi-criteria decision aid for end-use devices and supply technologies

Based on the required data input and the subsequent analysis of the current situation appropriate options for improved energy access and better health conditions have to be identified. Due to the multitude of devices for each end-use and their varying characteristics Multi-Criteria Decision Aid (MCDA) is introduced to support decision makers. Since the set of alternatives is a discrete and finite set $A = \{A_1, A_l, A_L\}, l \in Z$ of feasible and mutually exclusive alternatives, Multi Attribute Value Theory (MAVT) is applied for this research.

Standard decision theory is valid through the conditions of the Neumann-Morgenstern axioms, assuming maximization of all alternatives and without loss of generality (French, Maule, & Papamichail, 2009):

- If Z is a subset of R_r and
  - $A_1 \geq A_2$ and $A_1 \neq A_2 \Rightarrow A_1 \succ A_2$ for all $A_1, A_2 \in Z$
  - For all $A_1, A_2, A_3 \in Z$ such that $A_1 \succ A_2 \succ A_3$, it exists exactly one $\lambda \in (0, 1)$ such that $A_2 \sim [\lambda. A_1 + (1 - \lambda). A_3]$
- Then, it exists a real value function $v()$ such that
  - $A_1 \geq A_2 \Leftrightarrow v(A_1) > v(A_2)$
  - $A_1 \sim A_2 \Leftrightarrow v(A_1) = v(A_2)$

MCDA supports decision makers in choosing one alternative out of a list of feasible options while bearing in mind a set of real-valued criteria $C = \{C_1, C_k, C_K\}, k \in Z$ (French, Maule, & Papamichail, 2009). Each alternative A_L is described by K attributes: $A_L = \{a_{l1}, a_{l2}, a_{LK}\}$.

Then alternatives are ranked through compensatory approaches as the poor performance in one criterion can be balanced through good performance in another one. Through the compensatory approach a value system is created that aggregates the decision makers preferences, whereby the criteria preferences are strict assumptions of the preference solutions. All criteria are judged preferentially independent from one another. With the elicited preferences unique value functions are constructed (von Neumann & Morgenstern, 1944).

The overall value function $v(A_l)$ is expressed as:

$$v(A_l) = \sum_{k=c_1}^{c_K} w_k v_k(a_{lk}) \qquad \text{Eq. 14}$$

where w_k is the criteria weight and $v_k(a_{lk})$ is the value score of alternative A_L in attribute K through the value function. Each value function demonstrates the satisfaction of one criterion regardless of the remaining criteria and can either be minimized (Eq. 15) or maximized (Eq. 16). This research applies linear value functions due to the limited scoring scale which is composed of only 4 scores. For all criteria a qualitative scoring scale is introduced, whereby 0 means unsuitable, 3 partially suitable, 6 suitable and 9 extremely suitable. Accordingly, scores are associated to all attributes (combination of one alternative with one criterion). With the intention to avoid bad outcomes and/or to keep close to good outcomes, one may also apply non-linear value functions (Figure 3-5) (Matos, 2008) so that more or less influence on a decision is accounted for when increasing or decreasing towards the best or worst outcome. All value functions reflect the variation of satisfaction within the range of attributes.

$$v_k(a_{lk}) = \frac{a_k^{max} - a_{lk}}{a_k^{max} - a_k^{min}} \qquad \text{Eq. 15}$$

$$v_k(a_{lk}) = \frac{a_{lk} - a_k^{min}}{a_k^{max} - a_k^{min}} \qquad \text{Eq. 16}$$

For the criteria weights the swing weights method is selected since it reflects both the importance and variation of the attribute scales in the value functions. With swing weights the first step is to define the worst outcomes on all criteria for one alternative. Thereafter, the criterion that is valued most when changed from worst to best will be associated with a maximum weight of 100 (Pöyhönen & Hämäläinen, 2001). After having defined the most valuable transition, the improvements of each remaining criterion swing from worst to best need to be expressed in proportion to the most preferred swing (Hobbs & Meier, 2000). Subsequently, a ranking is established. While the associated weights of all criteria are still unnormalized, the final step is the normalization process, where

$$w_k = \frac{m_k}{\sum_1^k m_k} \tag{Eq. 17}$$

And all normalized criteria weights need to add up to 1.

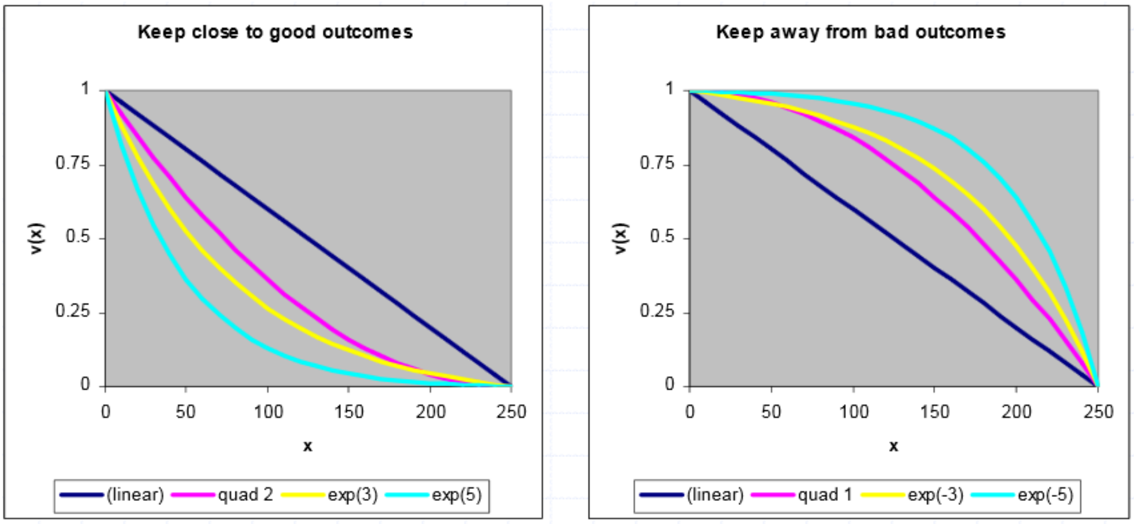

Figure 3-5: Types of value functions (Matos, 2008)

3.6. Proposing options to reach or improve minimum energy access

The objective of this research is to fulfill the minimum energy requirements (MER) in isolated communities. It is expected to propose multiple options for further analysis and evaluation, due to the vast diversity of available end-use devices and supply technologies.

Based on the division of end-use devices by resource and technology level, 5 MER options are proposed:

- MER 1: selects the best renewable based devices and technologies.
- MER 2: selects the second best renewable based devices and technologies.
- MER 3: selects the best fossil fuel-based devices and technologies.
- MER 4: selects the second-best fossil fuel-based devices and technologies.
- MER 5: intends to use intermediate technologies where possible. In case no intermediate technology is available for a certain end-use, then the best fossil fuel-based device/supply technology will be selected.

The possibilities of proposing the 5 options largely depend on the local resource availability. Indeed, the MCDA is only performed for devices and supply technologies that can be covered from the resources available. Upon completion of the MCDA all devices and supply technologies are ranked for each end-use. Due to the yet limited number of devices, there may be no best or second best renewable/fossil fuel-based devices available. In this case, the number of MER options proposed may be lower.

3.7. Option appraisal

In order to compare the proposed MER options and select the most appropriate solution according to the local characteristics, three appraisal phases are proposed with varying input requirements. Sensitivity analysis is also applied to analyze the impact of input changes on the results. Due to the variety of results it is advisable to present decision makers a diverse set of solutions under different conditions, input requirements and preferences.

According to the energetic assessment of the options built after the MCDA of devices and supply technologies (MCDA I), there are potentially up to 5 solutions. Since convergence with the energetic target must be reached for each option, the scores and subsequent preference order of the MCDA I lead to the most favored (appropriate) solution. At the same time, a decision for any of the options could be placed on the energetic performance.

For the further appraisal, only supply technologies may be altered within each option. The devices selected for each option according to the MCDA I remain unchanged throughout the further evaluations.

The energy demand of devices can either only focus on the vital needs to reach the minimum energy requirements or also include additional comfort requirements. Hence, all option appraisals are subject to two approaches (with and without additional energy requirements). Additional comfort devices, and the according additional generation from supply technologies, are referring to devices that solely contribute to ambient heating (AH), which is basically already fulfilled through the “by-product” of cooking and domestic hot water (DHW). Though, the wasted heat from cooking and DHW may not occur during the times it is needed most; in the evening, night or early morning and especially during winter months. Hence, additional heating devices may be proposed for comfort reasons, where the additionally required energy and costs can be assessed accordingly in the sensitivity analysis.

Additional comfort can also occur if certain households or services have more than the proposed number of devices already in place, for instance an extra television or an extra light. In such cases, only the minimum requirements, i.e. one television per household, is accounted. The second one is only considered from an energetic perspective – according to the energy requirements as per “Data” definition and the expected hours of use, so that no additional investment costs of the device are accounted. Yet, the proposed MER options always consider a replacement of (one of the) current devices (usually the weaker performing device, if the devices in use are differing), since it is believed that the new devices are substantially better in their performance.

Lastly, additional comfort also occurs if devices are used longer than the defined average daily hours of use in the minimum energy requirements. Once again, only costs associated to the additional energy use are considered. There is no limit imposed on the maximum hours a device can be used, since each hour above the daily limit can be considered through additional energy needs. The effect an additional use may have on the life time of devices is not considered.

3.7.1. Apply monetary assessment to all options

In the first phase of the options appraisal all options are monetized according to the procedures outlined in section 3.4.2 – monetary assessment. Costs have been calculated for all supply technologies that are feasible within an option.

Depending on the local resource availability, there is a limited set of renewables or fossil fuel-based technologies available. Hence, all locally suitable renewables-based technologies are considered for "MER 1" and "MER 2". Likewise, applicable fossil fuel-based technologies are considered for "MER 3", "MER 4" and "MER 5". In case a technology can use renewables and fossil fuels both (e.g. PV-diesel system), it will be considered a viable supply alternative for all MER options.

The monetization does not take into account any scores obtained in MCDA I. Results are solely driven by costs and support the identification of the most appropriate supply technology within each option. Subsequently, the option with the lowest total annual system cost may be proposed.

3.7.2. Full range of possibilities

In order to account for the results of the MCDA I and the total annual system cost a full range of possibilities is proposed. This again concerns solely the selection of the supply technology for each "MER X". As such the scores of the MCDA are ordered from highest to lowest and the costs from the monetization are ordered from lowest to highest. Thereafter, all potentially suitable technologies within a MER option have a preference order. Initially, the orders from the MCDA and monetization are given equal preference. In that way both approaches, MCDA I and the costs, are reflected in the selection of the most appropriate option.

As part of the full range of possibilities different preference ratios are applied to analyze how the orders change with a higher emphasis on either costs or MCDA. Prerequisite for the application of a full range of possibilities is the monetization of all options and supply technologies.

3.7.3. Analyze options through MCDA II

The monetization also forms part of the analysis of the overall option, for which another MCDA, including swing weights, is applied (according to section 3.5). The costs are considered a major driver for any decision maker and are strongly recommended to be included in the evaluation criteria.

For all other evaluation criteria, it is crucial to keep in mind that the value scores shall reflect the performance of the combination of "MER X" and the potential supply technology.

3.7.4. Sensitivity analysis

With the results obtained from all 3 appraisals (monetary assessment, full range of possibilities and apply MCDA II), the final step is the application of a sensitivity analysis. Thereby, parameter changes are performed to assess the impact on the outcome. For the monetization and full range of possibilities, cost variations through reductions and increases in the range of ±10%, ±20% and ±30% are performed for all cost components, including device cost, operation and maintenance (O&M) cost of non-electrical devices as well as investment cost, annual fixed O&M cost and variable O&M cost of the electricity generating systems. For the analysis through MCDA II parameter changes in the values of the criteria weights are applied.

4. Functionalities of tool

The sequential stages and connections of the proposed methodology are illustrated in the structuring method (Figure 4-1). It starts by defining the problem, i.e. reaching MER across all end-uses and sectors.[28]

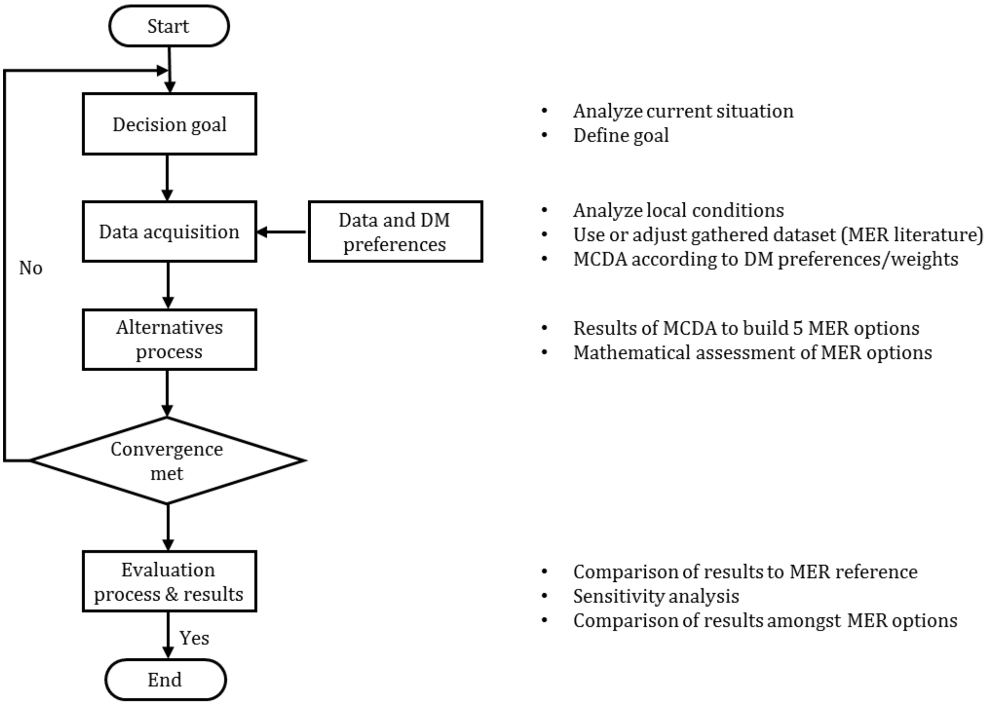

Figure 4-1: Structuring method

In order to follow all stages of the methodology and models a variety of tools can be applied. In this research all procedures and calculations are performed through spread sheets, where templates are created for each step.

Initially, the minimum energy requirements (MER) are defined for each end-use and service. This is done on a per capita/household/sector basis so that the requirements can be easily adjusted to the specifications of any community. Sectors include domestic, services such as education, health and community center, but also agricultural needs and water pumping for domestic and service needs. Other energy requirements such as for sanitation, industry or

[28] In cases where the MER have already been reached by a community, evaluations of the current situation are proposed for further improvements. Hence, the objective is not only to reach MER, but to improve the performance of end-uses and supply technologies while fulfilling the MER. All procedures of the structuring method still have to be followed.

transportation are excluded in this research.[29] For the definition of the MER various sources from the literature are gathered and summarized in the "MER ref" template. Where necessary missing data is provided based on the authors' best judgement.

In the next step, a comprehensive data set of possible end-use devices for each service (end-use) and sector is gathered and summarized in the "Data" template. Further additions and changes to the data set may be realized, because the rapid technological improvements of (new) devices should be added and/or updated on a regular basis so that more appropriate solutions can be found.

For the diagnosis of the current situation a template called "Base" is created. It follows the devices that are listed and characterized in the "Data" template and allows for an input of all local specification in terms of current devices and supply technologies in use. If different devices are already used in the community, then they should be added with all essential information to the "Data" template so that the corresponding energetic evaluations can be performed. Upon completion of the "Base" template, an overview of the current situation can be obtained through a comparison with the "MER ref" template, i.e. lack of end-use devices, use of pollutant devices, inefficient vs. efficient devices, type of technology and resource, etc.

In order to select end-use devices and to build the 5 MER options for further assessment a "MCDA I" template is created. It allows the input of local resource characteristics along with attribute values and criteria weights. With a completely filled "MCDA I" template, ranking of suitable devices is obtained for each of the MER options.

The 5 MER options differ in the resources to be used for the different end-uses, sectors as well as the type of end-use device, e.g. renewables, fossil fuels or intermediate technologies. A "MER X" template (X represents the number according to the defined options) is created which allows to implement the preferred technologies along with the expected daily working hours and the quantity of devices used within the community (devices for each sector and service). Upon completing the template an overview of the energy access is presented which can be compared with the "Base" template and "MER ref" template. The "MER X" templates identify the end-uses with the greatest improvements, but also where the community still has space for improvements. They also demonstrate if the MER for each end-use as well as for the community and per capita are met. If no convergence of the "MER X" is reached, the process needs to be repeated, whereas, amongst other, minimum requirements may be adjusted or

[29] Industry and transportation in such isolated communities are rarely existing. The transport of fossil fuel, if applicable, depends on a variety of factors (distance, type of fuel, frequency of transport, etc.) for which reason various assumption would be required. Likewise, for sanitation no common definition or references could be obtained.

operating hours, preferences may be altered. Only if a "MER X" option meets the "MER ref" for each end-use/service, it passes on to the evaluation process, where a monetary assessment, a full range of possibilities and an analysis of the overall option through "MCDA II" are applied. Finally, all results across the different appraisal methods are subject to sensitivity analysis so that the most appropriate solution can be defined.

4.1. Minimum energy requirements

The major data set is the definition of the minimum energy requirements, since it will be the benchmark for comparison when assessing the current situation and proposing potential options. For each sector and end-use MER are defined. The requirements for the non-domestic sectors consider a community size of around 40 households or 200 inhabitants. Further considerations to define or alter the MER are explained for each sector (see details of Table 4-1 to Table 4-6). Aspects such as the physical presence of additional buildings (another school or health center) or the costs for constructing such buildings are not considered.

Table 4-1: Minimum energy requirements: domestic sector – households adapted from (G8, 2001), (Ruijven, et al., 2011)

Human need	Energy end-use	Minimum requirements per capita or household*	Minimum duration or amount	Energy needs (koe per household per day)
Food preparation	Cooking	2 MJ_{UE} p.h.	per day	0.2488
Water heating	Domestic hot water	0.5 MJ_{UE} p.h.	per day	0.0597
Space heating**	Ambient heating	T<12°C	for each day	0.0090
Space cooling**	Ambient cooling	30° C> T	for each day	0.0576
Food preservation	Refrigeration	1 unit (100 W) p.h.	20 hours per day	0.1714
Illumination***	Lighting	1 unit (300 lumens) p.h.	5 hours per day	0.0171
	Radio	1 unit (5 W) p.h.	5 hours per day	0.0021
ICT	Telecommunication	1 unit (11 W) p.h.	3 hours per day	0.0028
	TV	1 unit (100 W) p.h.	5 hours per day	0.0428
Water access	Water pumping	5 liters p.c.	per day	see section water pumping
Comfort space	Floor space	4 m^2 p.c.		
Comfort facilities	Other electrical appliances			
	Sanitary facilities	1 unit p.h.		
	Cloth washing			
Comfort & hygiene	Cloth drying			
	Water desalination			
	Water purification			
	Sewage system	1 unit p.h.		
Total energy requirements per households (koe per day)				0.5981

* per capita and per household are abbreviated in the table with p.c. and p.h.; a household considers 5 habitants
** T stands for time in hours per day
*** 300 lumens can be achieved through a 40 W filament or incandescent lamp

Within the domestic sector (Table 4-1) cooking is the most consuming end-use and accounts for over 40% of all requirements. The second most consuming end-use is refrigeration, which makes up nearly 25%. All remaining end-uses have rather small requirements. It should be noted that the total minimum requirements largely depend on the climatic conditions, since space heating and space cooling have to be accounted for. The specific requirement for cooling and heating can be defined through the Cooling Degree Days (CDD) and Heating Degree Days (HDD). A comprehensive list of locations around the world can be found under http://www.degreedays.net/. All heating and cooling requirements can be identified accordingly. CDD indicate how long and by how much the outside air temperature was higher than the defined base temperature. HDD define for how long and by how much the outside air temperature was lower than the defined base temperature. In addition to the HDD and CDD the living area (square meter) and useful energy intensity are required (i.e. 130 kJ/m^2/degree-day) to define the minimum requirements.

The amount of ICT is very limited, since only radio, telecommunication and television are required. According to their power these devices are of very basic standard. While the daily per capita water consumption for domestic uses is defined with 5 liters, the energetic requirements for water pumping will be assessed for the whole community. At the end of Table 4-1 the total energy requirements per household and day are summed up. Thereby, an average of 5 habitants per household is considered.

Table 4-2: Minimum energy requirements: service sector – education adapted from (G8, 2001), (Ruijven, et al., 2011)

Human need	Energy end-use	Minimum requirements	Minimum duration or amount	# of devices per school*	Energy needs (koe per community per day)
Food preparation	Cooking	N/A	-	-	-
Water heating	Domestic hot water	0.5 MJ_{UE}	per day (equal to 5 capita)	1	0.0597
Space heating	Ambient heating	T<12°C	for each day	1	0.0359
Space cooling	Ambient cooling	30° C> T	for each day	1	0.2306
Food preservation	Refrigeration	N/A	-	-	-
Illumination	Lighting	1 unit (300 lumens)	4 hours per day	3	0.0411
	Radio	N/A	-	-	-
	Telecommunication	1 unit (11 W)	4 hours per day	1	0.0038
	TV	N/A	-	-	-
	Computer	1 unit (280 W)	4 hours per day	4	0.3838
ICT	Copy machine	1 unit (200 W)	1 hour per day	1	0.0171
	Modem and satellite dish	1 units (110 W)	4 hours per day	1	0.0377
	Other small electrical devices	N/A	-	-	-
Water access	Water pumping	1 liter per capita	per day	see section water pumping	
Comfort space	Floor space	80 m^2			
Comfort & hygiene	Sanitary facilities	5 units per school			
Comfort & hygiene	Sewage system	1 unit per school			
Total energy requirements education (koe per day)					**0.8098**

* The minimum requirements for a school are considering 100 students. If less students are attending the school, the same requirements are considered. Additional needs above the 100 students can be added proportionally; i.e. for 150 students each of the minimum requirements should be increased by 50%

Within the service sector (education) the major end-use are computers which account for almost 50% of all requirements (Table 4-2). Cooking and refrigeration, the major end-uses within the domestic sector, are not accounted. Climate conditions are defined by the location of the community under evaluation.

For health services the requirements are similar to those for education. There is a solid contribution of lighting and ICT, despite the usual space heating and space cooling. The major difference lies in the additional use of medical refrigeration and sterilization devices. These two devices alone account for a substantial share of the requirements within a health center (Table 4-3).

Table 4-3: Minimum energy requirements: service sector – health center adapted from (G8, 2001), (Ruijven, et al., 2011)

Human need	Energy end-use	Minimum requirements	Minimum duration or amount	# of devices per health center*	Energy needs (koe per community per day)
Food preparation	Cooking	N/A	-	-	-
Water heating	Domestic hot water	0.5 MJ_{UE}	per day (equal to 10 capita)	1	0.1194
Space heating	Ambient heating	T<12°C	for each day	1	0.0270
Space cooling	Ambient cooling	30° C> T	for each day	1	0.1729
Food preservation	Medical refrigeration	1 unit (165 W)	24 hours per day	1	0.3393
Illumination	Lighting	1 unit (300 lumens)	8 hours per day	3	0.0823
ICT	Radio	N/A	-	-	-
	Telecommunication	1 unit (11 W)	4 hours per day	4	0.0151
	TV	N/A	-	-	-
	Computer	1 unit (280 W)	4 hours per day	2	0.1919
	Copy machine	1 unit (200 W)	1 hour per day	1	0.0171
	Modem & satellite dish	1 unit (110 W)	3 hours per day	1	0.0283
	Other small electrical devices	N/A	-	-	-
Water access	Water pumping	1 liter per capita	per day	see section water pumping	
Comfort & hygiene	Sterilization	1 unit (500 W)	1 hour per day	1	0.0428
Comfort space	Floor space	60 m²			
Comfort & hygiene	Sanitary facilities	5 units per health center			
Comfort & hygiene	Sewage system	1 unit per health center			
Total energy requirements health center (koe per day)					**1.0361**

* The minimum requirements within the health center consider a community population of 200 inhabitants. If a health center is available for communities with less than 200 inhabitants, then the same minimum requirements are considered. Above the 200 inhabitants the minimum requirements can be added proportionally.

The community center, as the place of frequent gatherings and reunions, has noticeably lower requirements than the services for education and health. They basically only consist of lighting and a bit of ICT. All other end-uses are neglected since they are not essentially required.

Especially heating and cooling needs could be managed through adaptive behavior, such as additional clothing during cooler days or later times of reunions during hot summer days (Table 4-4).

Table 4-4: Minimum energy requirements: service sector – community center adapted from (G8, 2001), (Ruijven, et al., 2011)

Human need	Energy end-use	Minimum requirements	Minimum duration or amount	# of devices per community center*	Energy needs (koe per community per day)
Illumination	Lighting	1 unit (300 lumens)	4 hours per day	1	0.0137
ICT	Radio	N/A	-	-	-
	Telecommunication	1 unit (11 W)	4 hours per day	1	0.0038
	TV	N/A	-	-	-
	Computer	1 unit (280 W)	4 hours per day	1	0.0960
	Copy machine	N/A	-	-	-
	Modem & satellite dish	N/A	-	-	-
	Other small electrical devices	N/A	-	-	-
Water access	Water pumping	0.5 liters per capita	-	see section water pumping	
Comfort & hygiene	Sewage system	N/A			
Total energy requirements community center (koe per day)					**0.1134**

* A community center is considered only if the number of inhabitants exceeds 100. The requirements remain identical up to 200 inhabitants. Thereafter, proportional increases for each additional 50 inhabitants may be considered with a 25% increase based on the initial consumption.

Similar to the community center small businesses have little requirements that are only based on lighting and ICT (Table 4-5).

Table 4-5: Minimum energy requirements: service sector – small businesses adapted from (G8, 2001), (Ruijven, et al., 2011)

Human need	Energy end-use	Minimum requirements	Minimum duration or amount	# of small businesses per community*	Energy needs (koe per community per day)
Illumination	Lighting	1 unit (300 lumens)	4 hours per day	4	0.0548
ICT	Radio	N/A	-	-	-
	Telecommunication	1 unit (11 W)	4 hours per day	4	0.0151
	TV	N/A	-	-	-
	Computer	N/A	-	-	-
	Copy machine	N/A	-	-	-
	Modem & satellite dish	N/A	-	-	-
	Other small electrical devices	N/A	-	-	-
Total energy requirements small businesses (koe per day)					**0.0699**

* Within a small community of up to 200 inhabitants 4 small businesses are considered. Each business requires one lighting and one telecommunication device. Additional needs are not considered to cover the minimum requirements of a small business. Above the 200 inhabitants of a community, an additional small business is considered for each 50 inhabitants.

For public illumination the requirements are straightforward and only depend on the required lumen. In this case 5000 lumen per light are suggested.

Table 4-6: Minimum energy requirements: service sector – public illumination adapted from (G8, 2001), (Ruijven, et al., 2011)

Human need	Energy end-use	Minimum requirements	Minimum duration or amount	# of devices per community*	Energy needs (koe per community per day)
Illumination	Lighting	1 unit (5000 lumens) **	4 hours per day	4	0.1371
Total energy requirements public illumination (koe per day)					**0.1371**

* Within a small community of up to 200 inhabitants 4 devices for public illumination are considered. The requirements remain identical up to 200 inhabitants. Above the 200 inhabitants of a community, an additional public illumination device is considered for each 50 inhabitants.
** The 5000 lumens can be achieved through a 100 W bulb

While access to water is a major concern, frequently this also involves the need of a water pump. Hence, the requirements for each sector and capita are summarized. With a small 60 W pump up to 2.5 liter per minute can be pumped (i.e. this is an average value and does not take into account the absolute pumping height).

For each sector the total consumption has been added up to define the total hours of operation needed. In this specific case 10 hours are used every day to supply all needs within the community. It is assumed in this research that each pump can only work for a maximum of 8 hours per day, mainly during day light when the water is actually being used. Therefore, an additional pump will be required for every time the total duration exceeds an 8-hour window (1 pump for up to 8 hours, 2 pumps for up to 16 hours, etc.). In the end, the actual energetic requirements for domestic and service needs are assessed based on the number of pumps installed and the actual number of working hours.

Table 4-7: Minimum energy requirements: water pumping – domestic and service needs adapted from (G8, 2001), (Ruijven, et al., 2011)

Human need	Energy end-use	Minimum requirements per capita/center*	Minimum duration in h/day**	# of devices***	Energy needs (koe per community per day)
Water pumping (WP)	WP households (60 W)	# capita*5 liter = 100 liter/day	6.67	2	0.1028
	WP education (60 W)	# school*1 liter = 200 liter/day	1.33		
	WP health center (60 W)	# health center*1 liter = 200 liter/day	1.33		
	WP community center (60 W)	# community center*0.5 liter = 100 liter/day	0.67		
		Total	10.00		
Total energy requirements water pumping (koe per day)					**0.1028**

* In this example we assume a representative total population of 200 capita within the community
** A 60 W water pump is expected to pump 25 liters of water in 10 minutes
*** It is assumed that a water pump runs a maximum of 8 hours per day; for each 8 h block that is required an additional pump is needed; if applicable, during peak hours several pumps may work at the same time.

The last sector to be analyzed is agriculture. With that all needs for farming and feedstock shall be taken into account. Due to the diversity of end-use devices and the particular needs within each community it is inappropriate to define minimum requirements by end-use. Instead an overall number for agricultural purposes per household and day is given.

Based on the total number of households within the community a threshold for agricultural needs will be made available (Table 4-8). The frequency and duration to use the devices may then be adapted to the local needs and conditions. In fact, some devices, like electric motors may be used on a daily basis throughout the year, whereas others like the electrical grinding mill or pulveriser only run for a few weeks per year. Yet, most agricultural needs in these isolated areas are driven by human and animal power, which is not accounted for in energetic terms.

Table 4-8: Minimum energy requirements: agriculture adapted from (G8, 2001), (Ruijven, et al., 2011)

Human need	Energy end-use	Minimum requirements	Minimum duration or amount	# of households *	Energy needs (koe per community per day)
Farming and feedstock	Human & animal power	-	-	-	-
	Grain drying Electric grinding mill Electric pulveriser Electric skin pealing machine Electric motors (1 kW)	0.5 kWh per household per day	N/A	40	1.7136
Total energy requirements agriculture (koe per day)					**1.7136**

* A community of 40 households is considered; for each additional/fewer household the minimum requirements can be adjusted accordingly.

In the end, the total MER for the community can be obtained by aggregating the daily consumption for all households and sectorial requirements within the community. With the assumptions of 40 households and 200 inhabitants, the daily energy requirements for the entire community are defined with 27.73 koe. On a daily and yearly per capita basis the values in Table 4-9 are defined.

Table 4-9: Total minimum energy requirements per capita per day and per year

Daily per capita requirements		Yearly per capita requirements	
koe/ capita per day	0.14	koe/ capita per year	50.61
kWh/capita per day	1.61	kWh/capita per year	588.61

4.2. Data input for end-use devices

The data overview provides a comprehensive set of end-uses and potential devices. This set is not limited and may be extended by users of the tool.

Table 4-10 summarizes all devices considered in this research. Devices were gathered from the diverse references in the literature review (see section 2.3 and 2.4). All devices are grouped by end-use, whereas some devices may be used for multiple end-uses (i.e. cooking, DHW and AH or cooking and DHW). Likewise, the same devices may be applied across different sectors.

Table 4-10: Overview of devices by end-use

End-use	Device
Cooking-DHW-AH	Typical open fire (3 stone) Well-tended open fire (3 stone) Rocket stove Wood gas stove LPG ring stove Gas cooktop Paraffin "Primus" stove Kerosene stove Improved liquid fuel stove Improved solid fuel stove Coal stove
Cooking-DHW	Solar cooker Coal brazier (Basa Njengo Magogo) Electric induction stove Electric hotplate/cooktop Biolite
Domestic Hot Water	Electric geyser LPG geyser Solar hot water heater
Ambient Heating	Passive geothermal* Passive solar* Geothermal (Ground source heat pump) Electric heater LPG heater Solar air heating system Kerosene heater
Ambient Cooling	Wind passive * Solar PV fan Electric fan Evaporative cooling (air-water cooler) Electric ventilation Electric water cooler
Food preservation	Passive geothermal* Passive wind* Zeer Pot or Pot-in pot (6 - 30 °C)* Electric - Refrigerator (1 - 4 °C) Medical refrigeration Electric- Freezer (-18 - 0 °C)
Lighting	Biolite + LED (4 W) Candles Kerosene hurricane (lantern) (wick) High pressure (kerosene) lighting lamp Oil lamp (mantle) Oil lamp (Wick) Filament lamp (40 W) Incandescent lighting (40 W) Fluorescent (10 W) Compact fluorescent (CFL) (10 W) Light emitting diodes (LEDs) (4 W) Small portable solar lantern + LED (4 W) Medium portable solar lantern + LED (8 W)
Lighting- Street Lamps	Mercury vapor (gas lamp) (80 W) LED+PV solar street lamps (100 W LED) +Battery
ICT	Computer (desktop with monitor) Copy machine Rasberry Pie OLPXXO-1 computer (laptop) Modem & satellite Portable radio with battery Small radio

Table 4-10 continued

End-use	Device
ICT	Mobile phone with battery and charger TV Other small electrical devices Medical Sterilizator
Water pumping	Mechanical pump* Intermediate tech.: treadle pump* Intermediate tech.: vane-flapping turbine* Electric pump Solar PV DC pump Choti Bijli (diesel genset)
Agriculture machine work	Solar dryer* Human & animal power* Grain/food drying* Electric Grinding mill Electric Pulveriser Electric Skin pealing machine Electric Motor 0.01-100 kW (uses average of 1kW)
Solar water desalination	Several methods (Pearson pump, Clark pump, osmosis)
Water purification	Boiling, distillation, reverse osmosis
Sanitary unit	Sewage system

* Devices are driven by human/animal power or nature itself

Within the table several devices are marked with a star. These so called “Free” devices are powered by humans, animals or directly through nature. From an energetic point of few these devices are not considered in the calculations. However, in areas with no access or very inefficient devices an introduction to these “Free” devices is particularly encouraging to improve the comfort level of life and health conditions. Yet, such devices may also be considered in case the minimum level is already reached.

All listed devices have been analyzed in terms of energy carrier, resource availability, origin of resource, lifetime, cost (investment as well as operation and maintenance cost), expected average daily hours of use, efficiency of appliances, thermal efficiency of cooking and heating appliances, lumen (for lighting only) and power (Appendix 8.4). If no information could be obtained from the literature, inputs were made by the authors’ best judgement.

Resources include wood, dung, residues/waste, LPG, paraffin, oil, kerosene, coal, solar radiation, geothermal, wind, diesel as well as human and animal power. For possible generation units/devices the following are considered: diesel generator, gas generator, hydro generator, wind turbines, solar residential system, PV home system, Pico PV-system, biomass generator and pumped storage. The system size ranges from pico to micro systems, whereas individual units are no bigger than 5 kW; most PV systems are even only a few Watt. Subsequently, the origin of resource may be local, import and import or local. All other data is quantitative.

Additionally, each of the devices has been rated in terms of type of technology and efficiency, whereas 5 categories could be identified: traditional low (traditional technologies with low efficiency), traditional medium, intermediate medium, advanced medium and advanced high.

Lastly, the "x-factor" has been introduced to all devices to better account for their energetic performance. As a matter of fact, some devices use a significant amount of energy, but are extremely inefficient. If such devices were to be implemented across the whole community, then the per capita energy consumption would look rather good. However, it is those devices that lead to false conclusions. With the introduction of a x-factor it is intended to allow higher consumption levels for inefficient devices and lower consumption levels for very efficient devices. The x-factor is based on the consumption level (power) and efficiency, and acknowledges the level of technology of a device when assessing its performance in relation to the required/expected MER. The "Standard" level is considered with a x-factor of 1, which is mainly the case for intermediate technologies, but also the majority of electrical devices. When analyzing cooking devices, for instance, rocket stove and LPG ring stove are associated with a factor of 1, which means they are expected to reach the MER as indicated in the minimum requirements. In contrary, open wood fire is less efficient and very energy consuming, for which reason a factor of 2 has been applied, meaning that the amount of energy to be used through open wood fire may be twice as high as for "Standard" devices. Likewise, very efficient devices like the electric hotplate should only need half the energy of the standard (factor 0.5). For lighting a similar approach has been followed, whereby intermediate technologies such as oil lamps and kerosene lantern were associated with a factor of 1. All other lighting devices have noticeable lower x-factors, since they efficiency is higher and/or power is lower. Indeed, LEDs may only have a x-factor of 0.10 to 0.20. A complete overview of all x-factors by device is presented in the data set of devices in Appendix 8.4.

4.3. Assessment of current energy use

In order to plan adequate solutions for a community, it is vital to undertake a profound and detailed assessment of the current energy use. By means of a survey, as undertaken in (Santos Perez, 2015), (Borofsky, 2015) or (Gram Oorja Solutions Private Limited, 2014) (Appendix 8.5), the applicant will be guided through all stages of the "Current situation" so that all inputs are filled accordingly and information for potential solutions can be identified. Within the survey the number of devices within each household, but also within the community, their daily consumption pattern, or the type of devices in use is evaluated. The type of energy sources, the frequency of usage or the ownership are also important questions to be asked. Additionally, the surveys assess general community information such as the income, occupation of habitants, availability of services, preferences for future devices or the distance to the nearest network or water source.

Such a profound assessment of the current energy use is crucial to identify and diagnose shortages and/or excessive consumption, and also the end-use and/or sector where it occurs. Besides, the assessment validates if the initial expectations of the per capita energy consumption are achieved or if there are "Energy wasting" end-uses. In either way any proposed solutions need to take this initial assessment into account. Plus, it is necessary to define the local resource availability, since this will directly influence the devices eligible for MCDA.

The following order is proposed to assess the current conditions and energy use.

1) Resource availability

Limitations in the choice of end-use devices, but also electricity generating systems will occur if certain resources are unavailable or insufficiently available; i.e. no running water throughout the year prevents the use of hydro generation, or limitations in the import of coal prevent the use of coal fired devices. Hence, all possible resources should be identified.

2) Per capita energy consumption

Correspondingly, to the total useful energy needs UE_T the per capita consumption provides only a glimpse of the current situation, since various conclusions can be drawn from it. Ideally, the UE_{CAP} is already reaching or surpassing the minimum requirements, whereas only limited energy waste and excessive consumption occur. Following this total assessment of energy use, the following steps go into more detail.

3) Sectorial assessment

Follows the assessment of the per capita consumption but provides further details about each sector. Thereby, major shortages and excessive use by sector may already be identified. For the sectorial assessment each sector will be compared with the under the minimum requirements defined values. Major contributors or shortcomings to the per capita consumption can be identified.

4) End-use

Since each service/end-use is expected to be available for each resident and each service, this assessment mainly focusses on the number of devices available to cover each end-use within each sector. All shortcomings and/or additional uses will be highlighted in the spread sheet and can be easily identified. Since additional devices do not contribute to the per capita energy consumption, it is mainly the lack of devices that needs to identified. A large number of missing devices may already explain why the per capita consumption is much lower than expected. In contrary, all additional devices are summarized to identify the additional energy use within the community. All kinds of additional use are considered a means of comfort and not as basic essential requirements.

5) Devices

The devices in use are also a crucial contributor to the per capita consumption. Either very efficient or inefficient devices have a significant impact on the initial per capita assessment. In order to judge the performance of each device, they have been classified in very efficient, efficient (normal) and inefficient for each end-use. As a result of the diverse efficiencies the factors were introduced for a better comparison of the device performance in relation to the minimum requirements.

In the end, the assessment of the current energy use provides an overview of the devices in use and the average daily hours of use respectively. Therefore, the "Base" template has to be filled entirely. An extract of the "Base" template for the input of cooking devices in the domestic sector is presented in Table 4-11.

Table 4-11: Extract of "Base" template for current use of devices for cooking in the domestic sector

End-use	Device	# of devices per household*	Average daily use [hours]*	# of households	Total # of devices per end-use
Cooking	Typical open fire (3 stone)	1.00	7	20	40
	Well-tended open fire (3 stone)	1.00	4	5	
	Rocket stove	1.00	3	1	
	Wood gas stove	1.00	8	14	
	LPG ring stove	-	-	-	
	Gas cooktop	-	-	-	
	Paraffin "Primus" stove	-	-	-	
	Kerosene stove	-	-	-	
	Improved liquid fuel stove	-	-	-	
	Improved solid fuel stove	-	-	-	
	Coal stove	-	-	-	
	Solar cooker	-	-	-	
	Coal brazier (Basa Njengo Magogo)	-	-	-	
	Electric induction stove	-	-	-	
	Electric hotplate/cooktop	-	-	-	
	Biolite	-	-	-	

* The number of devices per household or operating hours may be greater than the MER definition - that needs to be compared with the "MER ref". For input purposes the additional device/hours need to be added as proportion of the actual number of households that use that device; i.e. if one of the 9 households with a kerosene stove was using a second kerosene stove, then the # of device per household was 1 plus 1/9 = 1.11. In the energetic assessment only one device is considered in the MER, the second one is considered as additional (comfort) requirement. In the same manner, the average daily hours of use are assessed. If a household uses more than the defined minimum – that needs to be compared with the MER ref – then the additional proportional requirements need to be added.

For all other end-uses and sectors the same information has to be filled, whereas profound surveys within the community are encouraged. As it can be seen from the extract of the “Base” template, the input data has a significant impact on the assessment of the current situation. Any discrepancies from the MER definition may either lead to a lack of energy devices (access) or additional energy requirements.

From the energetic perspective only the consumption as per “MER ref” is considered for further comparison with the “MER X”. The additional requirements will be highlighted in the “Base” template and are extracted in a separate energetic assessment of comfort requirements. This is particularly important for ambient heating, since the inclusion of any ambient heating devices leads to additional comfort requirements. All ambient heating requirements as per “MER ref” are already expected to be covered through the “Wasted heat” of cooking and domestic hot water devices.

4.4. Multi-criteria decision aid for device and technology selection

Within the MCDA the primary step is the definition of the applied criteria. Based on the author this research uses a total of 16 criteria from 5 different groups (Re. = resource, En. = environmental, Ec. = economic, So. = social and Tc. = technical). Each group consist of 2 (Ec. and En.) or 4 (Re., So. and Tc.) criteria (Table 4-12). Descriptions for the scoring scale are provided for each criterion to help decision makers in the scoring process. Plus, an indication about the minimization or maximization of the value functions is made.

The following qualitative scoring scale is applied: 0 unsuitable, 3 partially suitable, 6 suitable and 9 extremely suitable. Default values of attribute scores have been provided based on the authors best judgement for each of the 16 criteria (Appendix 8.6). This set may be applied by applicants of the tool, in case they cannot provide all attribute scores by themselves.

Table 4-12: Overview of criteria and description for scoring process

Aspect	Code	Criteria	Minimization or maximization	Description for scoring process
Resource	RE.1	Import dependency	Min	Only local use = 0, local & import use = 3, local or import = 6, only import = 9
	RE.2	Conflict between resource usage	Min	No conflict = 0, minor conflict for local resources = 3, conflict for imported resources = 6, conflict for all resources = 9
	RE.3	Land use to grow and store resource	Min	Very small = 0, small = 3, medium = 6, large = 9
	RE.4	Local resource use	Max	Rarely available = 0, sometimes available = 3, frequently available = 6, always available = 9
Environmental	EN.1	Emission	Min	Large reduction = 0, medium reduction = 3, small reduction = 6, very small reduction = 9
	EN.2	Indoor/local pollution	Min	Large reduction = 0, medium reduction = 3, small reduction = 6, very small reduction = 9

Table 4-12 continued

Aspect	Code	Criteria	Minimization or maximization	Description for scoring process
Economic	EC.1	Investment cost	Min	Very low cost = 0, low cost = 3, medium cost = 6, high cost = 0
	EC.2	Operation and maintenance cost	Min	Very low cost = 0, low cost = 3, medium cost = 6, high cost = 0
Technical	TC.1	Ease of use	Max	Complex use = 0, difficult use = 3, medium use = 6, easy use = 9
	TC.2	Efficiency	Max	Low efficiency = 0, medium efficiency = 3, high efficiency = 6, very high efficiency = 9
	TC.3	Implementation time for device/ technology	Min	Short term = 0, medium term = 3, long term = 6, very long term = 9
	TC.4	Level or degree of technology	Max	Traditional = 0, medium and intermediate = 3, modern and high = 6, very advanced= 9
Social	SO.1	Human vulnerability, pollutant, disease	Min	Very little = 0, little = 3, more than a bit = 6, a lot = 9
	SO.2	Social benefit	Max	Low = 0, medium = 3, high = 6, very high = 9
	SO.3	Social acceptability	Max	Low = 0, medium = 3, high = 6, very high = 9
	SO.4	Level of comfort	Max	Low = 0, medium = 3, high = 6, very high = 9

In order to apply swing weights the criterion with the most valued transition from worst to best has to be selected. Since linear value functions are applied and the scoring scale is defined, the value functions can be built accordingly. The minimization (e.g. import dependency or investment cost, etc.) and maximization (efficiency or social benefit, etc.) are presented in Figure 4-2: Minimization and maximization of value functions. The last step that remains from the decision makers side is the definition of the most valued criterion so that all remaining criteria swings can be set in relation.

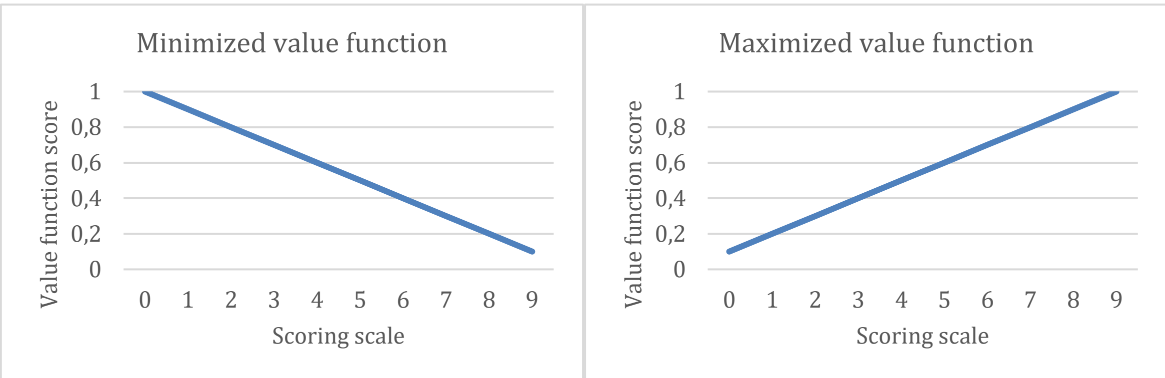

Figure 4-2: Minimization and maximization of value functions

Succeeding the local resource assessment and the criteria and attribute value definitions, criteria weights have to be defined to evaluate and order all applicable devices for each end-use. For devices with multiple end-uses (cooking, DHW and AH as well as cooking and DHW) only one overall ranking is applied.

4.5. Building options

In order to build the 5 MER options for further analysis, a variety of devices and supply technologies were gathered from diverse references that have been analyzed in the literature review (see section 2.3 and 2.4). No individual reference or group of studies provided a comprehensive overview as the one in Table 4-13. From the multitude of devices available the author grouped a selected number by end-use, whereby multiple end-uses were associated to the same device if needed. Simultaneously, devices and supply technologies are grouped by resource (fossil, renewables or either/both of the two) and technology level. Thereby, emphasis was placed on assigning intermediate technologies to end-uses where possible. Plus, energy free devices were explored, since they only require some constructural/architectural changes, simple constructions or run on human and/or animal power.

Table 4-13: Categorization of devices and supply technologies to build options

End-use	Device	Type		1) RES	2) Fossil fuels	3) Intermediate	4) "Free" devices
Cooking-DHW-AH	Typical open fire (3 stone)	RES	Trad	✓			
	Well-tended open fire (3 stone)	RES	Trad	✓			
	Rocket stove	RES/fossil	Int	✓		✓	
	Wood gas stove	RES/fossil	Int	✓	✓	✓	
	LPG ring stove	Fossil	Adv		✓		
	Gas cooktop	Fossil	Adv		✓		
	Paraffin "Primus" stove	Fossil	Trad		✓		
	Kerosene stove	Fossil	Int		✓	✓	
	Improved liquid fuel stove	Fossil	Adv		✓		
	Improved solid fuel stove	RES	Int	✓		✓	
	Coal stove	Fossil	Trad		✓		
Cooking-DHW	Solar cooker	RES	Adv	✓			
	Coal brazier (Basa Njengo Magogo)	Fossil	Trad		✓		
	Electric induction stove	RES	Adv	✓			
	Electric induction stove	Fossil	Adv		✓		
	Electric hotplate/cooktop	RES	Adv	✓			
	Electric hotplate/cooktop	Fossil	Adv		✓		
	Biolite	RES	Adv	✓			
Domestic Hot Water	Electric geyser	RES	Adv	✓			
	Electric geyser	Fossil	Adv		✓		
	LPG geyser	Fossil	Adv		✓		
	Solar hot water heater	RES	Adv	✓			
Ambient Heating	Passive geothermal	RES	Pas				✓
	Passive solar	RES	Pas				✓
	Geothermal (Ground source heat pump)	RES	Adv	✓			
	Electric heater	RES	Adv	✓			
	Electric heater	Fossil	Adv		✓		
	LPG heater	Fossil	Adv		✓		
	Solar air heating system	RES	Adv	✓			
	Kerosene heater	Fossil	Int		✓	✓	

Table 4-13 continued

End-use	Device	Type		1) RES	2) Fossil fuels	3) Intermediate	4) "Free" devices
Ambient Cooling	Wind passive	RES	Pas				✓
	Solar portable PV fan	RES	Adv	✓			
	Electric fan	RES	Int	✓		✓	
	Electric fan	Fossil	Int		✓	✓	
	Evaporative cooling (air-water cooler)	RES	Adv	✓			
	Evaporative cooling (air-water cooler)	Fossil	Adv			✓	
	Electric ventilation	RES	Adv	✓			
	Electric ventilation	Fossil	Adv		✓		
	Electric water cooler	RES	Adv	✓			
	Electric water cooler	Fossil	Adv		✓		
Food preservation	Passive geothermal	RES	Pas				✓
	Passive wind	RES	Pas				✓
	Zeer Pot or Pot-in pot (6-30 °C°)	RES	Int			✓	
	Electric - Refrigerator (1-4 °C)	RES	Adv	✓			
	Electric - Refrigerator (1-4 °C)	Fossil	Adv		✓		
	Electric- Freezer ((-18)- 0 °C)	RES	Adv	✓			
	Electric- Freezer ((-18)- 0 °C)	Fossil	Adv		✓		
Lighting	Biolite + LED (4 W) heat, charge & light	RES	Adv	✓			
	Candles	Fossil	Trad		✓		
	Kerosene hurricane (lantern) (wick)	Fossil	Int		✓	✓	
	High pressure (kerosene) lighting lamp	Fossil	Int		✓	✓	
	Oil lamp (mantle)	Fossil	Int		✓	✓	
	Oil lamp (Wick)	Fossil	Int		✓	✓	
	Filament lamp (40 W)	RES	Adv	✓			
	Filament lamp (40 W)	Fossil	Adv		✓		
	Incandescent lighting (40 W)	RES	Adv	✓			
	Incandescent lighting (40 W)	Fossil	Adv		✓		
	Fluorescent (10 W)	RES	Adv	✓			
	Fluorescent (10 W)	Fossil	Adv		✓		
	Compact fluorescent (CFL) (10 W)	RES	Adv	✓			
	Compact fluorescent (CFL) (10 W)	Fossil	Adv		✓		
	Light emitting diodes (LEDs) (4 W)	RES	Adv	✓			
	Light emitting diodes (LEDs) (4 W)	Fossil	Adv		✓		
	Small portable solar lantern + LED (4 W)	RES	Adv	✓			
	Medium portable solar lant. + LED (8W)	RES	Adv	✓			
Lighting-Street Lamps	Mercury vapor (gas lamp) (80 W) with electricity function	Fossil	Adv		✓		
	LED+PV solar street lamps (100 W LED) +Battery	RES	Adv	✓			
ICT	Computer (desktop with monitor)	RES	Adv	✓			
	Computer (desktop with monitor)	Fossil	Adv		✓		
	Copy machine	RES	Adv	✓			
	Copy machine	Fossil	Adv		✓		
	Raspberry Pie	RES	Adv	✓			
	Raspberry Pie	Fossil	Adv		✓		
	OLPXXO-1 computer (laptop)	RES	Adv	✓			
	OLPXXO-1 computer (laptop)	Fossil	Adv		✓		
	Modem & satellite	RES	Adv	✓			
	Modem & satellite	Fossil	Adv		✓		
	Portable radio with battery	RES/Fossil	Adv	✓	✓		
	Small radio	RES	Adv	✓			
	Small radio	Fossil	Adv		✓		
	Mobile phone with battery and charger	RES	Adv	✓			
	Mobile phone with battery and charger	Fossil	Adv		✓		
	TV	RES	Adv	✓			
	TV	Fossil	Adv		✓		

Table 4-13 continued

End-use	Device	Type		1) RES	2) Fossil fuels	3) Intermediate	4) "Free" devices
ICT	Other small electrical devices	RES	Adv	✓			
	Other small electrical devices	Fossil	Adv		✓		
	Electrical Medical Sterilization	RES	Adv	✓			
	Electrical Medical Sterilization	Fossil	Adv		✓		
Water pumping	Mechanical pump	RES	Int				✓
	Intermediate tech.: treadle pump	RES	Int				✓
	Intermediate tech.: vane-flapping turbine	RES	Int				✓
	Electric pump	RES	Adv	✓			
	Electric pump	Fossil	Adv		✓		
	Solar PV DC pump	RES	Adv	✓			
	Choti Bijli (diesel genset)	Fossil	Adv		✓		
Agriculture machine work	Solar dryer	RES	Pas				✓
	Human & animal power	RES	Trad				✓
	Grain/food drying	RES	Pas				✓
	Electric Grinding mill	RES	Int	✓		✓	
	Electric Grinding mill	Fossil	Int		✓	✓	
	Electric Pulveriser	RES	Adv	✓			
	Electric Pulveriser	Fossil	Adv		✓		
	Electric Skin pealing machine	RES	Adv	✓			
	Electric Skin pealing machine	Fossil	Adv		✓		
	Electric Motor 0.01-100 kW (uses average of 1kW)	RES	Adv	✓			
	Electric Motor 0.01-100 kW (uses average of 1kW)	Fossil	Adv		✓		
Electricity generating systems	(Micro-) Local Diesel generator	Fossil	Int		✓		
	(Micro-) Local PV-diesel system	RES/Fossil	Adv	✓	✓		
	(Micro-) Local Gas generator	Fossil	Adv		✓		
	(Micro-) Local Hydro generator (>5kW)	RES	Adv	✓			
	(Micro-) Local Wind generators	RES	Adv	✓			
	Local solar residential system (250W-4kW)	RES	Adv	✓			
	Local PV home system (up to 250W)	RES	Adv	✓			
	Local (Pico-) PV Pico system (1-10W)	RES	Adv	✓			
	(Micro-) Local Biomass power generator	RES	Adv	✓			
	Local Pumped storage	RES	Adv	✓			
	(Pico-)Wind Pico system (<100W)	RES	Adv	✓			
	(Pico-) Hydro system (<5kW)	RES	Adv	✓			

It is intended to meet the minimum energy requirements (MER) for each of the 5 options. Therefore, devices will be selected for each sector and end-use based on the results of the MCDA and according to the definitions of each MER option. The use of “Free” devices is always encouraged. Due to the limited information about their performance and consumption, free devices are not considered within the energetic assessment. Yet, these devices can, in combination with the proposed end-use devices, improve the level of living and comfort. The actual number of end-use devices available for each of MER option highly depends on the local conditions (for electricity generating systems) and the possibilities of imports.

In the same manner devices are associated to each “MER X”, a supply technology is selected for each option based on the MER definition, resource availability and MCDA.

4.6. Evaluation and comparison of MER options

With the options built, the next step is the energetic assessment. Hence, the tool compares the "MER X" with the "Base" and "MER ref". All energetic data is comprised in the "Results" template. The deciding question is if the "MER ref" is met by each of the "MER X". According to the selected end-use devices different levels of the MER may be achieved. Any discrepancies of the minimum requirements due to altered device efficiencies are highlighted through an adjusted "MER ref" value which takes into account the actual number of devices in use, the average daily hours of use and the x-factor. At the same time, the comparison defines gaps of energy use (i.e. the number of devices always must converge with the target; however, the energy use may be lower for some end-uses if a device is more efficient than the value defined through the x-factor), additional requirements and wasted energy for each end-use.

Succeeding the energetic assessment, all options are subject to further appraisals. This starts with the monetary assessment, which calculates the total annual system cost. There is a maximum of five cost components: I) device cost, II) O&M cost of non-electrical devices, III) investment cost of electricity generating system, IV) fixed O&M of electricity generating system, and V) variable O&M of electricity generating system. While I) and II) were already listed in the data input of section 4.2 (See also Appendix 8.4), III), IV) and V) are summarized in Table 4-14 along with further parameters for the cost analysis (Black & Veatch, 2012), (Tidball, Bluestein, Rodriguez, & Knoke, 2010), (Lazard, 2014). This includes the lifetime and subsequently the annual investment cost; i.e. all costs are broken down into annual present values (any kind of externalities or economic parameters are excluded regardless of the higher investment costs in the beginning of renewable energy projects compared to fossil fuels). Besides, the capacity factor under which each generating system usually operates and the typical system size (power) are presented.

In order to associate costs to each option, the capacity and annual consumption of the electricity generating system need to be identified. Thus, for each option the power of all electrically driven devices (i.e. peak capacity) and their annual consumption have to be summed up across the whole community. In the final step of the monetization all results can be compared across the MER options and the according suitable supply technologies. A preference order can be achieved for each MER by ordering the costs from lowest to highest.

Table 4-14: Technical and economic parameters of electricity generating systems (Black & Veatch, 2012), (Tidball, Bluestein, Rodriguez, & Knoke, 2010), (Lazard, 2014)

Electricity generating system	Lifetime [years]	IC [Euro/kW]	Annual IC [Euro/kW]	Fixed O&M [Euro/kW]	Var O&M [Euro/kWh]	Capacity factor [%]	Power [W]
(Micro-) Diesel generator (>1 kW)	25	800	32	15	0.35	60	1,000
(Micro-) PV-diesel System (>1 kW)	25	1,500	60	6	0.28	65	1,000
(Micro-) Gas generator (> 1 kW)	10	500	50	20	0.25	60	1,000
(Micro-) Hydro generator (>5 kW)	75	3,700	49	85	0.10	60	5,000
(Pico-) Hydro system (< 5 kW)	75	4,000	53	85	0.13	60	5,000
Pumped storage (> 10 MW)	75	3,700	49	85	0.27	20	100,000
(Micro-) Wind generators (>1 kW)	20	2,500	125	25	0.10	40	1,000
(Pico-) Wind system (200 W)	20	3,000	150	30	0.16	40	200
Solar Residential system (250-4000 W)	25	3,000	120	15	0.23	20	4,000
PV home system (up to 250W)	25	4,000	160	20	0.25	20	250
(Pico-) PV system (1-10W)	25	4,500	180	30	0.27	20	10
(Micro-) Biomass power generator (> 1 kW)	20	3,800	190	95	0.13	40	1,000

With the preference orders from MCDA I and from the monetization the next step is an evaluation of a full range of possibilities. Therefore, all preference orders are combined in the "Results" template for each suitable supply technology by "MER X".

In order to assess the preference of costs over MCDA or vice versa varied emphasis on the cost and MCDA values is proposed. Initially, both the MCDA I and cost preferences are considered with the same weight (50/50). Then the preference combinations of MCDA/cost are altered from 10/90 to 90/10. In that manner, 9 combined possibilities are assessed for each of the electricity generating systems per "MER X".

The final part of the appraisal process focusses on the identification of the most dominant combination of MER option and supply technology, where MCDA is applied. For that the "MCDA II" template with three criteria (local resource availability, total system cost and local acceptance) is created. Within the spread sheet the total system cost across all "MER X" and supply technologies are transformed into a value scale for costs, where a linear value function is built. Since the objective is to minimize costs, the highest value is associated to the lowest costs. For the resource availability and the local acceptance, qualitative scoring scales are applied. Both criteria are to be maximized through linear value functions. Hence the value functions follow the illustration of Figure 4-2 in section 4.4.

All three criteria use a value scale from 0 to 100. The extended scale in comparison to the assessment of the devices and supply technologies (in MCDA I) is proposed to better reflect and differentiate the impact the combination of each MER option and possible supply technology have.

Based on the value scales the success of alternatives against pairs of attributes can be plotted. With the defined criteria three possible plots can be illustrated. Within each plot the preference of an attribute pair increases towards the top right corner.

In the last step of MCDA II swing weights are applied to each criterion. Thereafter, the overall value functions for each combination of "MER X" and supply technology are defined.

After the results for each of the 3 appraisal phases are obtained, sensitivity analysis is imposed and summarized in template "MER sen". Through changes in the parameters the robustness of a solution is assessed. According to the appraisals performed, sensitivity focusses on changes of all cost components in the monetization and full range of possibilities phase. Each of the 5 cost components undergo cost increases and decreases in the range of ±10%, ±20% and ±30%. Further differentiations are not applied, since larger variations (mainly reductions) may only be reasonable for the investment cost of renewables. For the MCDA II the effects of varying weight values for each criterion are investigated.

5. Results of case study

5.1. General overview of Bihar, India

Energy access remains a major challenge for remote and/or isolated communities across South-Asia and Africa. Based on the potential to improve access for millions of people, who are confronted by similar conditions (not necessarily geographically, but politically, technologically, economically and socially), India has been selected to apply the proposed methodology. Simultaneously, India was the likely choice due to local connections and the presence of the Tata-Institute in Bihar, India, which works in close cooperation with MIT and furthermore with the MPP (MIT Portugal Program).

Bihar is one of the Indian states with the worst conditions when it comes to energy access and living standards alike. Bihar is located in the North-East of India and has borders with Nepal in the North and Bangladesh in the East (Figure 5-1).

Figure 5-1: Map of Bihar and location within India (India Map Store, 2017)

According to the 2011 state census Bihar has a population of around 104 Million inhabitants. Amongst the 20 most populated states in India it has seen the highest increase in the number of habitants (25.42%) between 2001 and 2011. Apart from the 5 smallest states Bihar also has the highest population density (more than 1,100 per km^2). In terms of literacy Bihar (61.80%) shows the lowest rate across the whole country (Office of the director of census operations, Bihar, 2011). Moreover, the population living below the poverty line[30] in terms of monthly per-capita expenditure is 42.1% in rural areas (Singh, Singh, Meena, & Kumar, 2013). Thus, the poor living conditions are a major driver for the use of solid fuels in poorly ventilated or cramped conditions that cause heavy indoor air pollution, respiration diseases and hazards.

One of the districts in Bihar with the highest rural population is Kaimur (95.97%), also known as Bhabhua, in the far south-west of Bihar. Within the district only 35.71% of communities have access to paved roads. The limited infrastructure is reflected through the fact that there is only one hospital available for every 5955 persons. Likewise, there is only one post office for each 1440 rural households and one bank per 2881 rural households (NREGA, 2010). The limitations within the district can be explained with the demanding geography. Kaimur is divided in a hilly area and a plain area. The hilly area comprises the Kaimur plateau and the plain western side is flanked by the rivers Karmanasha and Durgawati. Also, the climate in the district is somewhat extreme, i.e. quite hot during the summer and fairly cold during the winter. January is the coolest month with a mean minimum of 4°C and May is the hottest month with temperatures as high as 45°C. The rain season starts in mid-June and lasts until mid-September. Sometimes winter rains occur in January and February (NREGA, 2010).

From the 609 communities in Kaimur the majority is already electrified (75.5%). Despite having some areas in the district with an electrification rate close to zero, many of the communities are already using some form of electrical devices (lighting, TV, mobile or radio). The household electricity access amongst most community's ranges between 5 and 25 percent (Vasudha Foundation, 2013). Nevertheless, the population with access to clean and modern sources of energy (i.e. LPG, electricity or biogas) for cooking and heating is only 2.03%, which means that close to 98% of the population depends on polluting firewood, crop residue or dung (Vasudha Foundation, 2013).

5.2. Overview of community resource availability and energy used

Based on the limited budget and time a complete data set along with all local conditions, devices in use and decision maker input could not be gathered for an entire community. It was neither possible to arrange a longer field visit nor to establish a collaboration with an institute

[30] The poverty line refers to the minimum amount of money a person needs for living. In 2015 the world bank raised the poverty line from $1.25 in 2005 to $1.90 (The World Bank, 2015).

on site.[31] For those reasons, the insights of multiple studies within the MIT energy initiative, that focus on energy access challenges in isolated communities (Mwalenga, 2012), (Borofsky, 2015), (Santos Perez, 2015), (Vivian, 2016), were revised when combining the integrated hypothetical community and to validate the proposed methodological approach.

In order to keep the conditions for the community under evaluation as realistic as possible local aspects in and around the community were the first to be defined. Then an overview of the devices in use and consumption pattern had to be gathered. With the purpose of meeting all input requirements, this research considers two locations for input data. On the one side, the community of Sarwandag in Bihar is selected due to the poor energy access conditions within the state, but particularly for the community itself, and the therefore high potential to immediately apply this research to many similar communities within the state. On the other side, comprehensive energy data for a community with similar climatic conditions had to be collected, whereas the research of Gram Oorja Solutions Ltd. investigates such a case in their field study of Navapada in Maharashata (Gram Oorja Solutions Private Limited, 2014).

Sarwandag is located on a small plateau in the Adhaura block, around 150 km South-West of Patna; Kaimur districts capital (Figure 5-2). The community is surrounded by agricultural land in close proximity to the households. The nearest access to the North-Eastern river Dhoaba is around 3 km away from the community's center. There is only one small unpaved road leading to the community. The nearest main road is more than 10 km away. Likewise, there is no power network adjacent. Being located on a plateau, the community has good conditions to explore solar and wind. Likewise, the community is surrounded by forest areas, which are considered the major resource to fulfil the current energy needs.

The energetic requirements of the Navapada community in Maharashata consider a population of 200 inhabitants and 34 households. Besides, the community is home to 60-70 cattle. Water for domestic uses is lifted manually from a well and for agricultural purposes only rain water is available. The cattle are brought to the nearby river. The precipitation is much alike that of the Sarwandag community in Bihar, only the daily temperature differences are not as high. Since there is no power network available, the major resources are firewood, dung and kerosene. Electricity is only scarcely available in the form of small diesel generators and PV pico-systems (up to 10 W), mainly for some refrigeration, AC, lighting and ICT devices.

[31] Attempts were made to contact the Indian Ministry of Statistics and Program Implementation, India Stat as well as further researchers in this field. Yet, if responses were to be obtained the general consent was that the required data would be too complicated, time consuming and costly to be achieved, especially since field studies at the site locations would need to be undertaken.

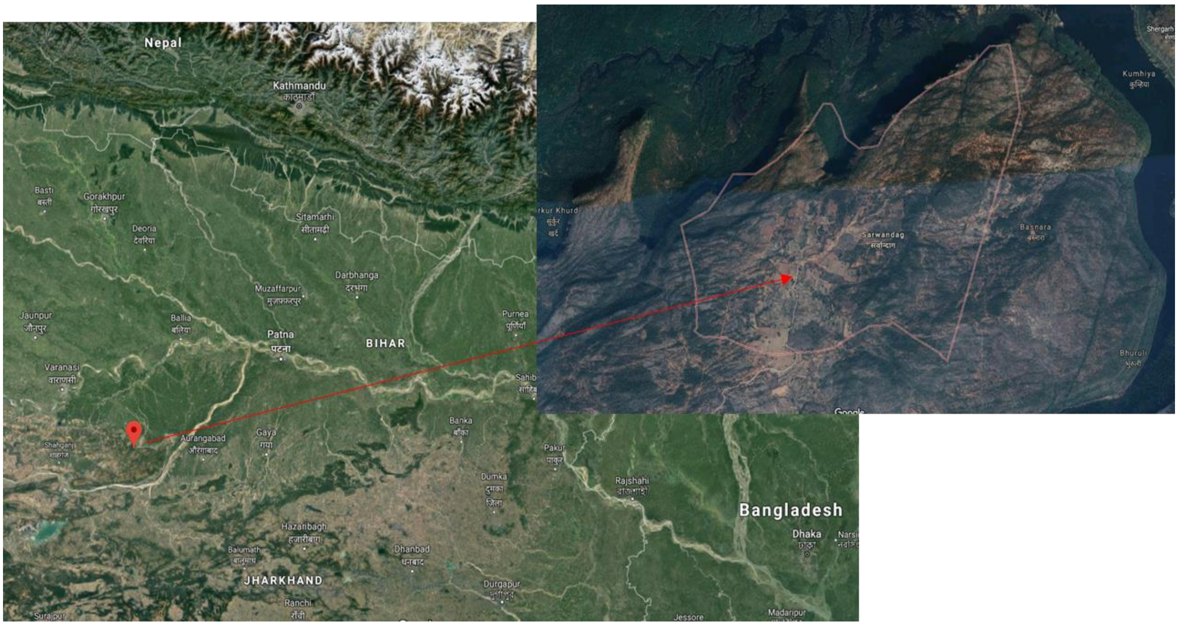

Figure 5-2: Location of Sarwandag community in Bihar (Google, 2017)

An overview of the devices in use for each service (end-use) and sector is presented in Table 5-1. Thus, the high dependency on local biomass resources becomes obvious. While in the domestic sector and for education most services are covered through multiple devices, the community has no health center, no community center and no public lighting. Hence, there is a substantial lack of devices for those end-uses. At the same time, water pumping for domestic and service needs as well as agricultural needs are covered through human and/or animal power. Accordingly, there is a lack of devices for those end-uses.

Table 5-1: Overview of current devices in use (Navapada)

Sector	Service (end-use)	Device	# per device	Total per end-use	# should be per end-use	# lack of end-use devices	# additional end-use devices
Domestic	Cooking	Typical open fire (3 stone)	12	34	34	-	-
		Well-tended open fire (3 stone)	7				
		Rocket stove	6				
		Kerosene stove	9				
	DHW	Typical open fire (3 stone)	12	34	34	-	-
		Well-tended open fire (3 stone)	7				
		Rocket stove	6				
		Kerosene stove	9				
	AH	Typical open fire (3 stone)	12	34	34	-	-
		Well-tended open fire (3 stone)	7				
		Rocket stove	6				
		Kerosene stove	9				
	AC	Electric fan	16	16	34	18	-
	FP	Refrigerator	24	24	34	10	-

Table 5-1 continued							
Sector	**Service (end-use)**	**Device**	**# per device**	**Total per end-use**	**# should be per end-use**	**# lack of end-use devices**	**# additional end-use devices**
Domestic	Lighting	Candles 1	5	34	34	-	-
		Kerosene hurricane (lantern) (wick)	2				
		Oil lamp (mantle)	3				
		Filament lamp (40 W)	20				
		Medium portable solar lantern + LED (8 W)	4				
	ICT	Portable radio with battery	10	34	34	-	-
		Small radio	24			-	-
		Mobile Phone/battery/charger	30	30	34	4	-
		TV	20	20	34	14	-
Education	Cooking	-	-	-	-	-	-
	DHW	-	-	-	1	1	-
	AH	-	-	-	1	1	-
	AC	Electric fan	3	3	1	-	2
	FP	-	-	-	-	-	-
	Lighting	Filament lamp (40 W)	4	4	3	-	1
Education	ICT	Computer (desktop with monitor)	1	1	4	3	-
		Copy machine	-	-	1	1	-
		Modem & satellite dish	-	-	1	1	-
		Portable radio with battery	1	1	-	-	1
		Mobile Phone/battery/charger	-	-	1	1	-
Health center	Cooking	-	-	-	-	-	-
	DHW	-	-	-	1	1	-
	AH	-	-	-	1	1	-
	AC	-	-	-	1	1	-
	FP	-	-	-	1	1	-
	Lighting	-	-	-	3	3	-
	ICT	Computer (desktop with monitor)	-	-	2	2	-
		Copy machine	-	-	1	1	-
		Modem & satellite dish	-	-	1	1	-
		Mobile Phone/battery/charger	-	-	4	4	-
		Sterilization	-	-	1	1	-
Community center	Lighting	-	-	-	1	1	-
	ICT	Computer (desktop with monitor)	-	-	1	1	-
		Mobile Phone/battery/charger	-	-	1	1	-
Small businesses	Lighting	Incandescent lighting (40 W)	4	4	4	-	-
	ICT	Mobile Phone/battery/charger	4	4	4	-	-
Public Illumination	Lighting	-	-	-	4	4	-
Water pumping	Water pumping	-	-	-	2	2	-
Agriculture	Agriculture	-	-	-	5	5	-

Since the number of devices that should be available for each end-use is also summarized in Table 5-1, it can easily be followed where the community has a lack of devices or already uses additional ones (i.e. education). The number of devices expected to be used is based on the "MER ref" (see section 4.1) which is following the investigations of the literature review. While the energetic needs for almost all sectors, except the domestic and agricultural ones, are usually set in reference to the number of inhabitants –in the "MER ref" we consider 200 inhabitants – the energetic needs can also be applied to the selected Navapada community as it has the same count of inhabitants. Consequently, adjustments to the minimum requirements had only to be made for the domestic and agricultural sectors and the accounted number of devices – now 34 instead of the 40 which were considered in the initial "MER ref".

In what regards the daily operating hours, the research of Gram Oorja Solutions Ltd. also provides helpful input (Gram Oorja Solutions Private Limited, 2014). Indeed, the average daily use for the various devices and end-uses is very much in line with the numbers that were gathered for the "Data" template. Therefore, no adjustments for the calculations within the "MER ref" in terms of hours of use have been considered.[32]

The results of the "MER ref" for the case study are summarized in Table 5-2, where the daily consumption within the entire community is 23.89 koe. The comparison of results with Table 4-9 in section 4.1 highlights the noticeably lower MER per capita (approximately 15% less), which is solely driven by the fact that the number of devices within each household is shared by a higher number of inhabitants.

Table 5-2: Total MER per capita per day and per year for current situation of case study

Daily per capita requirements		Yearly per capita requirements	
koe/ capita per day	0.12	koe/ capita per year	43.59
kWh/capita per day	1.39	kWh/capita per year	506.99

Moving back to the overview of the actual count of devices within each end-use of the community (Table 5-1), the lack of devices has been set in relation to expected number of devices as per MER definition (Figure 5-3). It shows where the community is missing devices for each end-use and how many devices should be in use for each end-use and sector. As a matter of fact, it can be seen that devices are basically missing in all sectors, except for small businesses. Hence, the MER cannot be fulfilled.

[32] Since cooking, DHW and AH all have very different requirements in terms of hours of use, no differentiation from the "MER ref" in section 4.1 has been made. In order to account the average daily hours of use for different devices, a modified MER with consideration of the actual type of device, its expected hours of use and x-factor has been provided for comparison in the target-performance comparison.

To set the current number of devices in relation to the absolute energy consumption, it is important to note that, with the inclusion of wasted heat for AH, the current consumption is already more than twice as high as the MER requirements considering current number of devices and x-factor. This is an indication about the performance of devices currently in use and leads to the conclusion that the community is wasting a substantial amount of energy due to the inefficiency of cooking/DHW/AH devices. In fact, the poor efficiency of those devices leads to a higher amount of wasted heat than the actual energy requirements within the community without considering wasted heat.

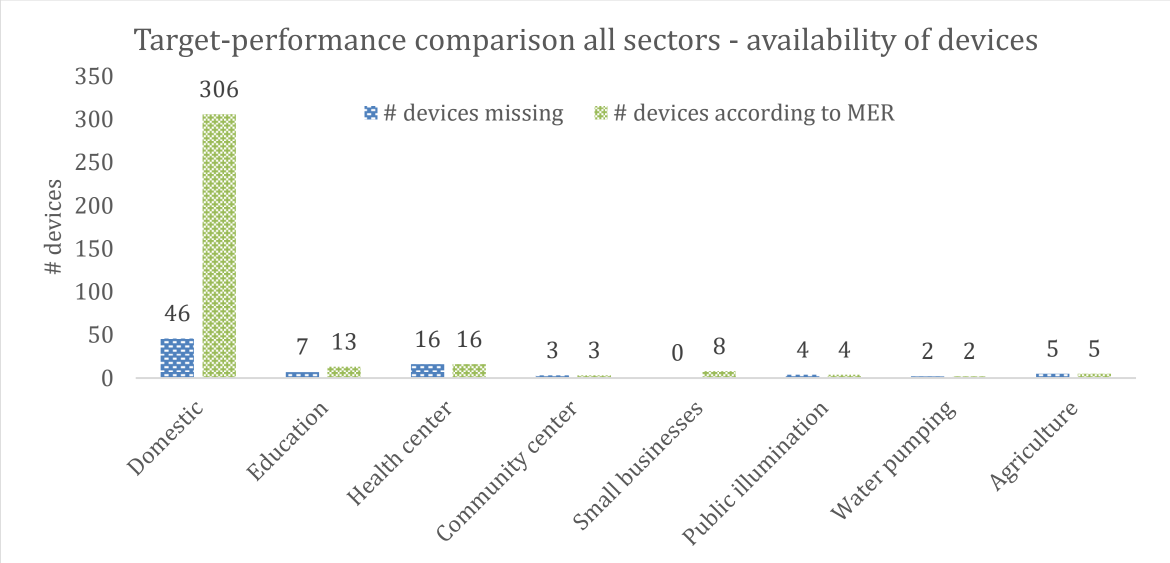

Figure 5-3: Target-performance comparison – devices in use

The issue with wasted heat can clearly be seen from Figure 5-4, where the target-performance comparison for the domestic sector is shown. While almost all end-uses have comparable values as defined in the “MER ref”, it is the wasted heat (as byproduct from devices with multiple end-uses) within ambient heating that puts the performance of the community at risk.

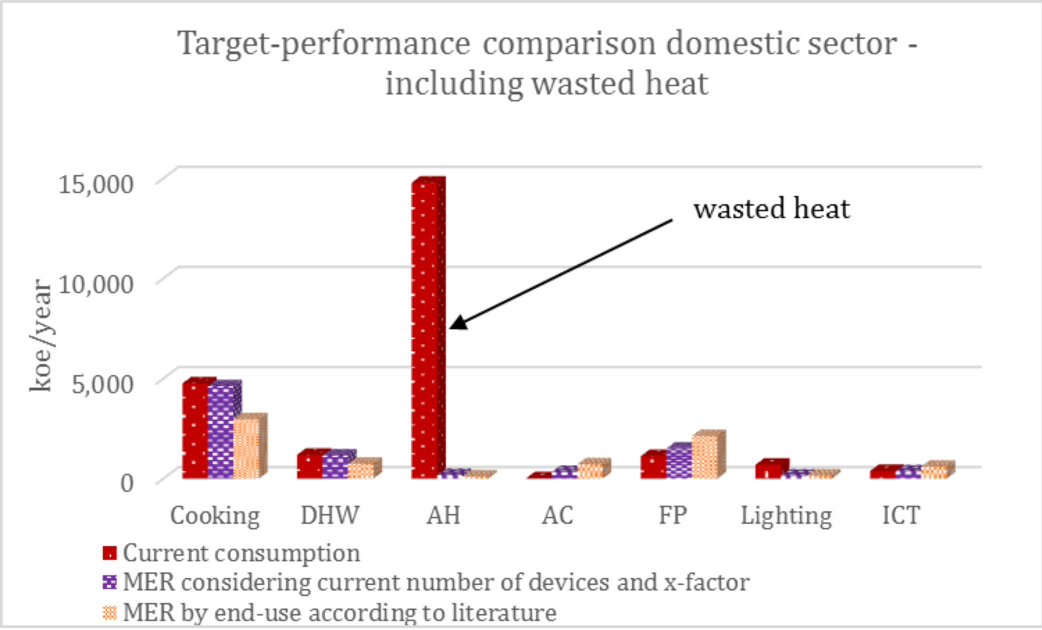

Figure 5-4: Effect of wasted heat on energetic performance

An adjusted target-performance comparison without the consideration of wasted heat for the domestic sector is presented in Figure 5-5. With that a better understanding of the actual performance of devices by end-use can be obtained. For cooking the current consumption (red bar) is noticeably higher than the MER defined in the literature (orange bar).

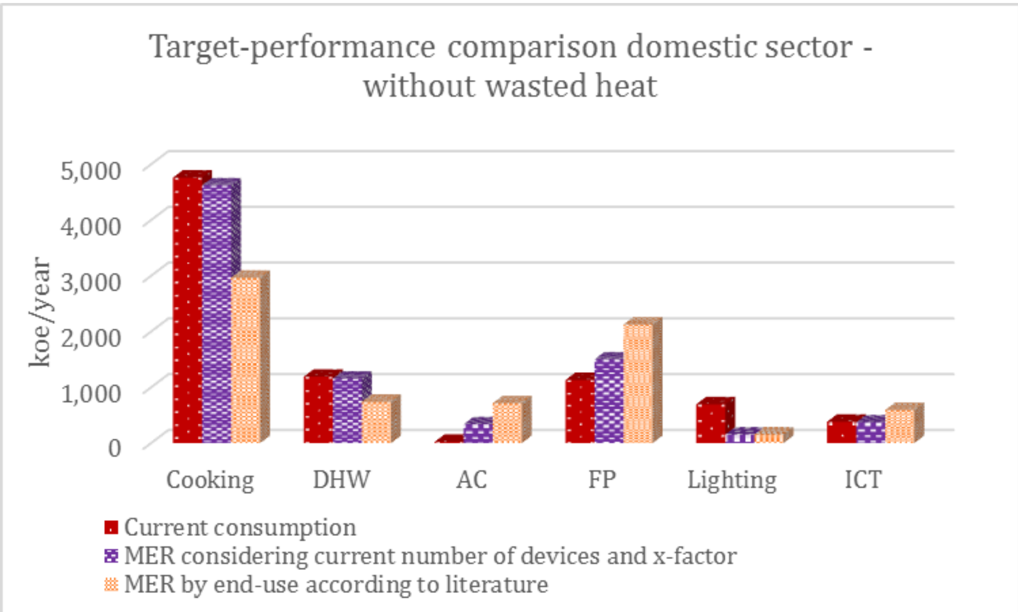

Figure 5-5: Comparison of current consumption in relation to MER

However, if the x-factor for the devices in use is considered (purple bar), then the current consumption is only slightly higher than the MER. In such cases it can be concluded that the community uses inefficient devices (e.g. cooking with open wood fire). The small difference between the current consumption and the device number and x-factor considered MER can still be a result of the device's efficiency (the x-factor does not represent the efficiency exactly in relation to the MER) or a lower number of operating hours.

If the purple bar is lower than the orange one, then this might also indicate that there are end-use devices missing (e.g. ambient cooling). For that reason, it is always suggested to keep in mind the initial data overview (as presented in Table 5-1).

The target-performance comparison for all non-domestic services is presented in Figure 5-6. It clearly shows that the MER are lacking across all community activities (except small businesses). For education the low current consumption in relation to the MER including device number and x-factor is the result of using a very small fan for AC within the school. Because of the size (capacity), and subsequently the output, the required cooling days cannot be achieved even though the fan is operating the expected hours.

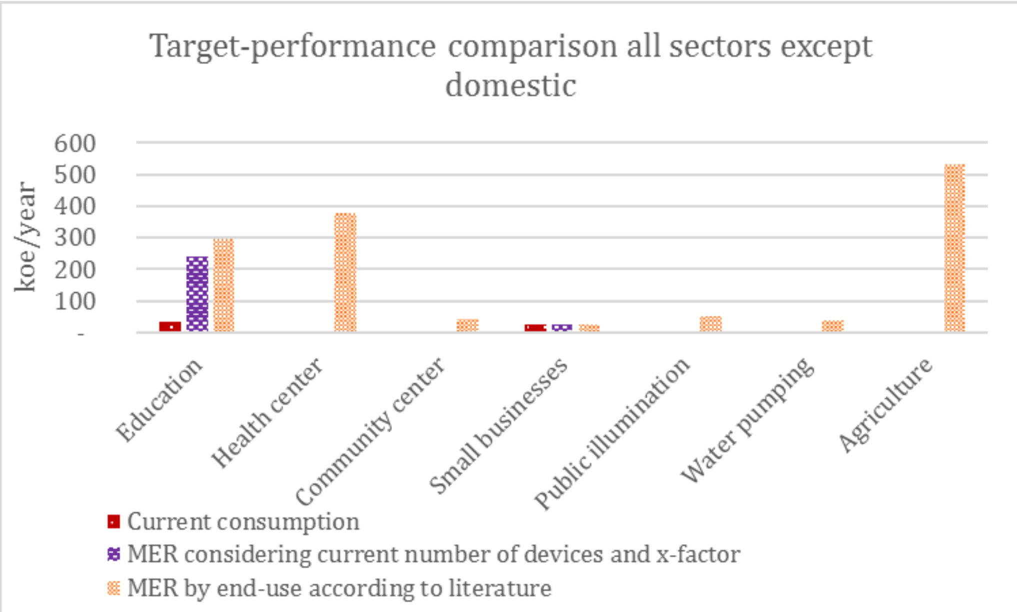

Figure 5-6: Target-performance comparison for all non-domestic sectors

Finally, a comparison of the domestic energy consumption vs. the defined "MER ref" is offered. The differences of "MER ref" (Figure 5-7) vs. "Base" (Figure 5-8) clearly emphasizes that using a single number to express the MER per capita is misleading; many times, inappropriate because one device may blur the results. Only by analyzing every end-use individually, meaningful conclusions can be drawn.

According to "MER ref" cooking and DHW are expected to be responsible for just over 1/2 of the total requirements. In the current situation of the case study cooking and DHW account for almost 3/4 of the total consumption. In contrary, food preservation (FP) and AC usually make up 1/3 of the requirements. In the case study AC is merely existing and FP just reaches half of the expected share. Lastly, the use of several inefficient lighting devices causes a much higher share in the current situation than what would be expected for lighting.

Due to the substantial differences of the shares presented in both tables, considerations of the x-factor are highly recommended when comparing the current situation or results with the “MER ref”. The “MER ref” may have two definitions: one that considers all end-use requirements according to the definitions of the literature and another that takes into account, the device performance through the x-factor and the actual count of devices. In cases were substantial differences in the average hours of use occur, an adjustment by the daily hours of operation should also be included in the adjusted “MER ref”.

In the end, the goal should be to meet the minimum requirements and to improve the living standard for each end-use and within each sector alike. Therefore, adequate understanding of the community’s end-use requirements per device is essential. Changing only a single end-use for better is just one part of the whole procedure but cannot lead to satisfying or sustainable results.

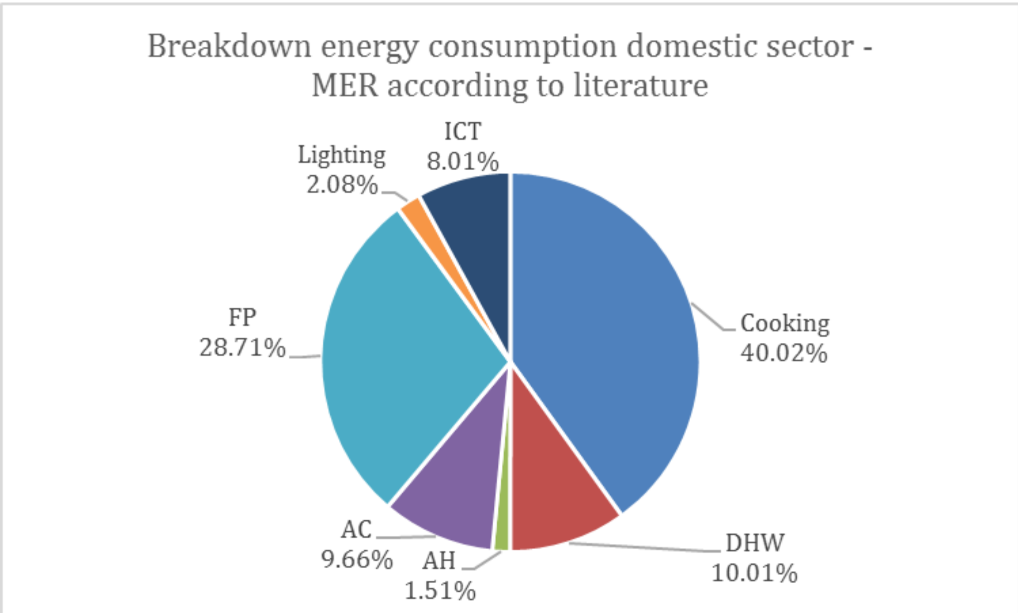

Figure 5-7: Breakdown of domestic energy consumption according to “MER ref”

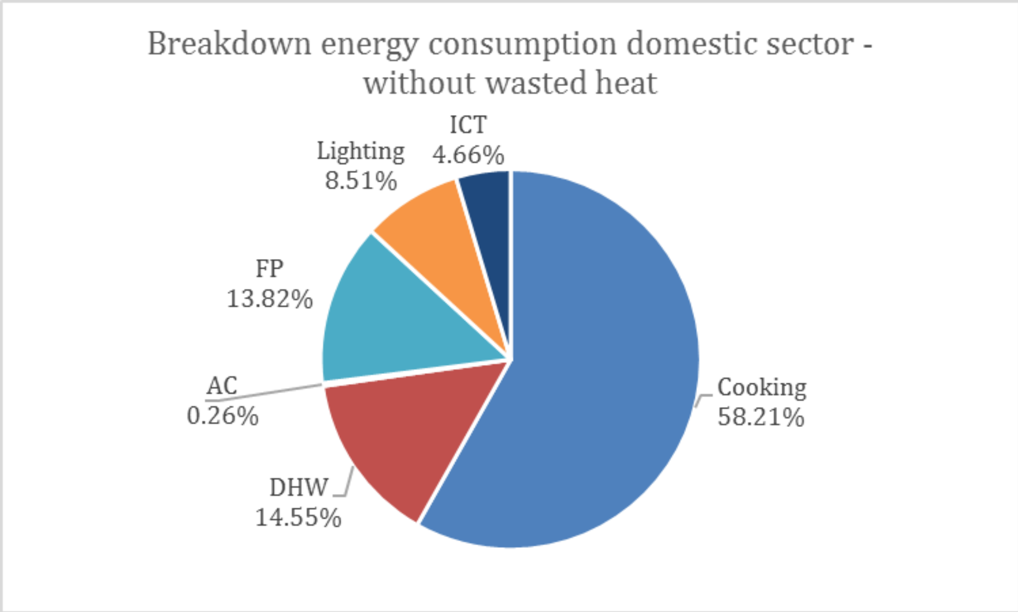

Figure 5-8: Breakdown of domestic energy consumption in case study

5.3. Feasible options of devices based on Multi-Criteria Decision Aid

After analyzing the current situation of the community, the next step is to understand its resource potential and define which end-use devices and electricity generation systems can be applied in each MER option. Based on the resource availability, the proposed definition of options and the order attained from the MCDA it is aimed to comprise 5 MER options.

Initially, local resource conditions have to be defined. In the case study, a centralized community, great access to biomass, wind and solar can be found. Since the community is not located next to a river, hydro power cannot be used to cover energetic needs. However, it may well be used for the cattle and irrigation or for washing. In what regards fossil fuel imports, almost no limitations have been made, since the effects of using fossil fuels will be assessed in the cost analysis. Only the import of coal, and the subsequent use of coal-based devices, is not deemed feasible. Regardless if a community is centralized or dispersed, the supply systems consider small scale dispersed units since no larger network shall be installed.

For the MCDA the swing weight methods is then applied on all proposed criteria. Thus, the minimization of human vulnerability and diseases is identified as the most valuable criteria. The satisfaction to decrease the human vulnerability and disease from maximum to minimum is the greatest and receives a maximum score of 100. All other criteria are then set in relation, so that the swing weights can be defined accordingly. It is important to mention that not all criteria perform a change from maximum to minimum (e.g. import dependency or investment cost). There is also a variety of criteria which perform the opposite trend. That is to say, an increase in the social benefit from minimum to maximum is desirable. Likewise, increases are favorable for performance improvements (efficiency), social acceptability or the ease of use. All criterion swings according to the author´s judgement along with the subsequent normalized criteria weights are summarized in Table 5-3.

Table 5-3: Criteria and weights for MCDA to evaluate end-use devices and supply technologies

Criteria			criteria swing			mq	wq
So.1	min	Human vulnerability, disease	a decrease of So.1 from 9-0 leads to the highest satisfaction	9	0	100	11%
En.2	min	Indoor pollution	a decrease of En.2 from 9-0 is equivalent to a So.1 reduction from	9	1	89	10%
Re.4	max	Resource availability	an increase of Re.4 from 0-9 is equivalent to a So.1 reduction from	9	1	89	10%
Ec.1	min	Investment cost	a decrease of Ec.1 from 9-0 is equivalent to a So.1 reduction from	9	2	78	9%
Re.1	min	Import dependency	a decrease of Re.1 from 9-0 is equivalent to a So.1 reduction from	9	2	78	9%
So.2	max	Social benefit	an increase of So.2 from 0-9 is equivalent to a So.1 reduction from	9	2	78	9%
So.3	max	Local acceptance	an increase of So.3 from 0-9 is equivalent to a So.1 reduction from	9	3	67	8%
So.4	max	Level of comfort	an increase of So.4 from 0-9 is equivalent to a So.1 reduction from	9	3	67	8%
Ec.2	min	Operation & maintenance cost	a decrease of Ec.2 from 9-0 is equivalent to a So.1 reduction from	9	4	56	6%
Tc.1	max	Ease of use	an increase of Tc.1 from 0-9 is equivalent to a So.1 reduction from	9	5	44	5%
Tc.4	max	Level or degree of technology	an increase of Tc.4 from 0-9 is equivalent to a So.1 reduction from	9	6	33	4%
Tc.2	max	Efficiency	an increase of Tc.2 from 0-9 is equivalent to a So.1 reduction from	9	6	33	4%
Re.3	min	Land use to grow and store resources	a decrease of Re.3 from 9-0 is equivalent to a So.1 reduction from	9	6	33	4%
Re.2	min	Conflict between resource usage	a decrease of Re.2 from 9-0 is equivalent to a So.1 reduction from	9	7	22	3%
En.1	min	Emission reduction	a decrease of En.1 from 9-0 is equivalent to a So.1 reduction from	9	8	11	1%
Tc.3	min	Implementation time for device	a decrease of Tc.3 from 9-0 is equivalent to a So.1 reduction from	9	8	11	1%
						889	100%

Now, with the local resource availability and criteria weights defined as well as the attribute values from section 4.4 (also see Appendix 8.6) the MCDA can be applied.[33] According to the categorization of devices by resource and level of technology (see section 4.5), the preference orders are obtained for renewable based, fossil fuel-based and intermediate technologies for each end-use. For devices with multiple end-use (either cooking, DHW and AH or cooking and DHW) only one preference order is applied. In the case of devices that only fulfil DHW a separate ranking is provided, since these devices are considered for comfort. “Energy free” devices are marked in light grey color in the table. These devices are always advised to be used in all options, since they help the community to increase comfort and well-being without direct additional energy requirements (Table 5-4).

[33] Even though it would be worthwhile to have local decision makers that define the criteria weights and attribute scores both, this research only makes the input of criteria weights mandatory, since the value of local characteristics can already be reflected within the criteria weights. For the attribute values, the author provides a complete set for further application. Nonetheless, it is recommended that decision makers complete their own set of attribute values to even have a greater recognition of the site-specific characteristics.

Table 5-4: Overview of devices, resource availability, type and results of MCDA by end-use

End-use	Device	Resource availability	Applicable for MCDA	Type by resource	Technology level	1) RES*	2) fossil*	3) intermediate
Cooking-DHW-AH	Typical open fire (3 stone)	locally available	yes	RES	Trad	0.483	-	-
	Well-tended open fire (3 stone)	locally available	yes	RES	Trad	0.625	-	-
	Rocket stove	locally available	yes	RES/ Fossil	Int	0.546	-	0.546
	Wood gas stove	locally available	yes	RES/ Fossil	Int	0.554	0.554	0.554
	LPG ring stove	import	yes	Fossil	Adv	-	0.467	-
	Gas cooktop	import	yes	Fossil	Adv	-	0.579	-
	Paraffin "Primus" stove	import	no	Fossil	Trad	-	-	-
	Kerosene stove	import	yes	Fossil	Int	-	0.346	0.346
	Improved liquid fuel stove	import	yes	Fossil	Adv	-	0.475	-
	Improved solid fuel stove	locally available	yes	RES	Int	0.633	-	0.633
	Coal stove	import	no	Fossil	Trad	-	-	-
Cooking-DHW	Solar cooker	locally available	yes	RES	Adv	0.779	-	-
	Coal brazier	import	no	Fossil	Trad	-	-	-
	Electric induction stove	locally available	no	RES	Adv	-	-	-
	Electric induction stove	import	no	Fossil	Adv	-	-	-
	Electric hotplate/cooktop	locally available	no	RES	Adv	-	-	-
	Electric hotplate/cooktop	import	no	Fossil	Adv	-	-	-
	Biolite	locally available	yes	RES	Adv	0.700	-	-
Domestic Hot Water	Electric geyser	locally available	yes	RES	Adv	0.750	-	-
	Electric geyser	import	yes	Fossil	Adv	-	0.625	-
	LPG geyser	import	yes	Fossil	Adv	-	0.496	-
	Solar hot water heater	locally available	yes	RES	Adv	0.808	-	-
Ambient Heating	Passive geothermal	architectural design not available	no	RES	Pas	-	-	-
Ambient Heating	Passive solar	architectural design can be added to current constructions	yes	RES	Pas	-	-	-
	Geothermal (Ground source heat pump)	technology too advanced for current building stock	no	RES	Adv	-	-	-
	Electric heater	locally available	yes	RES	Adv	0.775	-	-
	Electric heater	import	yes	Fossil	Adv	-	0.567	-
	LPG heater	import	yes	Fossil	Adv	-	0.488	-
Ambient Heating	Solar air heating system	locally available	yes	RES	Adv	0.783	-	-
	Kerosene heater	import	yes	Fossil	Int	-	0.346	0.346
Ambient Cooling	Passive wind	architectural design not available	yes	RES	Pas	-	-	-
	Solar portable PV fan	locally available: 2,000 kWh/m2	yes	RES	Adv	0.829	-	-
	Electric fan	locally available	yes	RES	Int	0.788	-	0.788
	Electric fan	import	yes	Fossil	Int	-	0.488	0.488
	Electrical Evaporative cooling (air-water cooler)	locally available	no	RES	Adv	-	-	-
	Electrical Evaporative cooling (air-water cooler)	import	no	Fossil	Adv	-	-	-
	Electric ventilation	locally available	yes	RES	Adv	0.733	-	-
	Electric ventilation	import	yes	Fossil	Adv	-	0.463	-
	Electric water cooler	locally available	yes	RES	Adv	0.746	-	-
	Electric water cooler	import	yes	Fossil	Adv	-	0.475	-

Table 5-4 continued

End-use	Device	Resource availability	Applicable for MCDA	Type by resource	Technology level	1) RES*	2) fossil*	3) intermediate
Food preservation	Passive geothermal	architectural design not available	no	RES	Pas	-	-	-
	Passive wind	use of passive wind is possible	yes	RES	Pas	-	-	-
	Zeer Pot or Pot-in pot	use of passive wind, humidity and solar is possible	yes	RES	Int	-	-	
	Electric - Refrigerator	locally available	yes	RES	Adv	0.725	-	-
	Electric - Refrigerator	import	yes	Fossil	Adv	-	0.483	-
	Electric- Freezer	locally available	yes	RES	Adv	0.721	-	-
	Electric- Freezer	import	yes	Fossil	Adv	-	0.479	-
Lighting	Biolite + LED	locally available	yes	RES	Adv	0.796	-	-
	Candles	import	yes	Fossil	Trad	-	0.467	-
	Kerosene hurricane	import	yes	Fossil	Int	-	0.421	0.421
	High pressure lighting lamp	import	yes	Fossil	Int	-	0.421	0.421
	Oil lamp (mantle)	import	yes	Fossil	Int	-	0.392	0.392
	Oil lamp (Wick)	import	yes	Fossil	Int	-	0.342	0.342
	Filament lamp	locally available	yes	RES	Adv	0.796	-	-
	Filament lamp	import	yes	Fossil	Adv	-	0.592	-
	Incandescent lighting	locally available	yes	RES	Adv	0.796	-	-
	Incandescent lighting	import	yes	Fossil	Adv	-	0.592	-
	Fluorescent	locally available	yes	RES	Adv	0.792	-	-
	Fluorescent	import	yes	Fossil	Adv	-	0.588	-
	Compact fluorescent	locally available	yes	RES	Adv	0.813	-	-
	Compact fluorescent	import	yes	Fossil	Adv	-	0.608	-
	Light emitting diodes	locally available	yes	RES	Adv	0.821	-	-
	Light emitting diodes	import	yes	Fossil	Adv	-	0.617	-
	Small portable solar lantern + LED	locally available	yes	RES	Adv	0.879	-	-
	Medium portable solar lantern + LED (8 W)	locally available	yes	RES	Adv	0.850	-	-
Lighting-Street Lamps	Mercury vapor (gas lamp) with electricity function	import	yes	Fossil	Adv	-	0.475	-
	LED+PV solar street lamps (100 W LED) +Battery	locally available	yes	RES	Adv	0.838	-	-
ICT	Computer	locally available	yes	RES	Adv	0.675	-	-
	Computer	import	yes	Fossil	Adv	-	0.471	-
	Copy machine	locally available	yes	RES	Adv	0.675	-	-
	Copy machine	import	yes	Fossil	Adv	-	0.471	-
	Rasberry Pie	locally available	yes	RES	Adv	0.675	-	-
	Rasberry Pie	import	yes	Fossil	Adv	-	0.471	-
ICT	OLPXXO-1 computer	locally available	yes	RES	Adv	0.675	-	-
	OLPXXO-1 computer	import	yes	Fossil	Adv	-	0.471	-
	Modem & satellite	locally available	yes	RES	Adv	0.675	-	-
	Modem & satellite	import	yes	Fossil	Adv	-	0.471	-
	Portable radio with battery	import	yes	RES/ Fossil	Adv	0.775	0.775	-
	Small radio	locally available	yes	RES	Adv	0.854	-	-
	Small radio	import	yes	Fossil	Adv	-	0.663	-
	Mobile phone with battery and charger	locally available	yes	RES	Adv	0.729	-	-
	Mobile phone with battery and charger	import	yes	Fossil	Adv	-	0.592	-
	TV	locally available	yes	RES	Adv	0.746	-	-
	TV	import	yes	Fossil	Adv	-	0.542	-

Table 5-4 continued									
End-use	Device	Resource availability	Applicable for MCDA	Type by resource	Technology level	1) RES*	2) fossil*	3) intermediate
ICT	Other small electrical devices	locally available	yes	RES	Adv	0.729	-	-
	Other small electrical devices	import	yes	Fossil	Adv	-	0.525	-
	Electrical Medical Sterilizator	locally available	yes	RES	Adv	0.725	-	-
	Electrical Medical Sterilizator	import	yes	Fossil	Adv	-	0.521	-
Water pumping	Mechanical pump	locally available	yes	RES	Int	-	-	-
	Treadle pump	locally available	yes	RES	Int	-	-	-
	Vane-flapping turbine	locally available	yes	RES	Int	-	-	-
	Electric pump	locally available	yes	RES	Adv	0.721	-	-
	Electric pump	import	yes	Fossil	Adv	-	0.500	-
	Solar PV DC pump	solar conditions: 2,000 kWh/m2	yes	RES	Adv	0.833	-	-
	Choti Bijli (diesel genset)	import	yes	Fossil	Adv	-	0.363	0.363
Agriculture machine work	Solar dryer	Locally available	yes	RES	Pas			
	Human & animal power	locally available	yes	RES	Trad	-	-	-
	Grain/food drying	locally available	yes	RES	Pas	-	-	-
	Electric Grinding mill	locally available	yes	RES	Int	0.654	-	0.654
	Electric Grinding mill	import	yes	Fossil	Int	-	0.413	0.413
	Electric Pulveriser	locally available	yes	RES	Adv	0.596	-	-
	Electric Pulveriser	import	yes	Fossil	Adv	-	0.354	-
	Electric Skin pealing machine	locally available	yes	RES	Adv	0.617	-	-
	Electric Skin pealing machine	import	yes	Fossil	Adv	-	0.375	-
	Electric Motor 0.01-100 kW (uses average of 1kW)	locally available	yes	RES	Adv	0.713	-	-
	Electric Motor 0.01-100 kW (uses average of 1kW)	import	yes	Fossil	Adv	-	0.471	-
Electricity generating units	(Micro-) Diesel gen. (>1 kW)	import	yes	Fossil	Int	-	0.367	-
	(Micro-) PV-diesel System (>1 kW)	locally available and import	yes	RES/ Fossil	Adv	0.508	0.508	-
	(Micro-) Gas gen. (> 1 kW)	locally available	yes	RES	Adv	-	0.671	-
	(Micro-) Hydro gen. (>5 kW)	locally available	no	RES	Adv	-	-	-
	(Pico-) Hydro system (< 5 kW)	locally available	yes	RES	Adv	-	-	-
	Pumped storage (> 10 MW)	locally available: 2,000 kWh/m²	yes	RES	Adv	-	-	-
Electricity generating units	(Micro-) Wind gen. (>1 kW)	locally available: 2,000 kWh/m²	yes	RES	Adv	0.729	-	-
	(Pico-) Wind system (200 W)	locally available: 2,000 kWh/m²	yes	RES	Adv	0.813	-	-
	Solar Residential system (250-4000 W)	locally available	yes	RES	Adv	0.775	-	-
	PV home system (up to 250W)	local conditions not available	no	RES	Adv	0.796	-	-
	(Pico-) PV system (1-10W)	wind average 2.79 m/s (generation 200 w/m²)	yes	RES	Adv	0.908	-	-
Electricity generating units	(Micro-) Biomass power generator (> 1 kW)	River too far away	no	RES	Adv	0.767	-	-

* Multiple devices within the same end-use can have the same ranking, since the final scores after the MCDA are identical. In such cases the ranking has been directly continued without taking into account how many devices might have the same ranking; i.e. if three devices within the same end-use achieve a ranking of 4, the following device is ranked with 5 and not 7.

Note 1: The "Energy free" devices that were categorized in Table 4-13 are marked in light grey color. Their implementation is recommended regardless of the option selected, since they can all improve the living conditions within the community without additional direct energy requirements.

Note 2: A color scale has been introduced for a better differentiation of the obtained preference order. The scale ranged from dark green (very good) to dark red (very bad).

With the preference order obtained from the MCDA (which also considers the resource availability), the 5 MER options can be build according to the definition for each MER. Table 5-5 lists the devices to be used for each of the 5 MER options, where the ICT devices only list the ones for the domestic sector. Additional ICT devices such as computer, modem, etc., which are used in other sectors (e.g. education or health center), are not listed in this table since they are the same across the different MER options. The difference in those options is how these electrical end-uses are supplied.

Also, for the agricultural needs only electric motors are listed for the best renewables and best fossil fuel option (MER 1 and MER 3). For the remaining options a mix of devices has been applied. Once again, it is not the devices itself that matter, since in all cases the same minimum requirements for agriculture need to be met. Thereby, the mix of devices in use is secondary.

Regardless of listing the electricity generating units according to the ranking obtained, it should be clear that the individual use of RES driven systems (apart from running hydro or biomass generators) does not comply with the requirements of operating power systems continuously. If RES systems are expected to meet the needs at all times, then adequate electric back-up or storage are indispensable. Consequently, in all MER options some form of fossil fuel back-up is recommended to avoid exorbitantly high costs of the supply system or significant oversizing of the same. Perhaps, in the future batteries are considered. All aspects of power systems, such as security of supply, frequency control, among others, are excluded from this research. Also, an hourly analysis of the time dynamics of demand and supply (resource availability) has not been considered, due to the limitations of hourly measures available. If adequate data is available it may be referred to another research project within the MIT Portugal Program at FEUP. Wimmler (2016) investigated potential supply solutions for isolated energy systems that aim to cover all electrical requirements from locally available renewables. The hourly time-series approach revealed that small shares of fossil fuel back-up of up to 4% of the energy mix are the most economic solutions when sizing the supply and storage systems (Wimmler C. , 2016). In regards to the system size in this work focus is placed on small to very small systems. For that reason, it was decided to associate the same unit costs to the different system sizes. For all non-electric end-use devices, the use of modern clean fuels (i.e. mainly the way fuels are being used in less pollutant devices and with fewer hazardous gases) is always preferred over traditional pollutant fuels.

Table 5-5: Overview of end-use devices and supply technology for each MER option

End-use	MER 1	MER 2	MER 3	MER 4	MER 5
Cooking	Solar cooker	Biolite	Gas cooktop	Wood gas stove	Improved solid fuel stove
DHW	Solar cooker	Biolite	Gas cooktop	Wood gas stove	Improved solid fuel stove
AH	Solar air heating system	Electric heater	Electric heater	LPG heater	Kerosene heater
AC	Solar PV fan	Electric fan	Electric fan	Electric water cooler	Electric fan
FP	Refrigerator	Refrigerator	Refrigerator	Refrigerator	Refrigerator
Lighting	Small portable solar lantern	Med. portable solar lantern + LED (8 W)	Light emitting diodes (LEDs) (4 W)	Compact fluorescent (CFL) (10 W)	Kerosene hurricane (lantern) (wick)[1]
ICT	Small radio Mobile TV	Small radio Mobile TV	Portable radio with battery Mobile TV	Portable radio with battery Mobile TV	Portable radio with battery Mobile TV
Street lighting	LED+PV solar street lamps (100watt LED) +Battery	LED+PV solar street lamps (100watt LED) +Battery	Mercury vapor (gas lamp) (80W)	Mercury vapor (gas lamp) (80W)	Mercury vapor (gas lamp) (80W)
Water pumping	Solar PV-DC pump	Electric pump	Electric pump	Choti Bijli (diesel genset)	Choti Bijli (diesel genset)
Agriculture	Electric motors	Electric grinding mill Electric pulveriser Electric skin pealing machine Electric motors	Electric motors	Electric grinding mill Electric pulveriser Electric skin pealing machine Electric motors	Electric grinding mill Electric pulveriser Electric skin pealing machine Electric motors
Electricity generating unit	(Pico-) PV Pico system	(Pico-)Wind Pico system	(Micro-) Diesel generator	(Micro-) PV-diesel system	(Micro-) Diesel generator

5.4. Energetic assessment and comparison of options

For the energetic assessment it may be referred to the analysis performed for the current situation ("Base" template) (section 5.2). Table 5-6 presents the number of devices used for each service (end-use) and sector for "MER 1". For all other MER options, the analysis follows the same procedures as in the forthcoming sections.

In every "MER X" the devices used for each end-use and sector have to be listed. Likewise, the numbers defined in "MER ref" (# should be per end-use) are taken into consideration for an initial overview. Through a comparison of the actual number of devices in use and the number of devices according to "MER ref" any discrepancies can be observed. Since one part of the primary objective in this research is to meet the minimum requirements for all end-uses and sectors across the community, the MER options are built in a manner that devices match the defined requirements. Yet, it may be that certain numbers diverge; for instance, it was stated in the initial overview that the chosen case study had no health center and no community center in place. Since convergence must be met to proceed to further evaluations (see structuring method), all options always need to take into account possible devices that meet the required device number according to "MER ref". Thus, it is assumed in Table 5-6 that the community would have a health and community center at the time measures are undertaken to increase energy access, regardless of not having the two buildings physically available at present.

Table 5-6: # of end-use devices by service and sector for MER 1

Sector	Service (end-use)	Device	# per device and end-use	# should be per end-use	lack by end-use	additional or comfort end-use devices
Domestic	Cooking	Solar cooker	34	34	-	-
	DHW	Solar cooker	34	34	-	-
	AH	No solar cooker, only solar air heating system*	34	34	34	34
	AC	Solar PV fan	34	34	-	-
	FP	Refrigerator	34	34	-	-
	Lighting	Small portable solar lantern + LED (4 W)	34	34	-	-
	ICT	Small radio Mobile phone with battery and charger TV	34 34 34	34 34 34	- - -	- - -
Education	Cooking	N/A	-	-	-	-
	DHW	Solar cooker	1	1	-	-
	AH	No solar cooker, only solar air heating system*	1	1	1	1
	AC	Solar PV fan	1	1	-	-
	FP	N/A	-	-	-	-
	Lighting	Small portable solar lantern + LED (4 W)	4	3	-	1
	ICT	Computer (desktop with monitor) Copy machine Modem & satellite dish Mobile phone with battery and charger	4 1 1 1	4 1 1 1	- - - -	- - - -
Health center	Cooking	N/A	-	-	-	-
	DHW	Solar cooker	1	1	-	-
	AH	No solar cooker, only solar air heating system*	1	1	1	1
	AC	Solar PV fan	1	1	-	-
	FP	Refrigerator	1	1	-	-
	Lighting	Small portable solar lantern + LED (4 W)	3	3	-	-
	ICT	Computer (desktop with monitor) Copy machine Modem & satellite dish Mobile phone with battery and charger Sterilization	2 1 1 4 1	2 1 1 4 1	- - - - -	- - - - -
Community center	Lighting	Small portable solar lantern + LED (4 W)	1	1	-	-
	ICT	Computer (desktop with monitor) Mobile phone with battery and charger	1 1	1 1	- -	- -
Small businesses	Lighting	Small portable solar lantern + LED (4 W)	4	4	-	-
	ICT	Mobile phone with battery and charger	4	4	-	-
Public Illumination	Lighting	LED+PV solar street lamps (100 Watt LED) +Battery	4	4	-	-
Water pumping	Water pumping	Solar PV DC pump	2	2	-	-
Agriculture	Agriculture	Electric motors (average 1 kW)	5	5	-	-

* AH cannot be provided as "byproduct" of solar cookers, hence causing a lack of devices. Solar air heating systems are introduced to meet the # of devices as per "MER ref". However, they are considered as comfort device that leads to additional energy requirements.

The 3 grey colored lines of AH require further explanation, since it seems that AH is double counted. AH is considered to be fulfilled from the wasted heat of devices with multiple end-uses (cooking, DHW and AH). Since the solar cooker does not fulfill the AH requirements as a “byproduct”, a lack by end-use occurs. On the other side, solar air heating systems are introduced in this option to meet the number of devices as per “MER ref”. Only through the solar air heating system convergence in the number of devices is met, so that the structuring method can be completed. Nevertheless, solar air heating systems are considered as comfort devices, since they only cover the AH requirements. Subsequently, additional comfort requirements occur.

Additional energy requirements also occur when the number of devices in use is greater than the number defined in “MER ref” for a certain end-use; i.e. lighting for education. Lastly, additional energy requirements occur when the daily average hours of use exceed the pre-defined value in “MER ref”. For cooking and DHW the minimum daily hours of use have been defined when assessing the x-factor, since they vary from one device to another. In fact, there is a direct relation between the device’s efficiency and the daily hours of use, since more efficient devices require less hours and inefficient devices more.

With the current devices gathered in the “Data” template, additional requirements for specific devices can occur only for DHW and AH, since those two end-uses include comfort devices that can only fulfil this end-use. As a matter of fact, with only DHW and/or AH missing it is likely to already have a device in place, that can fulfil multiple end-uses (basically a combination of cooking and DHW or cooking, DHW and AH).

Any discrepancies in the proposed “MER X” and “MER ref” can then be further analyzed in the target-performance comparison. Figure 5-9 provides an overview across all sectors, showing that the “MER ref” is covered in nearly all sectors. In fact, the devices selected in “MER 1” must be very efficient, since the purple bars (MER considering number of devices and x-factor) are smaller than the orange ones (definition according to the literature) in almost all sectors.

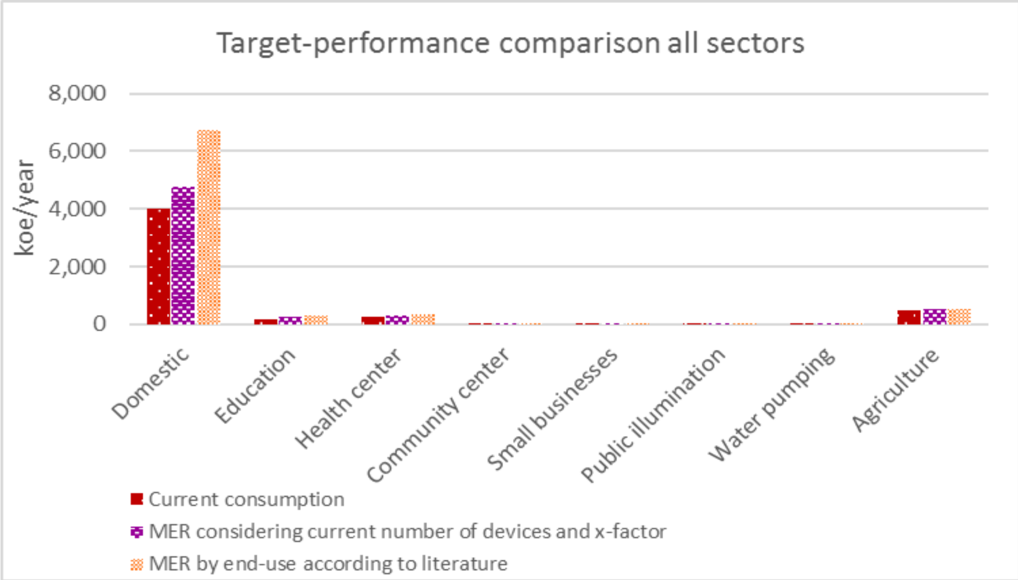

Figure 5-9: Target-performance comparison for MER 1 across all sectors

The most significant difference is seen in the domestic sector, which is due to the substantial savings that are expected for cooking and hot water (Figure 5-10). Indeed, the application of the x-factor leads to half of the cooking and DHW requirements (i.e. a x-factor of 0.5 is applied for both end-uses). The minor difference in current consumption and MER considering number of devices and x-factor is the consequence of having end-use devices that are even slightly more efficient than what was considered in the definitions of the x-factor. The major difference in AC is caused by the small capacity of the solar PV fan and the resulting low output.

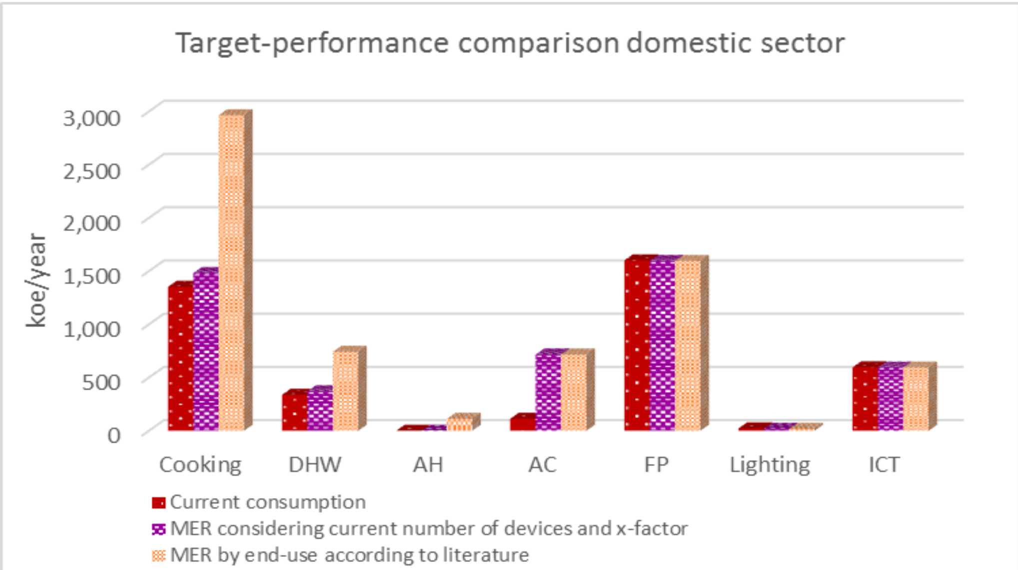

Figure 5-10: Target-performance comparison for MER 1 in domestic sector

According to the analysis performed in “MER 1”, the procedures are repeated for all remaining options. The detailed results for “MER 2” to “MER 5” are included in Appendix 8.7. Despite the obviously changing target-performance results across the “MER X”, there is one major aspect that needs further explanation. In “MER 3”, “MER 4” and “MER 5” the AH consumption is substantially exceeding the requirements. This is due to the use of multi-purpose devices. All three options use a cooking/DHW device that also generates AH. Hence, this heat could be considered as wasted heat, since it is the byproduct for other end-uses. When excluding wasted heat from the analysis, then the red bars in the 3 MER options could be taken out and the current consumption for AH would be zero in all three cases. Since additional devices for AH must be selected for each of the 3 MER to meet convergence in the structuring method, additional comfort requirements will occur as well.

After the detailed analysis of each “MER X”, now the results across all 5 options as well as the “Base” case (current situation) can be compared with the “MER ref” – once according to the definition of the literature and once according to the actual number of devices and x-factor (Table 5-7). The comparison is done on a per capita basis, but also for the whole community. All values are stated once in koe and once in kWh. The latter is presented for the identification and selection of electricity generating units.

In addition to the pure MER values 3 other parameters, which were identified as highly important in the analysis, are listed for each MER option. This includes the lack of energy requirements, additional energy requirements and wasted heat. The comparison of all options shows that “MER 1” and “MER 3” have the best performance. According to the MER considering number of devices and x-factor, the requirements are expected to be 25% lower than the literature definition. In fact, both options achieve actual consumption values even below the targeted value, which means that in both cases the selected devices perform very efficiently. The remaining MER (2, 4 and 5) have target values similar to those defined in the literature. However, the actual performance among the 3 options varies significantly. “MER 2” seems to have very efficient devices, since the actual consumption is still more than 10% below the expected one. For “MER 5” the actual consumption is almost as expected, but for “MER 4” the consumption is nearly 10% higher than expected.

The parameter analysis shows that the lack of energy requirements in each of the 5 options is very low (between 0.35% and 6.12% of “MER ref”). In the base case the lack is close to 28%. In contrary, the additional needs in the MER options are noticeably higher than in the base case. This is due to the additional use of AH devices in each of the options. Since those additional uses are a means of comfort, their energetic performance will not be considered in further assessments. Finally, the wasted energy indicates the heat that occurred as by-product of devices with multiple uses. In “MER 1” and “MER 2” no multi-purpose device is in use to supply the heating requirements. Hence, the wasted energy is zero. For the 3 other options wasted heat presents the by-product of other cooking and DHW devices. Yet, the amount of wasted heat is considerably lower than in the "Base" case. According to the parameters under evaluation, it can be concluded that all 5 MER options lead to substantial improvements of the community's performance. The lack of requirements can be reduced to a minimum (at least the number of devices for each end-use and sector must be met according to the convergence required in the structuring method), additional devices already provide further comfort and the amount of heat wasted is not excessive.

Table 5-7: Comparison of all MER options and base case

Numbers in [koe per year]	Base	MER1 - Res1	MER2 - Res2	MER3 - Fos1	MER4 - Fos2	MER5 - Int
Per capita results within community						
MER ref. literature	44	44	44	44	44	44
MER considering # of devices in use and x-factor	43	33	42	33	45	42
Actual per capita consumption	42	25	35	27	46	40
Overall community results						
MER ref. literature	8,694	8,694	8,694	8,694	8,694	8,694
MER considering # of devices in use and x-factor	8,578	6,521	8,455	6,603	8,929	8,484
Actual per capita consumption	8,410	5,008	7,051	5,419	9,102	7,979
Parameters for overall analysis of community						
Lack of energy for each end-use	2,426	164	164	29	29	655
Additional devices in use	5	2,035	2,261	2,261	4,746	3,390
Wasted energy	14,610	-	-	443	2,612	2,612

Numbers in [kWh per year]	Base	MER1 - Res1	MER2 - Res2	MER3 - Fos1	MER4 - Fos2	MER5 - Int
Per capita results within community						
MER ref. literature	507	507	507	507	507	507
MER considering # of devices in use and x-factor	499	379	492	384	519	493
Actual per capita consumption	489	291	410	315	529	464
Overall community results						
MER ref. literature	101,113	101,113	101,113	101,113	101,113	101,113
MER considering # of devices in use and x-factor	99,757	75,838	98,333	76,795	103,848	98,669
Actual per capita consumption	97,810	58,242	82,004	63,019	105,853	92,801
Parameters for overall analysis of community						
Lack of energy	28,214	1,906	1,906	342	342	7,616
Additional devices in use	56	23,662	26,296	26,291	55,198	39,427
Wasted energy	169,910	-	-	5,156	30,372	30,372

5.5. Option appraisals and comparison of results

After completing the energetic assessment further option appraisals (3 phases) are proposed. Based on the results achieved for each of the appraisals, sensitivity analysis is performed.

5.5.1. Monetary assessment

For the monetary assessment of all options, the five cost components need to be defined. This section explains the procedures for "MER 1". All results of the remaining "MER X" are provided in Appendix 8.4. The device cost is associated to each device based on the data gathered in the "Data" template. Updates and adjustments to the costs gathered are suggested on a regular basis, because especially renewables-based devices may experience frequent cost reductions. Likewise, the O&M of non-electrical devices can be associated to each device and multiplied by the annual consumption (Appendix 8.8). For the investment cost of the electricity generating system as well as the fixed and variable O&M cost of the same, the electrical requirements across all end-uses and sectors needs to be summed up in terms of peak capacity and annual power consumption (Table 5-8). According to the costs defined in Table 4-14 of section 4.6 the three cost components can be defined.

The sum of all power defines the size of the electricity generating system, since it is assumed that peak consumption occurs in the moment that all devices are operating simultaneously. While this might not be regularly the case, but operational matters are not considered in this research, the proposed sizing of the electrical generation system allows for a certain degree of back-up. Also, it is of great interest to have multiple generating units, rather than one large individual one, since a failure of a small individual unit can be better compensated. Any type of system failures or back-up issues are not considered in this work.

In the case of “MER 1” the required system size is 24.25 kW. For that multiple small generating systems shall be applied. This can include various system sizes, so that the total will be reached. Detailed cost differentiations of the different system sizes are not applied. Once the capacity is defined, the actually required annual operating hours (consumption) will be assessed. Therefore, the in Table 5-8 presented total consumption for electrically driven devices needs to be taken into account.

Based on the capacity factor of the selected generating system (Table 4-14) and the required system size an estimate of the annual consumption can be obtained. Indeed, if a Pico PV system of 10 W was to be selected, then 2,425 of those systems would need to be installed. With a capacity factor of 20% their annual generation would be 42,493 kWh, which is more than the required total consumption in the community (35,694 kWh). In this case, the total consumption of the community was higher than what could be generated by the supply system at the defined size and associated capacity factor, then the total consumption needs to be divided by the maximum annual operation hours (8760) and the capacity factor to define the required system size. Contrarywise, if the total consumption is significantly lower than the system size and its capacity factor respectively (i.e. generating systems with high capacity factors), then no adjustments of the system size will be performed (the additionally available capacity may be used as back-up). With the electrical system size and total consumption at hand, now all cost components of the “MER X” can be associated

Table 5-8: Size and consumption of electricity generating system for "MER 1"

End-use	Device	Power of all electrically driven devices [kW]									Consumption of all electrically driven devices [kWh]								
		Domestic	Service - Education	Service – Health*	Service – Community*	Service - small	Public illumination	Water pumping	Agriculture	Subtotal Power kW	Domestic	Service - Education	Service – Health*	Service – Community*	Service - ..	Public illumination	Water pumping	Agriculture	Total Consumption kWh
Cooking	Solar cooker																		
Domestic hot water	Solar cooker																		
Ambient heating	Solar air heating system																		
Ambient Cooling	Solar PV fan																		
Food preservation	Refrigerator	2.55	-		-					2.55	18,615	-		-					18,615
	Medical refrigeration			0.17						0.17			1,445						1,445
Lighting	Small portable solar lantern + LED (4 W)																		
Public Illumination	LED+PV solar street lamps (100 Watt LED) +Battery																		
ICT	Computer (desktop with monitor)	-	0.20	0.20	0.20	-				0.60	-	1,168	584	292	-				2,044
	Copy machine	-	0.08	0.08	-	-				0.15	-	27	27	-	-				55
	Modem & satellite	-	0.11	0.11	-	-				0.22	-	161	120	-	-				281
	Sterilization			0.50						0.50			183						183
	Small radio	0.85	-	-	-	-				0.85	310	-	-	-	-				310
	Mobile phone with battery and charger	1.12	0.01	0.01	0.01	0.04				1.20	410	16	64	16	64				570
	TV	17.00	-	-	-	-				17.00	6,205	-	-	-	-				6,205
Water pumping	Solar PV DC pump							0.02		0.02							146		146
Agriculture	Electric motors (average 1 kW)								1.00	1.00								5,840	5,840
	minimum requirements									24.25									35,694
	additional requirements									-									-

* While the overview of the community found no health and no community center, devices to meet the energetic requirements for those sectors and end-uses need to be considered. This is essential to meet convergence within the structuring method. Costs associated to the construction of buildings are not considered. It may also be that other buildings or empty ones will be used for alternative purposes.
Note: all numbers are rounded to the 2. digit after the comma, so that additions within the same end-use may not add up accordingly.

accordingly; device cost as well as O&M of non-electrical devices is obtained directly from the data table (Appendix 8.4).

Costs will be assessed for selected devices (based on each MER option) and all generating systems that are suitable according to the resource availability and MCDA. Hence, for "MER 1" there are 7 generating systems applicable. The total system cost is the sum of the annual device costs (1,397 €), the non-electrical O&M cost (145 €) and the cost of the electricity generating system respectively (Appendix 8.9).

Table 5-9 provides an overview of the total system cost for each of the electricity generating systems. Additional costs for comfort requirements, such as for AH, advanced devices, additional devices or additional hours of use are not reflected in that table. In the case of "MER 1" additional costs would only occur for the solar air heating system. Thus, additional annual device costs of 60 € and non-electrical O&M cost of 237 € would need to be added to the total system cost.

Throughout the remaining results most tables include a color scale to better differentiate the results. The scale starts from dark green (very good) and ranged to dark red (very bad).

Table 5-9: Cost overview of potential electricity generating systems for MER 1

Electricity generating system	Total system cost [€]
(Micro-) PV-diesel system (>1 kW)	4,214
(Micro-) Wind generators (>1 kW)	5,180
(Pico-) Wind system (200 W)	5,908
Solar Residential system (250-4000 W)	4,816
PV home system (up to 250W)	5,908
(Pico-) PV system (1-10W)	6,636
(Micro-) Biomass power generator (> 1 kW)	8,990

A comparison of all "MER X" solely based on total system costs is summarized in Table 5-10 and Table 5-11. When only considering MER without additional comfort requirements the options show similar results in multiple cases (Table 5-10).

Table 5-10: Comparison of total system costs [€] across all MER options

Electricity generating system	MER 1 - Res1	MER 2 - Res2	MER 3 - Fos1	MER 4 - Fos2	MER 5 - Int
(Micro-) Diesel generator (>1 kW)	-	-	7,922	6,857	5,788
(Micro-) PV-diesel system (>1 kW)	4,214	4,369	6,507	4,943	4,495
(Micro-) Gas generator (> 1 kW)	-	-	8,119	7,086	6,054
(Micro-) Hydro generator (>5 kW)	-	-	-	-	-
(Pico-) Hydro system (< 5 kW)	-	-	-	-	-
Pumped storage (> 10 MW)	-	-	-	-	-
(Micro-) Wind generators (>1 kW)	5,180	5,522	-	-	-
(Pico-) Wind system (200 W)	5,908	6,333	-	-	-
Solar Residential system (250-4000 W)	4,816	5,116	-	-	-
PV home system (up to 250W)	5,908	6,333	-	-	-
(Pico-) PV system (1-10W)	6,636	7,145	-	-	-
(Micro-) Biomass power generator (> 1 kW)	8,990	9,733	-	-	-

In fact, 4 out of 5 MER options have at least one alternative that is less than 20% more expensive than the best overall result. In all MER options the PV-diesel system leads to the lowest costs. Indeed, the PV-diesel systems in 3 out of 5 options are cheaper than any of the next best electricity generating systems (i.e. “MER 1” solar residential). Biomass generators are the most expensive for “MER 1” and “MER 2” and gas generators are the most expensive for “MER 3”, “MER 4” and “MER 5”.

The inclusion of additional comfort requirements leads to significantly higher costs (Table 5-11). The best (PV-diesel) and the worst (Biomass power generator and gas generator) electricity generating system within each MER option remain. However, the overall spread of results is far greater. Except for the biomass power generator all other electricity generating systems of “MER 1” are cheaper than that of “MER 2”, “MER 3” and “MER 4”. Only “MER 5” reaches comparable results with “MER 1”, but already 30% higher than the best supply system in “MER 1”. In fact, the best system in “MER 5” would only be the 4th best among the two options. The remaining 2nd and 3rd best system of “MER 5” are more expensive than any other system in “MER 1”, except for the highly expensive biomass power generator. While in the comparison without comfort requirements the worst options were less than 2.5 times more expensive than the best option, in the comparison with additional requirements the worst options are over 4.5 times more expensive.

Table 5-11: Comparison of total system costs [€] including additional requirements across all MER options

Electricity generating system	MER1 - Res1	MER2 - Res2	MER3 - Fos1	MER4 - Fos2	MER5 - Int
(Micro-) Diesel generator (>1 kW)	-	-	11,734	13,534	7,401
(Micro-) PV-diesel system (>1 kW)	4,510	7,552	9,689	11,620	6,108
(Micro-) Gas generator (> 1 kW)	-	-	12,496	13,762	7,667
(Micro-) Hydro generator (>5 kW)	-	-		-	-
(Pico-) Hydro system (< 5 kW)	-	-		-	-
Pumped storage (> 10 MW)	-	-		-	-
(Micro-) Wind generators (>1 kW)	5,477	10,940		-	-
(Pico-) Wind system (200 W)	6,204	12,831		-	-
Solar Residential system (250-4000 W)	5,113	9,994		-	-
PV home system (up to 250W)	6,204	12,831		-	-
(Pico-) PV system (1-10W)	6,932	14,723		-	-
(Micro-) Biomass power generator (> 1 kW)	9,287	20,406		-	-

As it could be already demonstrated in the energetic assessment, the reasoning for this enormous cost increase comes from ambient heating. In the analysis without comfort requirements the bulk of costs is associated to ICT in all options (Figure 5-11). Then follow food preservation and cooking in “MER 3”. With two more exceptions (AH in “MER 3” and AC in “MER 4”) all other end-uses have a share of less than 10% of the total system cost.

The high share for cooking in "MER 3" is at the expense of a gas cooktop which is selected for that option. Subsequently, the shares for ICT and food preparation are lower than those in the other MER options.

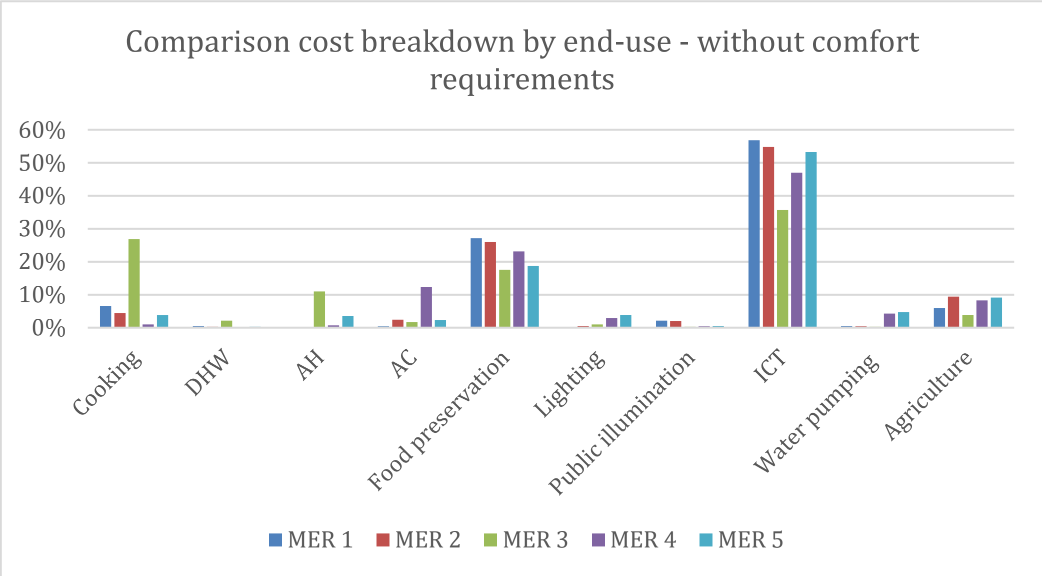

Figure 5-11: Comparison total cost breakdown by end-use - without comfort requirements

Now, that the comfort requirements are included, the expenses of AH become obvious (Figure 5-12). The most significant shift is felt in "MER 4", where the introduction of an LPG heater boosts the cost for AH. All other end-uses are cut accordingly. In contrary, the changes of "MER 1" are almost insignificant since the solar air heating system comes at a much lower cost (i.e. operation and maintenance costs are close to zero).

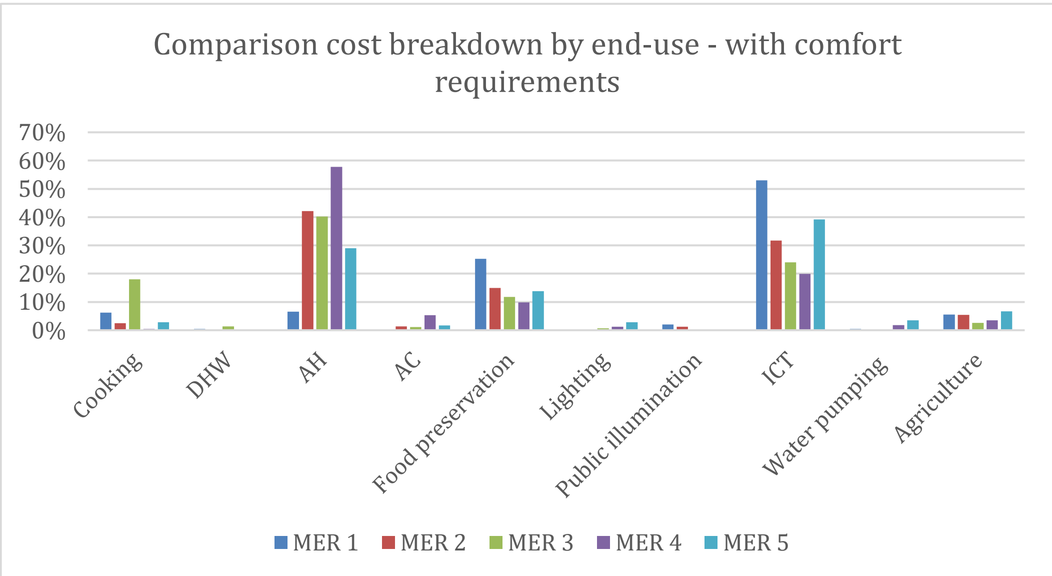

Figure 5-12: Comparison total cost breakdown by end-use - with comfort requirements

In general, it must be said that the costs associated to cooking, DHW, lighting (also public illumination) and water pumping are very low. On the one side because of the relatively small consumption (i.e. lighting or water pumping) and on the other side because of the low cost for the devices themselves. If one would consider those end-uses as the most essential ones, then it can be concluded, that they are the ones with the lowest budget needed. While it can be argued to what extent AH and ICT are part of the most essential ones, it is clear that food preservation has to be considered as an absolutely mandatory need. For both, AH and AC, adaptive behavior could be the initial step, even before spending any amount of an available investment/funding. ICT on the other hand is frequently more demanded and with the current adaptation trends towards new technologies those needs, and subsequently the costs, are likely to further increase.

5.5.2. Full range of possibilities

This research aims to provide multiple options along with a variety of potential electricity generating systems, where each of the proposed options needs to fulfil the "MER ref" in terms of number of devices used for each end-use and sector. Within the MCDA I and the monetary assessment different value preferences are obtained for all suitable[34] supply technologies within each option. Table 5-12 summarizes the 9 combinations of MCDA I and cost preferences for "MER 1" and "MER 2".

Table 5-12: Full range of possibilities with varying MCDA and cost preferences for MER 1 and MER 2

Electricity generating system	Preference MCDA I/cost								
	90/ 10	80/ 20	70/ 30	60/ 40	50/ 50	40/ 60	30/ 70	20/ 80	10/ 90
(Micro-) Diesel generator (>1 kW)									
(Micro-) PV-diesel system (>1 kW)	7	7	6	5	5	2	2	1	1
(Micro-) Gas generator (> 1 kW)									
(Micro-) Hydro generator (>5 kW)									
(Pico-) Hydro system (< 5 kW)									
Pumped storage (> 10 MW)									
(Micro-) Wind generators (>1 kW)	6	5	5	6	6	6	4	3	3
(Pico-) Wind system (200 W)	2	2	2	2	2	5	5	5	5
Solar Residential system (250-4000 W)	4	4	4	2	1	1	1	2	2
PV home system (up to 250W)	3	3	3	4	2	3	3	4	4
(Pico-) PV system (1-10W)	1	1	1	1	2	4	6	6	6
(Micro-) Biomass power generator (> 1 kW)	5	5	7	7	7	7	7	7	7

From the 7 potential supply technologies in "MER 1" and "MER 2" three electricity generating systems come in first place depending on the preferences associated (PV-diesel, solar residential and pico-PV system). When considering the performance across the full range of possibilities, then solar residential systems achieve the best result, because they show the most consistent ones. Thereafter follow pico-PV and home residential systems.

[34] Suitable in a sense that the local resources are available (renewables) or can be available through imports (fossil fuels).

The worst performance is achieved by the biomass generator (Table 5-12). At the same time, it is interesting to see that the PV-diesel system shows the widest spread across the 9 combinations. With a high cost preference, PV-diesel system is the preferred choice, but if the results of the MCDA I receive a higher share, the PV-diesel system becomes less favored.

For the remaining MER options the range of possibilities is limited, since only 3 supply technologies are considered as suitable within the community. At a 50/50 ratio diesel generators and PV-diesel systems come first choice. With a higher preference for costs the focus shifts to the PV-diesel system and with more emphasis on the MCDA results the diesel generator is the more favored fossil fuel solution (Table 5-13). The gas generator remains the least favored solution throughout all preference changes, because of the higher costs.

Table 5-13: Full range of possibilities with varying MCDA and cost preferences for MER 3, MER 4 and MER 5

Electricity generating system	Preference MCDA/cost								
	90/ 10	80/ 20	70/ 30	60/ 40	50/ 50	40/ 60	30/ 70	20/ 80	10/ 90
(Micro-) Diesel generator (>1 kW)	1	1	1	1	1	2	2	2	2
(Micro-) PV-diesel system (>1 kW)	2	2	2	2	1	1	1	1	1
(Micro-) Gas generator (> 1 kW)	3	3	3	3	3	3	3	3	3

The results of the full range of possibilities are the same for the approach with and the approach without additional energy (comfort) requirements, since the preference order of MCDA I does not change with higher energy requirements and the costs increase proportionally with a higher demand.

5.5.3. Analysis of options through MCDA II

Since neither the monetary assessment nor the full range of possibilities provide an in-depth view of the overall option and subsequent supply technology, a final appraisal is made to define the most preferred solution(s). Yet, this involves further decision maker input to judge the appropriateness of the combination of "MER X" and the supply technology. For that the overall options are appraised through a second MCDA (termed as MCDA II). The proposed criteria are: 1) annual total system cost, 2) local resource availability and 3) local acceptance. The first approach considers only costs associated to the MER without additional requirements, whereas the second approach also takes into account all costs associated to additional comfort requirements. The evaluation procedure for both approaches is identical.

The first step is the definition of value scales for all three criteria. For the resource availability and local acceptance, input from the decision maker should be applied. Alternatively, the author has provided a value score for both criteria based on its best judgement. All criteria apply linear value functions. In the case of the resource availability and local acceptance the value functions are maximized. The scoring scale ranges from 0 to 100, where Figure 5-13 proposes the value scores of the author.

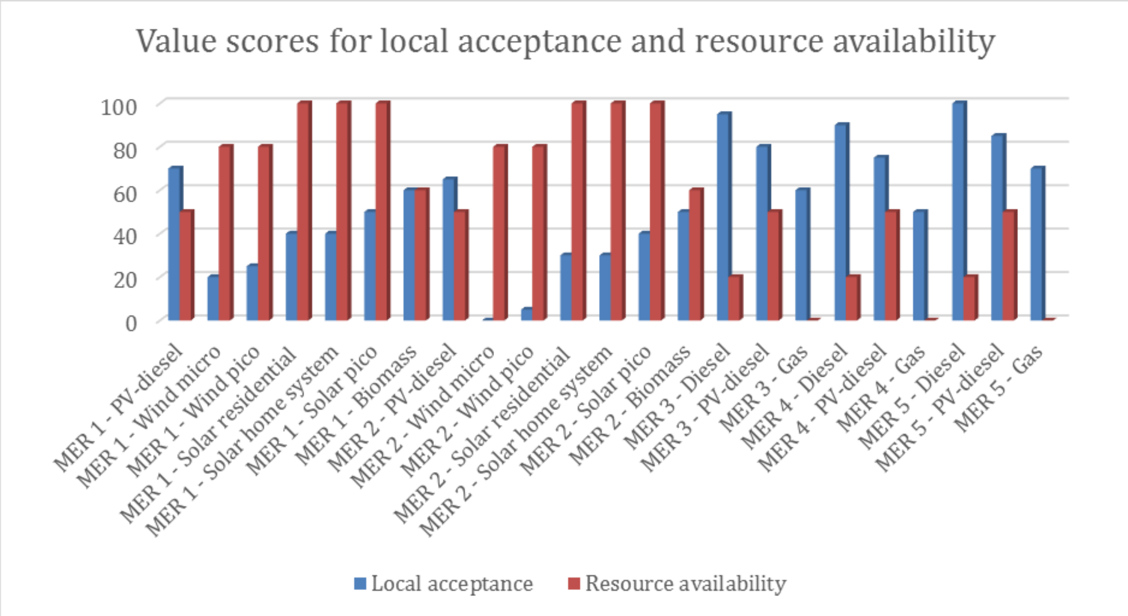

Figure 5-13: Value scores for local acceptance and resource availability

Attribute values for the resource availability only change among the different resources of supply technologies, but not from one option to another. The highest value is associated to solar based technologies. Since the resource availability has no impact on the size of the system, all three 3 technologies achieve the maximum score. Likewise, both wind technologies have the same value.

For the local acceptance, both, the option and supply technology are taken into account, since the combination of different technological advancements of devices and technologies leads to a varied local acceptance. Since the community's inhabitants are expected to accept known technologies and devices the most, the diesel system in combination with intermediate technologies achieves the maximum value of 100. The values are then decreased across the same supply technology within the different "MER X", where the better set of devices is preferred over the second best ("MER 1" is preferred to "MER 2" and "MER 3" is preferred to "MER 4"). Amongst the fossil fuel-based supply technologies "MER 5" is superior to "MER 3" and "MER 3" is higher valued than "MER 4". Renewables based supply technologies are generally valued less, whereas "MER 1" is higher valued than "MER 2". Thus, the lowest value is associated to micro wind systems of "MER 2". Amongst the different supply technologies of the same resource (PV and wind), a higher acceptance is achieved for smaller devices.

For the cost a minimization of the value function takes place. Therefore, the total system costs, that are defined in the monetary assessment, are transformed into a value score. Among all supply technologies and options the highest score of 100 is associated to the least expensive supply technology. The lowest score of 0 refers to the most expensive supply technology. Accordingly, all other supply technologies can be placed along the linear value function.

Following the initial association of values to all attributes, simple plots are drawn for a pair-wise assessment of attribute alternatives. Based on the selected criteria, three plots can be illustrated (Figure 5-14, Figure 5-15and Figure 5-16).

The comparison of costs versus local acceptance demonstrates that PV-diesel systems and diesel systems are dominating all other supply technologies. The PV-diesel system of "MER 1" is the most preferred in terms of cost and the diesel system in "MER 5" is the most valued for the local acceptance. The highest values for the combined approach of cost vs. local acceptance is obtained from the PV-diesel system of "MER 5" (Figure 5-14).

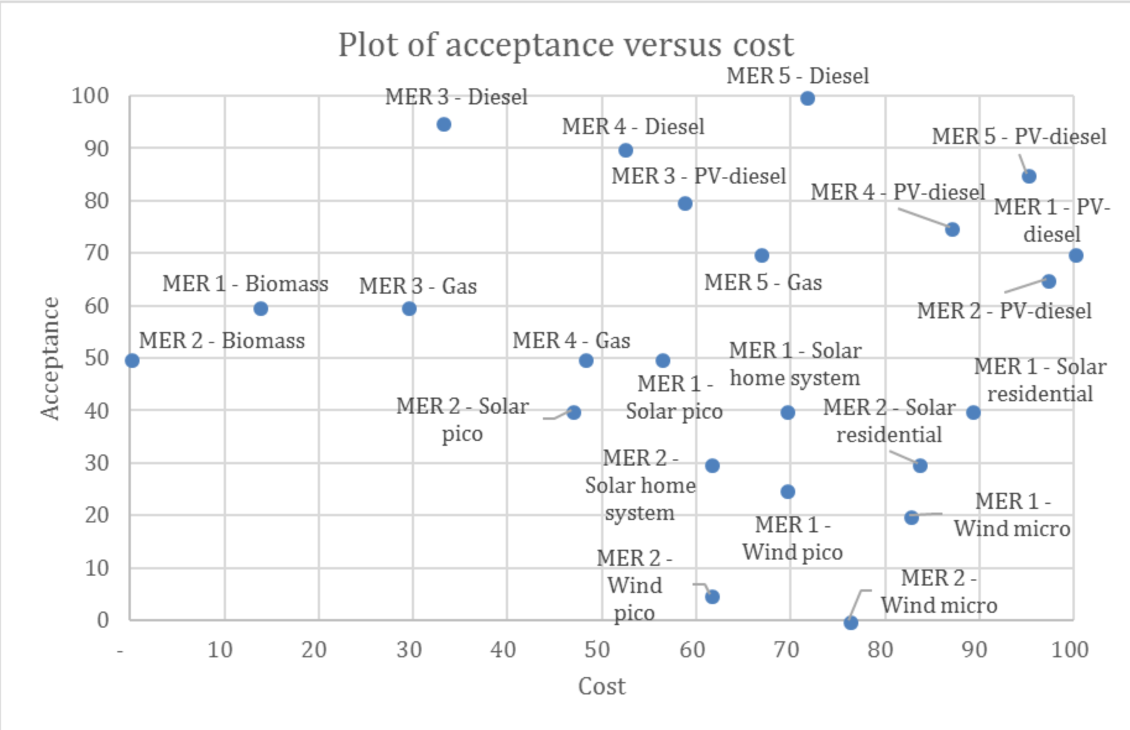

Figure 5-14: Plot of local acceptance versus total system cost

When comparing the resource availability and total system costs, the preferences have shifted noticeably, whereas the solar residential system of "MER 1" is the most preferred alternative. Likewise, the micro wind and the PV-diesel system of "MER 1" are considerable alternatives (Figure 5-15).

With the shift from local acceptance versus cost to resource availability versus cost, significant changes in the preferred combination of "MER X" and corresponding supply technology can be seen. The consideration of local acceptance places higher values on intermediate technologies and fossil fuels, whereas the resource availability favors the best renewables-based devices ("MER 1") and solar residential systems.

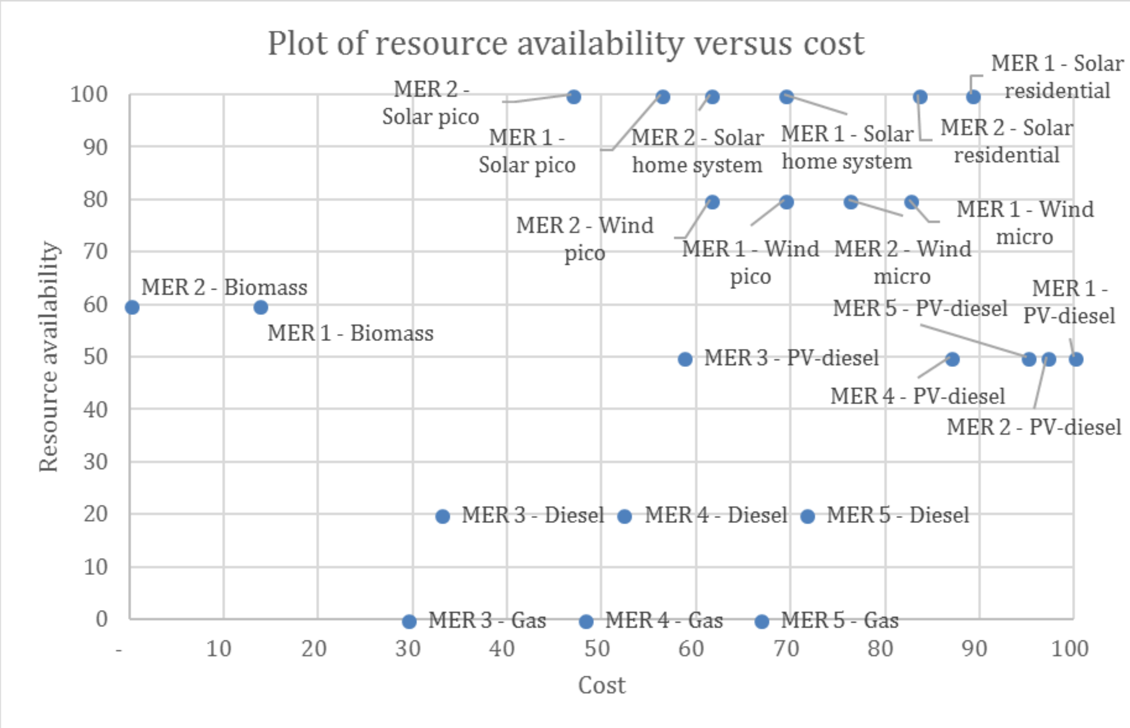

Figure 5-15: Plot of resource availability versus total system cost

Lastly, in Figure 5-16 the plot for the resource availability and local acceptance identifies solar pico of "MER 1" and PV-diesel of "MER 5" as the most preferred alternatives. Yet, there is no alternative that dominates all other ones and leads to an equally high preference value for both criteria.

Each of the plots indicates the most dominant attribute pair, basically the alternative(s) that are preferred to the remaining ones. When plotting the local acceptance versus the total system cost, the PV-diesel system is the dominant supply technology. For the "MER X" either "MER 1" should be selected from a cost perspective or "MER 5" from a local acceptance perspective.

If the additional costs for comfort requirements are considered in the second approach the plots change only slightly. The value scores for the approach with additional energy requirements follows the same procedures as outlined above. For the local acceptance and resource availability the values are the identical. The higher spectrum of the total system costs results in a greater difference between the attribute scores on the cost scale. Hence, the most preferred alternative (e.g. the solar residential system in the resource/cost plot) becomes even more dominant and moves towards the top right-hand corner.

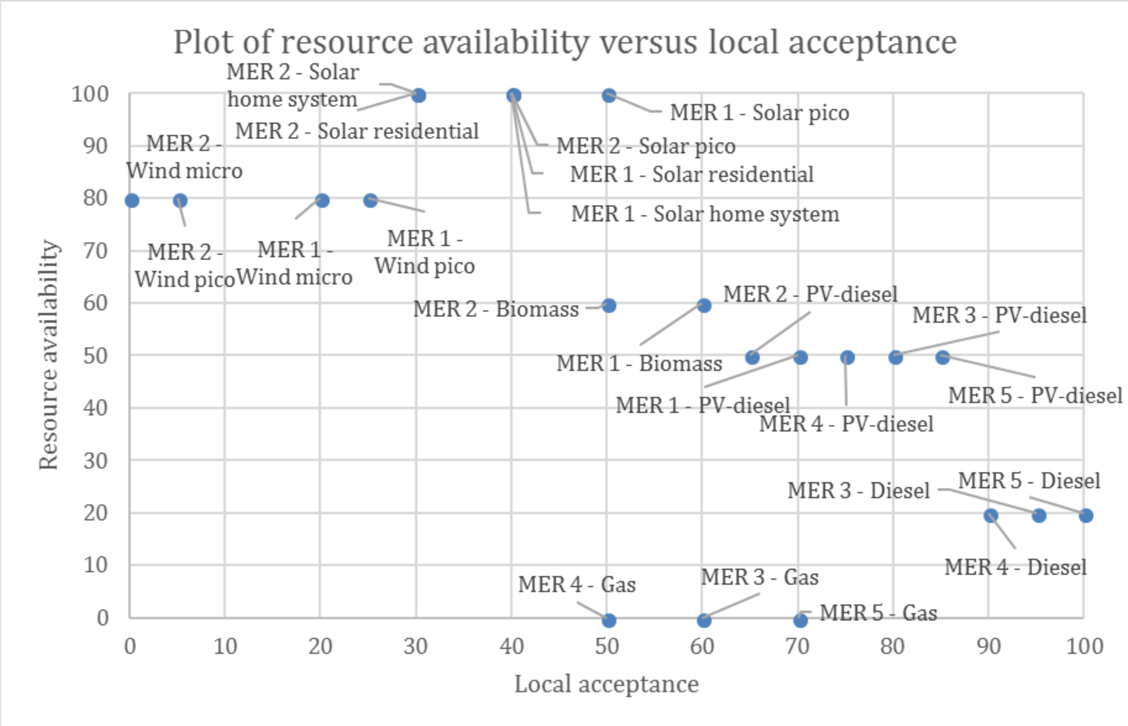

Figure 5-16: Plot of resource availability versus local acceptance

In order to define the weights for each of the three criteria, swing weights are applied. The cost is valued the most when changed from worst to best (most expensive to least expensive). Thereafter follows the local acceptance, which only deliberates a slightly lower weight than the cost. The resource availability is valued considerably lower (Table 5-14).

Table 5-14: Criteria and weights for MCDA model to evaluate options

Criteria		criteria swing			mq	wq
Cost	min	a decrease of cost from 9743-4214 leads to the highest satisfaction	9743	4214	100	38.90%
Resource	max	an increase of resource from 0-100 is equivalent to a cost reduction from	9743	6000	68	26.33%
Acceptance	max	an increase of local acceptance from 0-100 is equivalent to a cost reduction from	9743	4800	89	34.77%
					257	100%

With the associated attribute values and the defined weights, the overall value functions for each supply technology by “MER X” can be summed up. The results without additional energy requirements are presented in Table 5-15. The best combination of supply technology and MER option is the PV-diesel system of “MER 5”, which uses intermediate technologies. The preference for this solution is mainly driven by the facts that intermediate technologies (“MER 5”) receive the greatest acceptance within the community and PV-diesel systems represent the lowest priced supply technology. Amongst all other alternatives only the PV-diesel system of “MER 1” receives a similar result. It is also interesting to see that with the exception of the PV-diesel system in “MER 4”, none of the fossil fuel options is a worthwhile solution for the community.

Table 5-15: Results of MCDA by supply technology and MER option without additional energy requirements [value between 0-100]

Electricity generating system	MER 1 - Res1	MER 2 - Res2	MER 3 - Fos1	MER 4 - Fos2	MER 5 - Int
(Micro-) Diesel generator (>1 kW)			36.21	42.64	52.29
(Micro-) PV-diesel system (>1 kW)	61.81	59.59	47.81	57.74	63.03
(Micro-) Gas generator (> 1 kW)			24.18	29.32	40.83
(Micro-) Hydro generator (>5 kW)					
(Pico-) Hydro system (< 5 kW)					
Pumped storage (> 10 MW)					
(Micro-) Wind generators (>1 kW)	49.22	42.50			
(Pico-) Wind system (200 W)	45.16	37.85			
Solar Residential system (250-4000 W)	59.25	54.94			
PV home system (up to 250W)	51.57	46.38			
(Pico-) PV system (1-10W)	48.57	42.79			
(Micro-) Biomass power generator (> 1 kW)	27.70	20.28			

Bearing in mind the additional energy requirements of the second approach, the results change noticeably, not in absolute values, but in the alteration of supply technologies. In fact, the best solution is now the solar residential system of “MER 1”, which is slightly higher valued than the PV-diesel system of “MER 1” and “MER 5”. Across all options, the preference for a selection of “MER 1” is manifested, since the additional energy requirements have the least effect on the “MER 1’s” energetic performance and the wasted energy is the lowest.

Table 5-16: Results of MCDA II by supply technology and MER option with additional requirements [value between 0-100]

Electricity generating system	MER 1 - Res1	MER 2 - Res2	MER 3 - Fos1	MER 4 - Fos2	MER 5 - Int
(Micro-) Diesel generator (>1 kW)			44.63	39.17	56.29
(Micro-) PV-diesel system (>1 kW)	61.88	53.29	51.27	45.49	61.09
(Micro-) Gas generator (> 1 kW)			32.12	26.89	46.05
(Micro-) Hydro generator (>5 kW)					
(Pico-) Hydro system (< 5 kW)					
Pumped storage (> 10 MW)					
(Micro-) Wind generators (>1 kW)	53.65	36.02			
(Pico-) Wind system (200 W)	52.94	32.46			
Solar Residential system (250-4000 W)	62.01	47.92			
PV home system (up to 250W)	59.34	40.99			
(Pico-) PV system (1-10W)	59.69	38.49			
(Micro-) Biomass power generator (> 1 kW)	49.62	20.28			

5.5.4. Sensitivity analysis

Upon completion of the option appraisals a diverse set of results is obtained. Yet, with different main focus the best solution varies. In order to take into account the impact of small parameter changes on the results, sensitivity analysis is applied to all appraisal stages. Parameter changes mainly concern the 5 cost components, since it is presumed that the cost is of great interest for most decision makers. For the analysis of options through MCDA II changes of all criteria weights are performed.

From the results of the monetary assessment the lowest priced supply technology for each "MER X" is selected for the sensitivity analysis. Indeed, the PV-diesel system is the preferred choice in all 5 options. When applying the cost variations across the 5 cost components the results in Table 5-17 are obtained. If prices change with the same percentage across all parameters, "MER 1" always provides the lowest costs. However, if costs for the renewables-based options slightly increase (+10%) while intermediate technologies receive a price reduction (-10%), then the overall system costs become highly competitive. If the costs are the single decision making aspect, then the two fossil-fuel based options should not be selected as the preferred options, because their costs are noticeably higher than all other MER options.

Table 5-17: Comparison of total system costs [€] for lowest priced supply technologies by MER option within monetary assessment

	MER 1	MER 2	MER 3	MER 4	MER 5
Electricity generating system	PV-diesel	PV-diesel	PV-diesel	PV-diesel	PV-diesel
unchanged	4,214	4,369	6,507	4,943	4,495
Device -30%	3,795	3,974	6,166	4,565	4,161
Device -20%	3,934	4,106	6,280	4,691	4,272
Device -10%	4,074	4,237	6,393	4,817	4,383
Device +10%	4,353	4,501	6,620	5,070	4,606
Device +20%	4,493	4,632	6,734	5,196	4,717
Device +30%	4,633	4,764	6,848	5,322	4,829
O&M -30%	4,170	4,325	5,730	4,923	4,347
O&M -20%	4,185	4,339	5,989	4,930	4,397
O&M -10%	4,199	4,354	6,248	4,937	4,446
O&M +10%	4,228	4,384	6,766	4,950	4,544
O&M +20%	4,243	4,399	7,024	4,957	4,593
O&M +30%	4,257	4,414	7,283	4,964	4,642
IC - 30%	3,777	3,882	6,057	4,370	4,003
IC - 20%	3,923	4,045	6,207	4,561	4,167
IC - 10%	4,068	4,207	6,357	4,752	4,331
IC +10%	4,359	4,531	6,657	5,134	4,659
IC +20%	4,505	4,694	6,807	5,325	4,823
IC +30%	4,650	4,856	6,957	5,516	4,986
f. O&M -30%	4,170	4,320	6,462	4,886	4,446
f. O&M -20%	4,185	4,337	6,477	4,905	4,462
f. O&M -10%	4,199	4,353	6,492	4,924	4,478
f. O&M +10%	4,228	4,385	6,522	4,963	4,511
f. O&M +20%	4,243	4,402	6,537	4,982	4,528
f. O&M +30%	4,257	4,418	6,552	5,001	4,544
v. O&M -30%	3,893	4,033	6,167	4,490	4,169
v. O&M -20%	4,000	4,145	6,280	4,641	4,277
v. O&M -10%	4,107	4,257	6,393	4,792	4,386
v. O&M +10%	4,321	4,481	6,620	5,095	4,603
v. O&M +20%	4,428	4,593	6,734	5,246	4,712
v. O&M +30%	4,535	4,705	6,847	5,397	4,821

The main driver for the cost changes within each MER are the costs associated to the electricity generating system. Hence, IC, fixed O&M and var O&M have been altered (±10%,

±20%, ±30%) for the full range of possibilities. Then the 50/50 preference combination for MCDA and costs is applied. Table 5-18 shows the results for "MER 1" and "MER 2". Considering the cost variations of the electricity generating system, in all changes the solar residential system performs best. However, the pico wind system also comes in 1st place in multiple occasions. The worst performance is achieved by the biomass generator.

Table 5-18: Effects of varying costs on preference order of supply technology for MER 1 and MER 2

Electricity generating system	v. O&M -30%	v. O&M -20%	v. O&M -10%	f. O&M -30%	f. O&M -20%	f. O&M -10%	IC - 30%	IC - 20%	IC - 10%	MER 1 Ranking	IC +10%	IC +20%	IC +30%	f. O&M +10%	f. O&M +20%	f. O&M +30%	v. O&M +10%	v. O&M +20%	v. O&M +30%
(Micro-) Diesel generator (>1 kW)																			
(Micro-) PV-diesel System (>1 kW)	5	5	5	4	4	4	5	5	5	5	5	5	4	5	5	5	5	5	5
(Micro-) Gas generator (> 1 kW)																			
(Micro-) Hydro generator (>5 kW)																			
(Pico-) Hydro system (< 5 kW)																			
Pumped storage (> 10 MW)																			
(Micro-) Wind generators (>1 kW)	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
(Pico-) Wind system (200 W)	1	1	1	1	1	1	2	2	2	1	2	2	1	2	2	2	1	1	1
Solar Residential system (250-4000 W)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
PV home system (up to 250W)	3	3	3	4	4	4	2	2	2	3	2	2	4	2	2	2	3	3	3
(Pico-) PV system (1-10W)	3	3	3	3	3	3	2	2	2	3	2	2	3	2	2	2	3	3	3
(Micro-) Biomass power generator (> 1 kW)	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7

The effects of the varying costs on the preference of the fossil fuel supply technologies is marginal. As a matter of fact, the 3 systems to choose do not show any changes throughout the parameter changes. Hence, the diesel generator and PV-diesel system come first in all 9 combinations.

Following the preference orders the total system costs for all supply technologies that come in first place for a "MER X" at one point may be compared through cost variations (Table 5-19).

For "MER 1" and "MER 2" the major cost driver is the investment cost of electricity generating systems (pico-PV and pico-wind). Only high reductions (30% and more) in the investment cost can lead to similar costs as those of "MER 5". All O&M as well as device costs have a rather insignificant impact on the results, which shows that these cost components are relatively low.

In the third scenario the preference set with equal weights (50/50) for the costs and MCDA I is applied. This may lead to options, where multiple electricity supply systems have the same preference value. Indeed, in all "MER X", except "MER 2", there are two electricity generating systems with the same combined value.

From all options presented, "MER 3" (both the PV-diesel and diesel generator) along with the diesel generator in "MER 4" have the highest costs. The pico-wind generator in "MER 1" is also one of the more expensive supply systems. Only high reductions in the investment cost of the wind generator lead to lower, thus more adequate, costs. Likewise, the diesel generator in "MER 5" shows a moderate cost range across all cost modifications. An impact on cost reductions is only achieved by cutting variable O&M.

Table 5-19: Comparison of total system costs [€] for scenario with equally combined cost and MCDA preference

	MER 1		MER 2	MER 3		MER 4		MER 5	
	Solar residential	Pico Wind	Solar residential	PV-diesel	Diesel gen.	PV-diesel	Diesel gen.	PV-diesel	Diesel gen.
unchanged	4,816	6,333	5,116	6,507	7,922	4,943	6,857	4,495	5,788
Device -30%	4,397	5,939	4,721	7,144	7,581	4,590	6,478	4,299	5,454
Device -20%	4,537	6,070	4,853	7,258	7,695	4,717	6,605	4,420	5,565
Device -10%	4,677	6,202	4,985	7,372	7,808	4,844	6,731	4,541	5,677
Device +10%	4,956	6,465	5,248	7,600	8,035	5,099	6,983	4,783	5,899
Device +20%	5,096	6,597	5,379	7,713	8,149	5,226	7,110	4,904	6,011
Device +30%	5,236	6,728	5,511	7,827	8,263	5,353	7,236	5,025	6,122
O&M -30%	4,773	6,289	5,072	6,417	7,146	4,945	6,837	4,488	5,641
O&M -20%	4,787	6,304	5,087	6,773	7,404	4,954	6,843	4,546	5,690
O&M -10%	4,802	6,319	5,101	7,129	7,663	4,963	6,850	4,604	5,739
O&M +10%	4,831	6,348	5,131	7,842	8,181	4,980	6,864	4,720	5,837
O&M +20%	4,845	6,363	5,146	8,198	8,439	4,989	6,871	4,778	5,886
O&M +30%	4,860	6,378	5,161	8,555	8,698	4,997	6,878	4,837	5,935
IC - 30%	3,943	5,035	4,142	7,036	7,682	4,398	6,552	4,172	5,526
IC - 20%	4,234	5,468	4,467	7,186	7,762	4,589	6,653	4,335	5,613
IC - 10%	4,525	5,901	4,792	7,336	7,842	4,780	6,755	4,499	5,700
IC +10%	5,108	6,766	5,441	7,636	8,002	5,162	6,959	4,826	5,875
IC +20%	5,399	7,199	5,765	7,785	8,082	5,353	7,061	4,989	5,963
IC +30%	5,690	7,632	6,090	7,935	8,162	5,544	7,163	5,152	6,050
f. O&M -30%	4,707	6,171	4,995	7,441	7,809	4,914	6,714	4,613	5,665
f. O&M -20%	4,744	6,225	5,035	7,456	7,847	4,933	6,762	4,629	5,706
f. O&M -10%	4,780	6,279	5,076	7,471	7,884	4,952	6,809	4,646	5,747
f. O&M +10%	4,853	6,388	5,157	7,501	7,959	4,990	6,905	4,678	5,829
f. O&M +20%	4,889	6,442	5,197	7,516	7,997	5,009	6,953	4,695	5,870
f. O&M +30%	4,926	6,496	5,238	7,531	8,034	5,029	7,000	4,711	5,911
v. O&M -30%	4,816	6,333	5,116	7,145	7,015	4,518	5,648	4,340	4,918
v. O&M -20%	4,816	6,333	5,116	7,259	7,317	4,669	6,051	4,447	5,208
v. O&M -10%	4,816	6,333	5,116	7,372	7,619	4,820	6,454	4,555	5,498
v. O&M +10%	4,816	6,333	5,116	7,599	8,224	5,122	7,260	4,769	6,078
v. O&M +20%	4,816	6,333	5,116	7,712	8,527	5,274	7,663	4,877	6,368
v. O&M +30%	4,816	6,333	5,116	7,826	8,829	5,425	8,066	4,984	6,658

The remaining four options ("MER 1" pico wind, "MER 3" PV-diesel, "MER 3" diesel generator and "MER 4" diesel generator) show relatively similar cost ranges from lowest to highest. In all four cases a highly reduced investment cost leads to the best results. All O&M for the solar residential system in "MER 1" and "MER 2" have almost no impact, whereas the higher impact for the PV-diesel generator in "MER 4" and "MER 5" is seen for changes in the device cost as well as variable O&M. With the exception of 30% or more reduction on the investment cost of the solar residential system in "MER 1", all other parameter changes as well as the initial (unchanged) cost show better results for the PV-diesel system in "MER 5".

The comparison of the MER options across the 2 cost-driven appraisals leads to different "dominant" "MER X". When following the scenario with the lowest cost, then the PV-diesel system in "MER 1" shows the best results. In the scenario which combines the preferences of costs and MCDA equally, the PV-diesel system in "MER 5" presents the best solution.

In both cases the best performance is achieved when the investment costs of the electricity generating system can be reduced. The second most important cost component is the device cost in "MER 1" and the variable O&M in "MER 4" and "MER 5". Cost changes on the O&M of devices as well as on the fixed O&M have very little influence.

With additional requirements for comfort and well-being across all 5 options the results would generally look alike. PV-diesel systems become the best choice in terms of the supply system. "MER 1" achieves the lowest overall costs, followed by "MER 5" and "MER 2". However, this time the cost difference between "MER 1" and "MER 5" would be over 30%. Following the monetary assessment in the previous chapters, the costs for "MER 3" and "MER 4" would be substantially higher due to the cost associated to AH. Neither of the two alternatives is recommended as solution.

Finally, sensitivity analysis is applied to the investigation of options through MCDA II. For that all supply technologies across the different options are considered. Each of the 3 weights is changed, whereas proportional increases/decreases of the remaining weights are undertaken. The results of the sensitivity analysis for the cost weight are presented in Figure 5-17.

At the currently defined weights the PV-diesel system of "MER 5" is the preferred solution – see highest intersection at $w_{cost} = 0.39$. Only if the cost weight exceeds 50%, then the PV-diesel system of "MER 1" becomes the preferred solution. As a matter of fact, the variation of the cost weight leads to the conclusion that the PV-diesel is the most preferred supply technology. This is true for all weight changes, as long as cost weight does not fall below 5%. At such a low influence of the costs, the solar pico system would be preferred. Yet, there are also 5 combinations whose performance decreases with an increase in the cost weight: "MER 1" and solar pico system, "MER 1" and biomass generator, "MER 2" and solar pico system, "MER 2" and biomass generator and "MER 3" and diesel generators.

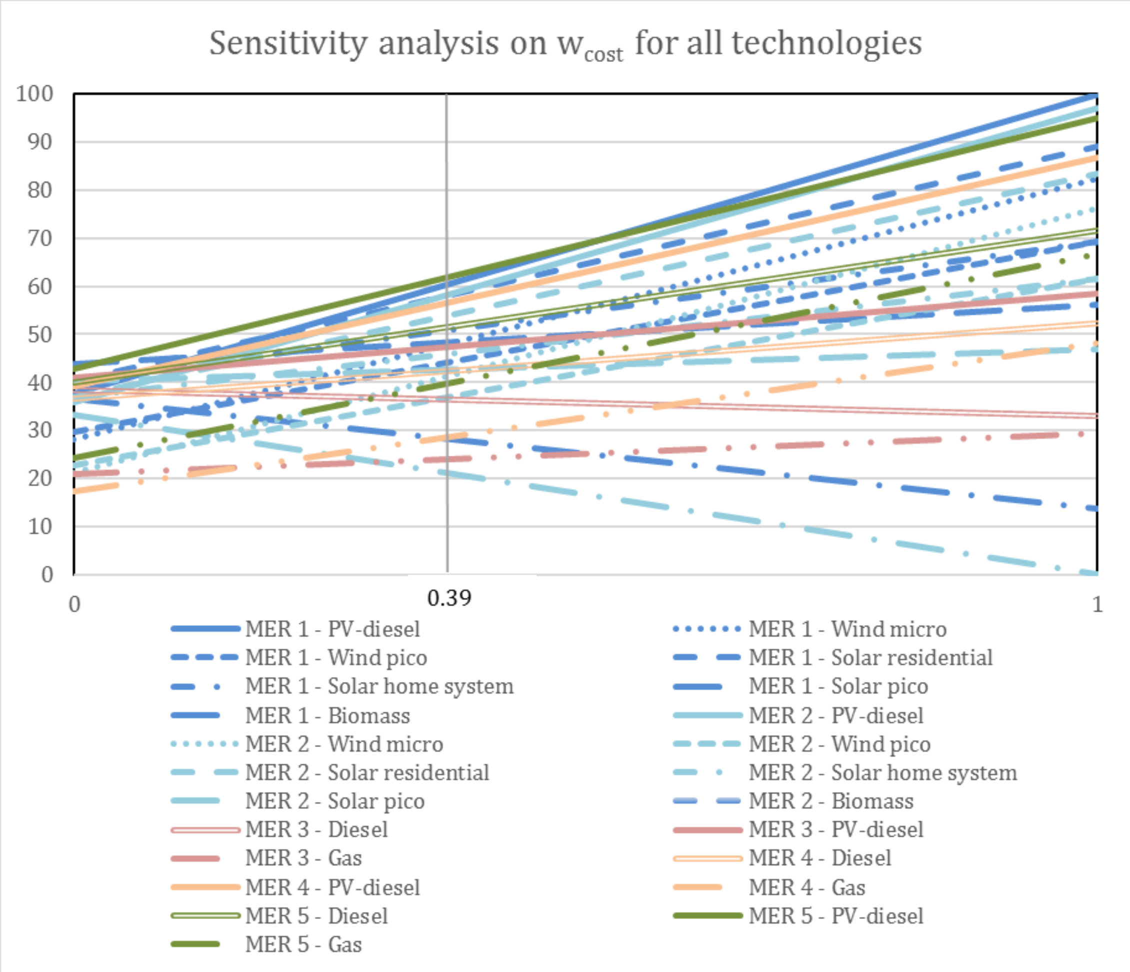

Figure 5-17: Sensitivity analysis on cost weight

When performing the sensitivity analysis on the local acceptance weight, then similar conclusions can be drawn. Any increase in the local acceptance weight favor the PV-diesel system. Only if the influence of the local acceptance weight is lowered, then the solar residential system and pico-PV system of “MER 1” are preferred. As a matter of fact, within the parameter changes of the local acceptance, for most part “MER 1” is the favored solution. Only the selected supply technology changes with a varying local acceptance (Figure 5-18).

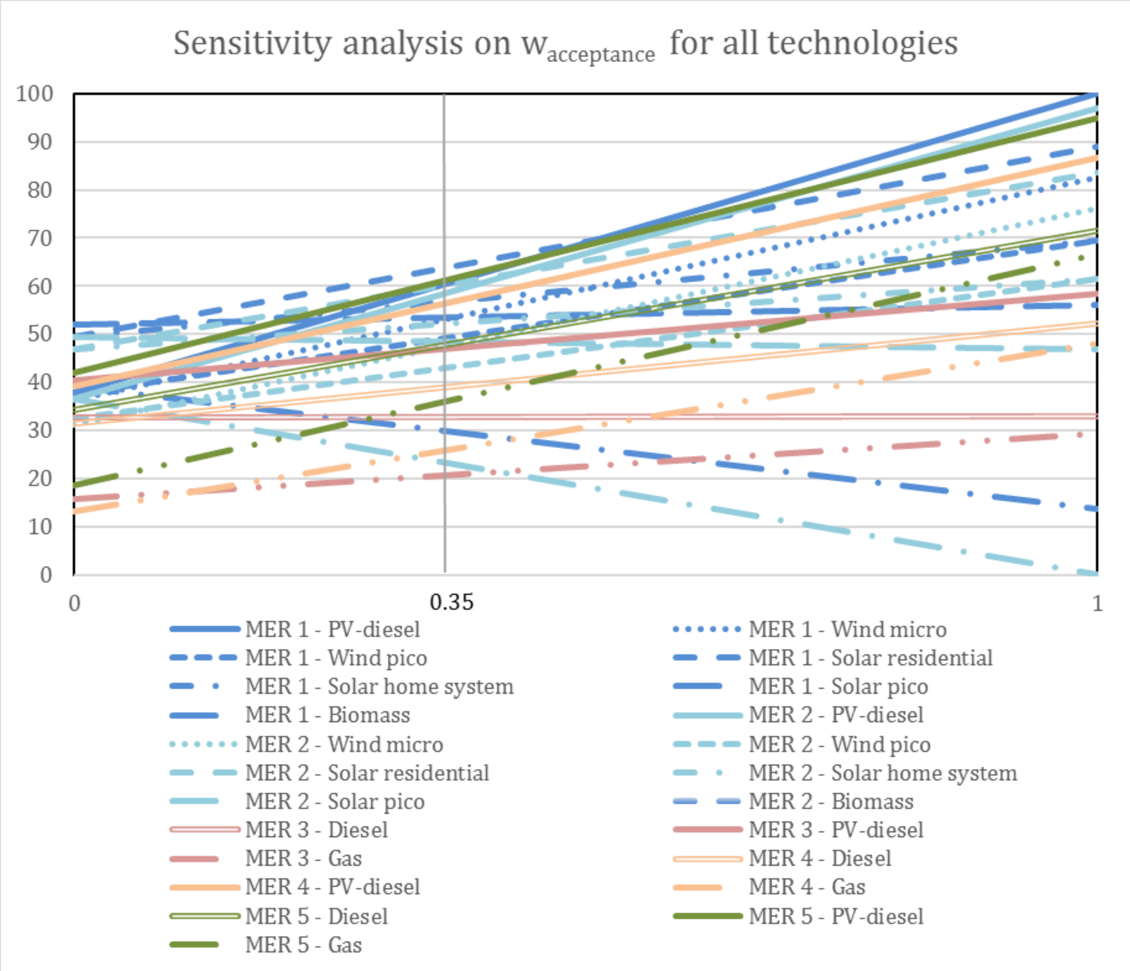

Figure 5-18: Sensitivity analysis on local acceptance weight

According to the procedures described above, the impact of the higher cost variations due to the inclusion of additional comfort requirements, is evaluated. Because of the substantial differences in the cost for each option, “MER 1” becomes the clear favorite across all parameter changes. Only if the cost weight is decreased, then the PV-diesel system of “MER 5” becomes favored. In all other cases, the PV-diesel, solar residential or solar pico of “MER 1” are clearly ahead of the remaining supply technologies and options (Figure 5-19).

Following the sensitivity analysis, the number of potential options and supply technologies can be narrowed down to a minimum. Indeed, there are only “MER 1” and “MER 5” which should be recommended for the implementation of devices. At the same time, the supply through a PV-diesel system seems the most likely choice for the fulfilment of the minimum energy requirements. If additional comfort requirements shall also be covered, then solar residential and solar pico systems also should be accounted an alternative.

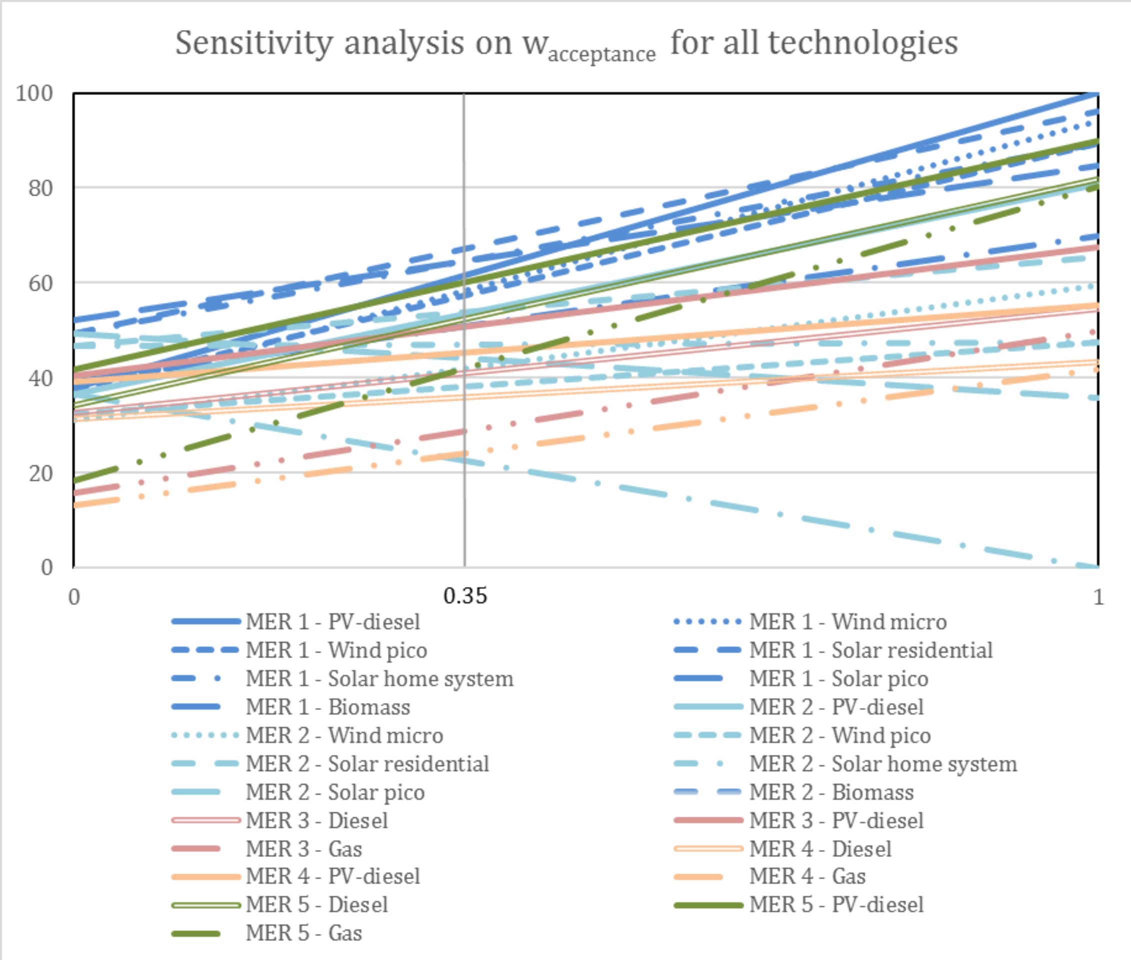

Figure 5-19: Sensitivity analysis on local acceptance weight considering additional comfort requirements

5.5.5. Most appropriate solution

Upon completion of the option appraisals all results were subject to sensitivity analysis. In that way the robustness of the solutions has been evaluated.

According to the different appraisal stages different solutions may be proposed. The selection of the most appropriate solution for a community largely depends on the parameter (changes) the decision maker values the most. Likewise, it is a matter of the additional input that is requested from decision makers to perform the appraisal methods.

In Table 5-20 the results from each appraisal stage are listed. Therefore, the main focus points are summarized for each stage. Even though the energetic assessment could be considered as result, it is mainly the end-use devices that are evaluated at that stage. The supply technology would depend to a great extent on the preference order of MCDA I.

Table 5-20: Most appropriate solution by appraisal stages

Stage	Focus point(s)	Without additional requirements	With additional requirements
Energetic assessment	- Reach defined energetic target - Preference order of MCDA I - Linear value functions - Swing Weight	- MER 1 + Pico PV system	
The following stages are all based on the results achieved from the energetic assessment. The device selection for each "MER X" remains unchanged and the energetic target is met in all options.			
Monetary assessment (Phase I)	- Solely financial aspects of overall option	- MER 1 + PV-diesel system - Sensitivity analysis proves robustness of solution	
Full range of possibilities (Phase II)	- Combines financial aspects of monetary assessment and results from MCDA I	- MER 1 + solar residential - MER 2 + solar residential - MER 3, MER 4 and MER 5 with diesel generator or PV-diesel system - Sensitivity analysis initially confirms MER 1 + solar residential, but with cost changes the PV-diesel system of MER 5 is favored	
MCDA II of options (Phase III)	- Total system cost - Resource availability - Local acceptance - Linear value functions - Swing weights	- MER 5 + PV-diesel system for cost approach - MER 1 + solar residential for local acceptance and resource availability	- MER 1 + solar residential system
		- Sensitivity analysis proves results, and indicates shifts in the preferred solution if substantial changes of the criteria weights occur	

In the end, the most appropriate solution is subject to a variety of evaluation criteria. While "MER 1" and "MER 5" as well as the PV-diesel and solar residential system lead to the best results among all the appraisal aspects, the PV-diesel system of "MER 1" is suggested by the author. This is not only the most common solution across the appraisal stages, but also responds to other essential energy planning concerns. On the one side, the PV-diesel system is available when needed, and can respond to any shortages without the need for additional storage or back-up. On the other side, the "MER 1" showed the best energetic performance with the least energy requirements and the least energy wasted. While there may be initial resistance with the local acceptance, the environmental and health aspects in favor of "MER 1" cannot be ignored. It is part of the process to achieve sustainable livelihoods and hence, the use of modern and clean resources, devices and technologies is highly recommended.

6. Conclusions

This last chapter of this thesis concludes the work. It summarizes the main results and findings and provides ideas and concept improvements for future work.

6.1. Summary of findings

Energy access still remains a major challenge in many remote and/or isolated areas of developing countries. Since there is no common agreement on what defines energy access and energy poverty, planners often disagree on the best way to provide access to energy for all. The discrepancies also arise from the limited information about the people that actually need the energy. Besides, there is no common consent on the definition of the minimum energy requirements, since that actually entails the consideration of local conditions and aspects. The often referred to per capita or community consumption may easily be misinterpreted if only a single end-use is not in line with the considerations made in the definitions. Hence, it is unsuitable to apply lessons learned from the developed world, or even other communities with differing geographical, political, cultural conditions, as each community needs to be considered on its own. Local conditions and acceptance of the local inhabitants are major aspects that cannot be predicted from the outside, and therefore, always require special consideration in the planning process.

This work comprises a methodological bottom-up approach to analyze the current situation of any given community and to propose options that improve energy access and reach the minimum energy requirements across all end-uses and sectors. Specific focus is placed on isolated communities in developing countries, where energy network services are unlikely to be implemented in the foreseeable future.

Because of the variety of factors that can influence the planning process and the fact that even small nuances may have great impacts, planning support needs to start with defining the current consumption, analyzing the local conditions and setting energy objectives that can be reached. Still, energy planning approaches that deal with minimum energy requirements, particularly from the community perspective, are very scarce. Due to the high number of end-use device types and supply technologies, decision support is then strongly recommended to find the most appropriate option(s) for a community. Thereby, the technological level of devices has to be differentiated and kept in mind when identifying suitable devices, and subsequently options, for the community. In fact, too much too soon can lead to project failures, not to say, rejections from the local habitants. Subsequently, this research focusses on the most essential needs within each end-use and sector and seeks alternatives to reach the minimum energy requirements based on the preferences of decision makers and according to the local conditions.

The assessment of the current consumption, devices in use and local conditions forms the first step of the methodological approach. It is imperative to understand where a community stands, what resource and devices are being used, how and how long technologies and devices are being used and what resources are abundant and/or locally available. While this information requires local assessments and involvement of decision makers, another major part is the gathering and management of data sets for devices, electricity generating systems and minimum energy requirements by end-use and sector. While the former (devices and supply systems) can be gathered and updated on a regular basis, the latter (MER) should be well-defined, since minimum energy access cannot be defined with a single number. It is inappropriate to attest a community that minimum energy access has been reached, because the per capita consumption is higher than the definition. This can be absolutely misleading. In fact, it is paramount to analyze the current consumption and devices in use thoroughly. Within the MER values have to be defined for each end-use and sector.

Besides, it was found essential to define the MER based on the technology level since devices have different levels of technological advancement, ranging from traditional to intermediate and advanced devices. For that reason, a x-factor has been implemented, which is a reflection of the device's performance (i.e. power and efficiency). Accordingly, an adjustment of the MER for each device was made. In the herein gathered data set most intermediate technologies remain unchanged and were given a x-factor of 1. Devices that perform better than the standard have lower requirements and poorer performing devices have higher requirements. A clustering of devices by x-factors is essential to neither threaten the overall results of a community nor blur the actual level of consumption. In the end, the x-factor associates a more accurate MER to each device and end-use so that the performance within the current consumption or potential options can be better judged.

The matter of not only associating the per capita or household consumption to the MER shall be highlighted in more depth, because frequently, only the overall results are being evaluated. When dealing with minimum energy access, this is misleading, not to say, counterproductive, since only one very poorly performing device could make a community reach its minimum requirements. This may especially account for the energy-intensive cooking (particularly devices with multiple end-uses, i.e. cooking, DHW and AH), which in many isolated communities is based on traditional devices (e.g. open wood fire) with very low efficiencies. As a consequence of the inefficiency, many cooking devices produce a significant amount of ambient heat. For cooking devices that are used inside the house, a part of the heat could actually be used for ambient heating purposes. That may be an important source to meet the AH requirements in areas with a high number of heating degree days. However, in warmer climates (such as in India) the additional heat inside the houses can become an additional burden, since even further cooling needs would be quantified. Everything that exceeds the AH requirements and anything that is generated outside the houses is wasted heat, since it is just a by-product of cooking/DHW with no additional use. Subsequently, the use of inefficient devices for cooking/DHW causes major problems in the energetic evaluation of communities. Especially communities with a high degree of wasted heat – in some cases the actual needs within the domestic sector are even surpassed solely by wasted heat – may achieve contradictory results in meeting the MER if the heating issue is not considered appropriately. In order to prevent false conclusions about a community's energetic performance, an adjustment of the community's energy needs without the wasted heat should be performed.

The effects of performance, and subsequently wasted heat, should be kept in mind in the preference order of devices within the MCDA. Meanwhile, each location is unique and each decision maker has different local conditions and preferences, so his/her input for attribute values and criteria weights is deemed crucial. This is imperative, since there is no pre-defined set of criteria weights and attribute scores that reflects all aspects of a given location. It has been shown in the literature review that pre-defined approaches to increase energy access are only partially successful. Consequently, for an effective application of the proposed methodological approach it is paramount to involve local decision makers in the decision making process. Preferences need to be well defined and the most important criteria need to be set. While for some decision makers only the financial aspects are of importance, others have a higher focus on social or environmental aspects. Others again want a holistic approach under the umbrella of sustainability that considers all those aspects with a similar preference. In the end, this research allows to easily adapt to the preferences of the applicant, whereas a data set has been defined that can be used as benchmark based on the authors judgement.

Once the devices have been selected, the energetic assessment proposes options that meet the defined minimum requirements for each end-use and service. Besides, the expected daily operating hours should be met. While in the analysis of the current consumption any discrepancies can be observed to better understand where the community is lacking energy, in the proposed options all end-uses are fulfilled. Additional energy needs (devices), which already lead to comfort or that occur due to the additional use of devices, are highlighted in both cases (current consumption and MER options).

Based on the energetic assessment the monetary one is performed. Thereby, it can be seen where costs are the highest on the end-user side. In fact, the major cost drivers are not the more energy intensive uses (e.g. cooking or DHW), but ICT, refrigeration and AH. The devices used for those end-uses have a significant impact of the overall cost of each option. Yet, the major cost driver for all options is the electricity generating system. All end-uses that can work independently without electricity have a noticeably lower influence on the overall cost as long as they are not driven by expensive fossil fuel imports. Indeed, solar cookers are much preferred to gas cooktops or kerosene stoves.

In the analysis of the electricity generating systems the PV-diesel system has been identified as the most cost-effective across all 5 options (i.e. best and second-best renewables-based options, best and second-best fossil fuel-based options and intermediate technology option) proposed. Indeed, with a high emphasis on economic aspects the PV-diesel system shows the best overall performance. As a matter of fact, the PV-diesel system is also very practical from a technical point of view. Renewables, for instance in the form of solar radiation, can be used whenever they are available. In times where demand exceeds the solar supply, diesel can be added to the system so that a constant demand-supply match can be guaranteed. In terms of size of the system either PV or diesel alone could supply all needs when operating at their peak capacity. Nonetheless, from a cost perspective, the major generation should come from the abundantly available solar radiation. A reversion to fossil fuels should only be encouraged when absolutely needed. Accordingly, transportations costs of fossil fuels have to be accounted.

Other supply systems solely based on RES bear a major factor of insecurity, which may then also lead to the rejection of the technology. As a matter of fact, any type of technology needs to be maintained and operated, so someone in the community needs to be responsible and take care of it. This required foremost an in-depth understanding of how the system works and what should be done if the machinery fails. Hence, in the proposal of options for the community any expertise with existing or proposed electricity generating systems should be carefully investigated. If the community does not have a trained technician to oversee, run and maintain the devices, then the implementation of advanced technologies is not recommended. In such a case, it is much preferred to use traditional or intermediate technologies, whereas the technician is familiar with the use and does not abandon the generating system in the event of failures. In fact, a malfunction on the supply side leads to a community-wide failure of electrical appliances. If this point is reached, then the most cost-effective and best option cannot help the community and trust in the decision makers diminishes.

In addition to the purely cost driven analysis, a full range of possibilities has been evaluated and sensitivity analysis has been applied to assess the most favored option and supply technology. In the end, there is no standard solution for a community, since each and every community is unique in its local features and possibilities. Consequently, the proposed methodological approach provides support in finding various options that meet the minimum energy requirements. The option that is most preferred should then be judged by the local decision maker based on its expertise and preferences. This work identified “MER 1” (best renewables) and “MER 5” (intermediate technologies) as the most favored options. Due to the better energetic performance and the better environmental performance, “MER 1” is suggested as most appropriate solution. Even though this may lead to initial resistance of the community, the advantages for the inhabitants towards sustainable livelihoods – better living conditions, more comfort, less health hazards – are indubitable. From the supply perspective the PV-diesel system achieves a high preference value for nearly all parameter changes that were performed. With less importance on the total system cost, supply systems in the form of solar residential or solar pico become worthwhile. They may also be interesting with drastic cost reductions. However, the use of variable renewable energy sources necessitates the use of storage or back-up.

In the end, getting a community lifted from basically no or very limited energy access to meet the MER across all end-uses and sectors requires careful planning, starting from the analysis of the current situation to the final evaluation of suitable options. Sensitivity of decision makers to local conditions and understanding the expectations and capabilities of the community’s inhabitants hold major keys to success when selecting the most appropriate option.

6.2. Future work

This research has started from a very broad context and gradually narrowed its focus down on the critical elements of meeting the minimum energy requirements. Yet, this work left a variety of aspects that can lead to future research themes. Hence, a diverse set of potential future works in suggested:

- An impact assessment of options is recommended since it would enhance the quality of the work and provide evidence if the methodological approach fulfills its objectives.
- A more precise association/clustering of x-factors is recommended. As of now this was an exercise to practice the method and has only been done for cooking, DHW, AH, lighting and water pumping. Hence, it may also be possible for the remaining end-uses. While the x-factor presents a rough proxy for the concept, further improvements could be applied through the use of the 2nd law of thermodynamics. Through the use of an exergy metric the indifferences in the accounting of heat and work at the useful energy level could be minimized.
- Take advantage of already implemented devices and do not start from scratch with each option. If devices that are selected in the option are already used in the community (relatively new and not already reaching the end of their lifetime), then they do not need to be replaced. They can remain, whereas the proposed option needs to be adjusted by the number of devices already in place. In the end, this will lead to different financial savings when comparing the various options. Also, this will help in reaching a better acceptance within the community, since not all devices need to be replaced. In that way the options are easier to be implemented, since there will be less local resistance. The saved costs could be used elsewhere or even for comfort devices, if those financial means were available. In the end, a greater local acceptance of the proposed option makes it easier for the community to adapt and implement an option.
- In order to better understand the cost variations and the scale of investments a life cycle assessment could be applied. This also provides an alternative to account devices over different time periods as well as devices that might already be used within the community and do not need an immediate replacement.
- Extend the number of considered devices, especially for end-uses that have been limited so far, e.g. refrigerators in particular but most electrical appliances in general could be clustered by their efficiency rating (A+++ to G). That would increase the spectrum considered in the minimum energy requirements and allow for a more extensive consideration of the x-factor across further end-uses.

- Ex-post and ex-ante evaluation system to assess the current situation and proposed solution. Define indicators, either single or composite ones, for evaluation procedure.
- While this work puts a lot of emphasis on the fact that heat is wasted with inefficient cooking/DHW devices, the waste of electricity due to an “overproduction” is not considered. As a matter of fact, the solutions proposed in this work do not take into account any aspects of storage or back-up. This has mainly to do with the limited data that could be obtained about daily consumption pattern. However, it must be clear that if variable renewables-based electricity supply systems were to be selected, storage or back-up systems would be essential to match supply and demand. Otherwise, any exceeding generation, for instance during the lunch time when the solar radiation is the most intense, would be wasted if not used at the moment. Hence, it would be highly recommended to further study the performance of supply systems based on only renewables and what size of the systems, both for generation and storage, would be required. Similar to the results obtained in this research, which always favored a PV-diesel system, other studies have shown that minor contributions of fossil fuel supply are recommended when assessing the economic aspects of a supply system for isolated areas (Wimmler C. , 2016).
- Trade-off analysis when comparing options and the different electricity generating systems. In terms of cost trade-offs, no considerations have been made. While there can be minor cost differences, the ranking instantly differentiates any cost change, even if it is just a single cent. Larger differences are not reflected accordingly, so that there might be two electricity systems with almost similar costs but a noticeable scoring difference, while two other electricity systems with substantial cost differences might have the same difference in the total ranking score.
- Define different levels of energy access, where a gradual increase may be more suitable for a community rather than an instant increase from the current situation to MER. In that regard it may also be differentiated in the most essential needs (cooking, DHW, lighting, etc.) and end-uses that already lead to comfort (mainly ICT).
- Due to the foreseen cost reductions of batteries, there may be major change in the possible supply alternatives, as variable renewable energy technologies can be applied to a larger extent. Likewise, technical concerns, e.g. security of supply, can be reduced.
- Consider two or more nearby communities together and eventual increases in the demand requirements that can already be foreseen for the upcoming decade(s).
- The set of alternatives is built by combining the devices in different ways. Yet, the substitution of this manual definition of the alternatives by an optimization process is suggested.

- Apply the methodology in multiple communities under varying conditions and considering local decision maker inputs. Also, consider the possibilities of defining supply technologies for Panchayats, where 5-15 communities are grouped together.
- Perform ex-post evaluation of the proposed solutions to understand if the option was adapted by the community.

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8. Appendices

8.1. Overview of energy planning and modelling tools

Table 8-1: Overview of energy planning and modeling tools

Tool	Type of model	Description	Goal	Scale
Accounting				
COMMEND (Sezgen, Huang, Atkinson, Eto, & Koomey, 1994)	Economic (E.)	Commercial energy end-use model in tertiary sector	I.	L.
COMPOSE (Blarke, 2008)	Techno-economic	Sustainable energy platform	O.+I.	R./N.
COSMEE (Otero-Novas, Meseguer, Batlle, & Alba, 2000)	Economic (E.)	For the behavior of a wholesale electricity market	O.+I.	N./In.
DNE21 (Akimoto, Tomoda, Fujii, & Yamaji, 2004), (Tahir & Banares-Alcantra, 2012)	Integrated	Optimal mitigation strategy against global warming	S.+I.	N./In.
DTI (Evans & Hunt, 2009)	Economic	Energy model from top-down	I.	L./R.
ELFIN (Kagiannas, Didis, Askounis, & Psarras, 2003)	Techno-Economic (E.)	Supply side management-generation expansion planning	S.+I.	R./N.
E2M2s (EWIS, 2008)	Economic	Stochastic European Electricity Market strategic long-term planning	O.+I.	N./In.
E3ME/E3MG/MDM (Barker, 2013)	Economic	Energy, environment and economy modules for understanding and comparing the impact of different policy options	S.+I.	N./In.
Elfin (Milligan, 2002)	Economic	Quantify the potential value of wind	O.	L./R.
EMCAS (DIS, Argonne National laboratory, 2013)	Economic	Electricity Market Complex Adaptive System model	I.	R./N.
Energy Costing Tool (UNDP, 2006)	Economic (A.)	Energy investments study to meet the Millennium Development Goals (MDGs)	I.	R./N.
ENPEP (Argonne National Laboratory, 2008), (International Atomic Energy Agency, 1997)	Economic (E.)	Energy demand forecasting in tertiary sector	S.+I.	R./N.
ESPAUT (Amerighi, Ciorba, & Tommasino, 2010)	Economic	Resilience of the energy system against shocks of energy prices and supply of primary sources	I.	N./In.
GEMIS (Fritsche, Leuchtner, Simon, Rausch, & Matthes, 1993)	Environmental	Global emission model for integrated systems	O.+I.	L./R./N
genEris (Haller, 2006)	Economic-Environmental	Assess the role of CO_2 mitigation options in electricity sector	I.	R./N.
H2A analysis (Steward, 2012)	Economic	Technology neutral cost calculator for development of cost targets for hydrogen production technologies	I.	P.
INFORM (TVA, 1994)	Economic	Industrial sector forecasting	S.	L./R.
Invert (Stadler, Kranzl, Huber, Haas, & Tsioliaridou, 2007)	Economic	Design of efficient promotion schemes for RET	I.	R./N.
JMM (EWIS, 2008)	Techno-Economic	Joint Market Model is a power analyser based on the size of the scenario	O.+I.	R./N.

Table 8-1 continued

Tool	Type of model	Description	Goal	Scale
LEAP (Stockholm Environment Institute, 2005)	Integrated	Energy policy analysis and climate change mitigation assessment	S.+O.+I	L./R.N.
MACRO (Messner & Schrattenholzer, 2000)	Economic	Optimal generation with least cost energy supply	O.	L./R./N
MACTool (ESMAP, 2013)	Economic	Marginal Abatement Cost Curve	O.	L./R./N
MESSAGE (Schrattenholzer, 1981) (Messner & Schrattenholzer, 2000)	Techno-economic (E.)	Energy Supply Strategy Alternatives and their General Environmental Impacts	O.+I.	R./N.
MDG Assessment (UNDP, 2010)	Economic (A.)	Practical interventions to meet the MDGs in a country	I.	L./R./N.
MTSIM (Zani, 2012)	Economic	Zonal electricity market simulator to calculate hourly clearing of market	O.	R./N.
PLEXOS (Energy Exemplar, 2013)	Economic	Analytical framework for power market modellers	O.+I.	R./N.
RET Screen (RETScreen® International Clean Energy Decision Support Centre, 2008)	Integrated	Evaluation of clean energies	I.	L.
RCDM (TVA, 1994)	Economic	Residential Conditional Demand Model, end-use energy planning	S.	L./R.
SWITCH (Nelson, et al., 2012)	Economic-Environmental (E.)	To evaluate least cost and impact from generator plants	I.	R./N.
UPLAN-E (Kagiannas, Didis, Askounis, & Psarras, 2003)	Economic	Supply side management-generation expansion planning	S.	R./N.
WASP (Kagiannas, Didis, Askounis, & Psarras, 2003)	Economic	Supply side management-generation expansion planning	S.	R./N.
WEM (OECD/IEA, 2011)	Economic	World energy projection model	I.	N./In.
Advanced planning				
BALMOREL (Ravn, 2001) (Balmorel Project, 2001)	Technical	Electricity and CHP market	O.+I.	N./In.
BCHP Screening (MacDonald, 2007)	Economic	Assess central heating power (CHP) for commercial building	O.	L.
CHPSizer (Aldi, Anundson, Bigelow, & Capulli, 2010)	Techno-Economic	Preliminary tool for CHP	O.	L./R.
COMPASS (Performance Systems Development, 2015)	Techno-Economic (E.)	Load and demand side management tool to measure, track and evaluate performance	T.+I.	L./R./N
COMPETES (Ozdemir, Scheepers, & Seebregts, 2008)	Technical (E.)	Supply side management-transmission expansion planning	O.	N./In.
DSMANAGER (Logan, Neil, & Taylor, 1994)	Techno-Economic	Analyses demand side management programmes	T.+I.	L./R./N
ENACT (IIASA, 2012)	Economic-Policy (A.)	Assesses future policy choices and their effectiveness in achieving energy access goals	S.	R./N.
EFM (TVA, 1994)	Economic	Electricity Forecasting Model	S.	L./R.
EnergyPro (EnergySoft,LLC, 2011)	Techno-Economic	World class Building analysis	S.	L.
FINNESS (TVA, 1994)	Economic	Revenue and cost forecasting	S.	L.
HELM (TVA, 1994)	Technical	Peak Load forecasting	S.	L./R./N
LEED (USGBC, 2011)	Technical	Building performance	O.	L.
ITEMS (Enterdata, 2013)	Integrated	Integrated Transport Effects Modelling System	S.	N.
IRP-MANAGER (Kagiannas, Didis, Askounis, & Psarras, 2003)	Integrated	Energy resource planning	S.+O.+I	L./R./N
MARKEL/TIMES (Loulou, Goldstein, & Noble, 2004) (IEA, 1976)	Integrated	Market Allocation Model Energy Technology Systems Analysis Program (ETSAP)	S.+O.+I	L./R./N

Table 8-1 continued

Tool	Type of model	Description	Goal	Scale
I-PLACE³S (Czachorski, Silvis, Barkalow, Spiegel, & Coldwell., 2008)	Techno-Environmental	Planning for Community Energy, & Sustainability	O.	L./R.
POLES (Joint Research Center, 2010)	Integrated	Develop long-term energy supply and demand scenarios	S.	N./In.
PRIMES (Capros, 2012)	Techno-Economic	EU Market equilibrium solution	S.	N./In.
PROMETHEUS (Capros, 2011)	Integrated	Simulation model of energy supply, demand and energy prices	S.	N./G.
RESM (TVA, 1994)	Economic	Regional economic simulation	S.	R.
REEPS (TVA, 1994)	Economic (E.)	Residential Energy End-use planning system	O.	L./R.
Forecasting				
Econometric (Enterdata, 2013)	Economic	Short term forecasting through econometric approach	I.	N.
STIFS (U.S. Energy Information Administration, 2009)	Integrated	Modelling database from which forecasting equations are estimated	S.	N.
RSTEM (U.S. Energy Information Administration, 2009)	Integrated	Utilizes estimated econometric relationships for demand, inventories and prices to forecast energy market outcomes	S.	R./N.
Simulation				
Balmorel (Unger, et al., 2010)	Integrated	Partial equilibrium framework	S./I.	R./N.
COAL1 (Kiani, Mirzamohammadi, & Hosseini, 2010)	Policy-Economic	Assess Impact of energy limits on US economic growth	S.	N.
COAL2 (Kiani, Mirzamohammadi, & Hosseini, 2010)	Policy-Economic	Assess Impact of energy limits on US economic growth	S.	N.
CO2DB (Segurado, Pereira, Pipio, & Alves, 2008)	Economic-environmental	Selects technologies and calculates efficiency of energy conversion chains	I.	N.
DESPOT (Martini, Pelacchi, Cazzol, Garzillo, & Innorta, 2001)	Economic	Decision –support for power trading	S.	N./In.
DIMENSION (Richter, 2011)	Integrated (E.)	Dispatch and Investment Model for Electricity Markets in Europe	S.+O.+I	N./In.
DOS (Unger, et al., 2010)	Economic	Calculate electricity demand at different electricity price levels	S./I.	N.
E3Database (Segurado, Pereira, Pipio, & Alves, 2008)	Integrated	Model and calculate hydrogen value chains (and other supply chains)	I.	L./R./N.
ECON-classic (Unger, et al., 2010)	Economic	Maximize sum of producer and consumer surplus	S./I.	N.
ELECTRIC1 (Ford, 1983)	Techno-Economic	Policy evaluation for U.S. investor-owned electric utility industry	S.	N.
EMELIE (Lise, et al., 2006)	Economic-Environmental	Optimization of maximize profit in electricity market	S.	N./In.
EMPS (Wolfgang & Graabak, 2011)	Economic	Multi-area Power-market Simulator	S.+O.	R./N.
Energy 2020 (Backus & Amlin, 2009)	Integrated	Multi-fuel model for prices, demand/supply and pollution	S	L./R./N.
Energy Plus (National Renewable Energy Laboratory (NREL), 2018)	Economic	HVAC & micro generation	S.	L.
EPPAM (Teufel, Miller, Genoese, & Fichtner, 2013)	Policy	Financial and regulatory model for electricity utilities	S.	R./N.

Table 8-1 continued

Tool	Type of model	Description	Goal	Scale
FOSSIL1 (Backus et al., 1977)	Policy-Economic	Policy analysis model for US energy transition	S.	N.
FOSSIL2 (Naill, Belanger, Klinger, & Petersen, 1991)	Policy-Economic-Environmental	Assess emission reduction potential and costs of several policies	S.	N.
FREE (Fiddaman, 1997)	Economy-Environmental	Effects of energy on US economy and externalities	S.	N.
GREET (Argonne National Laboratory, 2012)	Economic-Environmental	Characterizes total lifecycle energy and emissions of various transportation processes	S.	L./R./N.
GTAP-E (Unger, et al., 2010)	Economic-environmental	Analysis of energy and environment issues	S.	N.
GTMax (International Atomic Energy Agency, 2002)	Techno-Economic	Dispatch of electric generation units and economic trade of energy among utilities	S.	R./N.
HOMER (HOMER Energy, 2009)	Techno-Economic (E.)	Optimizing microgrid design in all sectors	S.+O.+I	L.
HUD CHP screening tool (U.S. Department of Energy, Oak Ridge National Laboratory, 2009)	Economic	Evaluate combined cooling, heating, and power in multi-family housing	S.+I.	L.
HYDROGEMS (Briguglio, Ferraro, Andaloro, & Antonucci, 2008) (Ulleberg, 1998)	Techno-Economic	Library of integrated hydrogen systems and Renewable Energy	S.	L./R.
HYPRO (James, Perez, & Schmidt, 2007)	Techno-Economic	Evaluate competing hydrogen pathways	S.+I.	R./N.
IDEAS (Kiani, Mirzamohammadi, & Hosseini, 2010)	Integrated	Long-term policy simulation	S.	N
INFORSE (International Network for Sustainable Energy Europe, 2010)	Techno-Economic	Balancing model for national energy systems	S.	N./R.
Martes (Unger, et al., 2010)	Integrated	Analysis of local district heating	S.	L./R.
MEDEE (Lapillonne, 1978)	Techno-Social-Economic	Long term energy demand evaluation sectorial end user	S.	N.
MEDEE- Transport (Enterdata, 2013)	Techno-Environmental	Long-term transport demand evaluation	S.	N.
MED-PRO (Enterdata, 2013)	Techno-Economic	Energy demand by product and end-use for long term	S.	N.
NARE (Deloitte Center for Energy Solutions, 2011)	Technical	Simulates how regional interactions between fuel supply, generation, inbound/outbound transmission, load, and consumption interact to determine market clearing prices, flowing energy, and new capacity additions	S.	R./N./ In.
NEMS (Chien, 2005), (Decision Analysis Corporation of Virginia and ICF Resources Incorporated, 2001)	Economic-Environmental	Project impacts of alternative energy policies on U.S. energy, economy, environment and security	S.	N.
ORCED (Hadley & Hirst, 1998)	Integrated	Strategic planning and analysis tool	S.	R./N.
PERSEUS (Fichtner, Goebelt, & Rentz, 2001)	Economic	Energy and material flow model	I.	In.
PIES (Backus & Amlin, 2009)	Policy-Economic	National policy evaluation	S.	N.
POWERS (Energy Research Centre of the Netherlands, 2011)	Integrated	Role of CCS and wind energy in reducing CO2 emissions	S.	N./In.

Table 8-1 continued

Tool	Type of model	Description	Goal	Scale
RAMSES (Danish Energy Agency, 2013)	Techno-Economic	Simulates electricity and district heating production	S.	R./N.
Ready Reckoner (Commonwealth Department of Industry, Tourism & Resources, 2002)	Techno-Economic	Preliminary technical and financial analysis of cogeneration at their site	S.	P.
SAMLAST (SINTEF, 2012)	Techno-Economic	Integrated market simulations with load-flow analyses	S.	R./N.
SESAM (Strunz & Brock, 2006)	Integrated	Integration of renewable energy sources with stochastic power output in electricity and hydrogen infrastructures	S.	L./R./N.
STEC (Jones, Blair, Pitz-Paal, Schwarzboezl, & B., 2001)	Techno-Economic	Library of models for solar thermal electric systems	S.	L./P.
SAGE (EIA, 2003)	Techno-Integrated	From end use energy demand to match supply and demand	S.+I.	R.
SimREN (Lehmann, et al., 2003)	Technical	Design supply-demand models	S.	R./N.
SIVAEL (Connolly, Lund, Mathiesen, & Leahy, 2010)	Techno-Economic	CHP Power system simulation	S./O.	R./N.
TIMER (de Vries, van Vuuren, den Elzen, & Janssen, 2001)	Environmental	System-dynamics, simulation model of the global energy system	S.	In.
TRNOPT/GENOPT (University of California, 2016)	Economic	Optimization based on TRNSYS	I.	-
UniSyD3.0 (Connolly, Lund, Mathiesen, & Leahy, 2010)	Integrated	Multi-regional partial-equilibrium tool for national energy and economic systems	S.	L./R./N.
VTT-EMM (Unger, et al., 2010)	Economic	Model to minimize cost of electricity production	S./I.	N.
WORLD 2 & WORLD 3 (Turner, 2008)	Socio-Economic	Forecast future development of energy sector	S.	N./In.
X-Bruk (Unger, et al., 2010)	Econometrics	Energy demand forecast model	S.	N.
Optimization				
CGEN (Chaudry, Jenkins, & Strbac, 2007), (Chaudry, Jenkins, & Strbac, 2008)	Economic	Combined gas and electricity network optimization	O.	R./N.
CHP Optimizer (Hudson, 2005)	Economic	Cooling, Heating and power in distributed energy CHP projects	O.+I.	L./R.
DEARS(THERESIA) (Shunsuke, Yoshiaki, Kenshiro, & Masashi, 2008)	Integrated	Global warming mitigation measures	S.	R./N./In
DER_CAM (Microgrids at Berkeley Lab, 2013)	Economic - Environmental	Distributed Energy Resources Customer Adoption Model	O.+I.	R./N.
DEECO (Lindenberger, Brucker, Groscurth, & Kummel, 2000)	Economic - Environmental	Dynamic energy, emissions, and cost optimization	O.	L.
EGEAS (Porat, Irith, & Turvey, 1997)	Economic	Modular production costing and generation expansion software package	O.	R./N.
EMINENT (Segurado, Pereira, Pipio, & Alves, 2008)	Techno-Economic	performance and potential impact of the early stage technologies (EST), in energy supply chain,	S.	N.
ENERGYPLAN (Connolly D. , 2010)	Integrated	Fluctuating renewable energy sources, CHP and different energy storage options	S.+O.	L./R./N.
ERIS (Miketa & Schrattenholzer, 2004)	Techno-Economic	Primary energy and investment (bottom-up)	I.	L./R.
IKARUS (Martinsen, Krey, Markewitz, & Voegele, 2006)	Economic-Environmental	Strategies to reduce energy related emission of GHG	O.+S.	N.
ISPA (Kouvaritakis, et al., 2005)	Economic-Environmental	Integrating System for Priority Assessment	O.	-

Table 8-1 continued

Tool	Type of model	Description	Goal	Scale
MELP (Lisboa, Marzano, Saboia, Maceira, & Melo, 2008)	Technical	Determine optimal generation and interconnection expansion	O.	N.
MIUH (Fora, 2011)	Techno-Economic (E.)	Operation Planning model for Hydro thermal plant(Monthly)	O.	R./N.
NEWAVE (Maceira, Terry, Costa, Damazio, & Melo, 2002) (Toscano, 2009)	Techno-Economic (E.)	Operation Planning model	O.	R./N..
ODIN (Zambelli, Toscano, Filh, Santos, & Noguera, 2010)	Techno-Economic (E.)	Operation Planning model for Hydro thermal plant	O.	R./N.
OSeMOSYS (KTH, SEI, 2013)	Integrated	Long-term Energy modelling	O.+S.+I	R./N.
PoMo (Unger, et al., 2010)	Economic	Forecasting wholesale electricity spot prices	O.	N.
ProdRisk (Mo, Gjelsvik, & Grundt, 2001)	Techno-Economic	Optimization and simulation of hydro-thermal systems	O.	R./N.
PROVIEW (Hobbs, Rouse, & Hoog, 1993)	Economic	Comprehensive resource planning model that considers benefits/value that electricity consumers receive	O.	L./R.
SPSEK (Jankowski, Pellekaan, & Winter, 1993)	Economic-Environmental	Analyses and optimizes future energy system development in relation to economic growth and environmental requirements	O.+I.	N.
SUISHI_O (ONS, 2010)	Techno-Economic (E.)	Operation Planning model for Hydro thermal plant	O.	R./N.
SUPER (Olade, 2013)	Integrated (E.)	Inter-Connection Hydrothermal Power System Generation	O.+I.	L./R./N
System Optimizer (BC Hydro, 2012)	Techno-Economic	Aid in the development of resource plans	O.	L./R.
TRACE (ESMAP, 2013)	Techno-Economic (E.)	Tool for Rapid Assessment of City Energy Efficiency	O.	L./R.
UREM (Cai, et al., 2008)	Economic-Environmental	Supporting long-term energy systems planning	O.	L./R.
Wilmar (Connolly, Lund, Mathiesen, & Leahy, 2010)	Techno-Economic	Analyse optimal operation of power systems	O.	In.
Externalities and environmental impact calculation				
AERMOD (Kesarkar, Dalvi, Kaginalkar, & Ojha, 2007), (Cimorelli, et al., 2005)	Environmental	Prediction of spatial variation of the concentration of a pollutant	S.	R./N.
ASF (United States Environmental Protection Agency, 1990)	Environmental	Provides emission estimates for nine of the world's regions	S.	In.
AIM (Kainuma & Morita, 2001), (Matsuoka, Morita, & Kainuma, 2001)	Environmental	Analyses GHG emissions and the impacts of global warming in the Asian-Pacific region	S.	N./In./G.
Aspen (Enerdata, 2013)	Environmental	Assess country emission permits	S.	N./In.
CCP (COMMEND, 2013)	Economic	Local climate inventories and action plans	I.	L.
DICE (Nordhaus & Boyer, 2000)	Economic-Environmental	Weighing costs and benefits of taking steps to slow greenhouse warming	S.	In./G.
ECOSENCE (IEHIAS, 2013) (University of Stuttgart, 2013)	Environmental	Integrated Environmental Health Impact assessment system	S.	L./R./N
EFFECT (ESMAP, 2013)	Integrated	Energy Forecasting Framework and Emission Consensus Tool	S.+I.	R./N.
EPPA (Paltsev, et al., 2005)	Economic	Emissions Prediction and Policy Analysis	S.	N./In.
ESCAPE (Hulme & Raper, 1995)	Energy/ Economic	Evaluation of Strategies for Climate change by Adapting to and Preventing Emissions	S.	N./In./G.
GCAM (Joint Global Change Research Institute, 2013)	Environmental	Exploring consequences and responses to global change	S.	N./In./G.

Table 8-1 continued

Tool	Type of model	Description	Goal	Scale
GTEM (Gurney, et al., 2007)	Energy-Environmental	Assess the impacts of economic growth	S.	N./In.
HEAT (ESMAP, 2010)	Techno-Economic (A.)	Climate vulnerabilities and adaptation options in the energy sector of your country	O.+I.	N.
IPM (U.S. Environmental Protection Agency, 2012)	Environmental	Analyze the impact of air emissions policies on the U.S. electric power sector	S.	R./N.
MAGICC (Hulme & Raper, 1995)	Energy-Economic-Climate	The Assessment of Greenhouse Gas Induced Climate Change)	S.	R./N./ In./G.
MARIA (Intergovernmental Panel on Climate Change, 2000)	Environmental	Assess technology and policy options to address global warming	S.	G.
MERGE (Manne, Mendelsohn, & Richels, 1995)	Economic-Environmental	Evaluating regional and global effects GHG reductions policies	S.	N./in.
Mesap PlaNet (Schlenzig, 1999)	Economic-Environmental	Calculates energy and emission balances	S.	R./N.
MiniCAM (Chien, 2005)	Environmental	Forecasts CO2 and other GHG emissions; estimates impact on GHG atmospheric concentrations, climate, and the environment	S.	In./G
REM (Urban, Benders, & Moll, 2009)	Techno-Economic (E.)	Develop scenarios for rural electrification for the period 2005–2030 and to assess the effects on greenhouse gas emissions, primary energy use and costs	S.	R.
RICE (Nordhaus & Boyer, 2000)	Economic-Environmental	Analyze the relationship between climate policy and technical change	S.	N./In.
SURE (Cherni, 2004), (Cherni J. , et al., 2007)	Technical (E.)	Ex-post evaluation for the impact of renewable technology	S.	R.
POLES (Enerdata, 2013)	Economic	Prospective Outlook on Long-term Energy Systems.	S.	N./In.
VLEEM (Vleem Consortium , 2005)	Environmental	Very Long-Term Energy Environment Model	S.	N.
WITCH (Bosetti, et al., 2009) (FEEM, 2010)	Economic-Environmental	Integrated assessment model	I.	In.
Data Base				
CO2BD (Strubegger, 2003)	Integrated	Carbon mitigation technologies	O.	L.
E2database (Segurado, Pereira, Pipio, & Alves, 2008)	Economic	Calculate all possible energy chains from the energy source to end-user.	S.	L./R./N.
ECDB (IIASA, 2014)	Environmental	Displays energy use, carbon emissions, and resulting energy and carbon intensities of the world and top 27 carbon-emitting nations	S.	N./G.
IRAKUS (Segurado, Pereira, Pipio, & Alves, 2008)	Techno-Environmental	Optimization Instruments for Greenhouse Reduction Strategies	S.	N.
REAP (Stockholm Environment Institute, 2009)	Economic-Environmental	Helps policy-makers to understand and measure the environmental pressures associated with human consumption	S.	L./R./N.
SAFIRE (Energy for Sustainable Development, 2013)	Economic	Evaluates markets and impact of new energy technologies and policies	S.	L./R./N.

Table 8-1 continued

Tool	Type of model	Description	Goal	Scale
STATcompiler (Rutstein & Rojas, 2006)	Social	Provides demographic and health surveys in a comprises and easily comparable online tool.	T.	N./In.
STREAM (Riso DTU Climate Centre, 2013)	Technical	Provides insight into the different potential energy mixes and create scenarios on demand	S.	L./R./N.
Tools under development				
AEOLIUS (Rosen, Tietze-Stockinger, & Rentz, 2007)	Technical	Simulation of power plant scheduling	S.	L./R./N.
CDA (Newsham & Donnelly, 2013)	Technical	Energy use estimator	O.	L.
ETOAG (Chubu Electric Power Company, 2012)	Techno-Economic (E.), (A.)	Evaluate electricity technology options	O.	L./R./N.
H2RES (Duić, Krajačić, & da Graça Carvalho, 2008), (Krajačić, Duić, & da Graça Carvalho, 2009)	Integrated	Decartelized simulation model for isolated regions and Islands	O.	L.
META (Chubu Electric Power Company, 2012)	Techno-Economic (E.), (A.)	Evaluate electricity technology options	O.	L./R./N.
ODESSE (ENEA, 2012)	Technical	Optimal Design for Smart Energy (HVAC in building)	O.+S.	L.
ROM (Instituto de Investigacion Tecnologica - Universidad Pontificia Comillas, 2013)	Techno-Economic	Determine technical and economic impact of intermittent generation and other types of emerging technologies	S.	R./N.
SMART (Parpas & Webster, 2014) (Powell, et al., 2012)	Integrated	Long-term power planning	O.+I.	R./N.
WEAP (Stockholm Environment Institute, 2013)	Integrated	Integrated approach to water resources planning	S.	L./R.
XEONA (Brucker, Morrison, & Wittmann, 2005)	Environmental	Distributed generation simulation for energy policy	S.	L./R./N.

Abbreviations:
O = Optimization; S = Simulation; I = Investment; Tracking
L = Local; R = Regional; N = National; In = International; G = Global
E = Electrification; A = Access

8.2. Overview of selected composite indicators

1- EDI: Energy development Index

EDI is a composite indicator that helps to measure energy development and presents the role of energy in human development by tracking progress in a country's transition towards modern fuel and electricity access at household and community level (IEA, 2012), (OECD/IEA, 2011).

Table 8-2: Energy development index values for selected countries

Indicator (country)		Minimum	Maximum	Afghanistan	Bangladesh	Bhutan	India	Nepal	Maldives	Pakistan	Sri-Lanka
EDI value		0.01	0.923	-	0.168	-	0.294	0.102	-	0.270	0.258
Per capita commercial energy consumption	Index*	0	1	-	0.031	-	0.139	0.006	-	0.102	0.085
	Indicator(toe)	0.03- 2.88									
Per capita electricity consumption in the residential sector	Index	0	1	-	0.051	-	0.098	0.023	-	0.164	0.112
	Indicator(toe)	0.001-0.08									
Share of modern fuels in total residential sector energy use	Index	1.4	100	-	0.253	-	0.221	0.012	-	0.235	0.097
	Indicator (%)	1.4-100									
Share of population with access to electricity (%)	Index	11.1	100	-	0.051	-	0.72	0.37	-	0.58	0.74
	Indicator (%)	11.1-100									

*Note: Index defined for each indicator using actual maximum and minimum values for developing countries

Table 8-3: Energy development index results for selected countries, 2010

			Afg.	Bhu.	Ban.	Ind.	Mal.	Nap.	Pak.	Sri.
Rank (increasing level of energy development)			-	38	48	41	-	74	44	42
EDI			-	0.32	0.23	0.3	-	0.08	0.28	0.29
Household level energy access	Access to electricity indicator	Electrification rate	-	0.69	0.47	0.75	-	0.76	0.67	0.77
		Per-capita residential electricity consumption	-	0.19	0.07	0.11	-	0.03	0.18	0.16
		Electricity access indicator	-	0.36	0.18	0.29	-	0.16	0.35	0.34
	Access to clean cooking facilities indicator	Share of modern fuels in residential total final consumption	-	0.02	0.21	0.14	-	0.02	0.18	0.04
	Household Level indicator		-	0.19	0.19	0.22	-	0.09	0.26	0.19
Community level energy access	Public Services	Per-capita public services electricity	-	0.68	0.01	0.06	-	0.01	0.03	0.11
	Productivity use	Share of economic energy uses in total final consumption	-	0.23	0.52	0.69	-	0.14	0.57	0.65
	Community level indicator		-	0.45	0.26	0.38	-	0.08	0.3	0.38
Use of additional assumptions 5= max use of original data, 0= assumptions based on cross-country comparison			-	4	5	5	-	5	5	5

Note: Afg: Afghanistan, Bhu.: Bhutan, Ban: Bangladesh, Ind.: India, Nep.: Nepal, Mal.: Maldives, Pak.: Pakistan, Sri.: Sri-Lanka.

2- MEPI: Multidimensional Energy Poverty Index

Since this metrics is closer to real life issue and is based on energy deprivation for energy services, it is necessary to explain it in more detail (Nussbaumer, Bazilian, Modi, & Yumkella, 2011).

There is an analytical gap for the definition of energy poverty. MEPI is a metric to measure energy poverty, as it tracks the energy requirements for end-users. The scope's limit is referred to the household's energy requirement to fulfil their needs of cooking, lighting, space heating and cooling, communication, entertainment, electric appliances, mechanical power and lighting. There are some sources available in demographic and health surveys of the International Energy Agency (IEA) or the United States Agency for International Development (USAID). As the data sets are not fully available on the public domain, it seemed infeasible having all data for regional/local level evaluation as proposed in this research.

In the algorithm they consider cooking, including the type of fuel, and indoor air pollution issues (with or without chimney). Since there is a correlation between cooking and space heating, the MEPI does not consider space heating and cooling. As many services such as education, entertainment or communication are contingent on electricity access, they present indicators related to appliances to capture elements connected to the consumer side. However, the lack of reliable data forces to omit mechanical power in the analysis. Nussbaumer et al. presented 6 indicators in 5 dimensions (Nussbaumer, Bazilian, Modi, & Yumkella, 2011).

Table 8-4: Dimension and respective variable with cut-offs (Nussbaumer, Bazilian, Modi, & Yumkella, 2011)

Dimension	Indicator(Weight)	Variable	Deprivation cut-off (poor if)
Cooking	Modern cooking fuel (0.2)	Type of cooking fuel	Use any fuel beside electricity, LPG, kerosene, natural gas or biogas
	Indoor pollution (0.2)	Food cooked on stove or open fire (no chimney) if using any fuel beside electricity, LPG, natural gas or biogas	True
Lighting	Electricity access (0.2)	Has access to electricity	False
Services provided by means of household appliances	Households appliance ownership (0.13)	Has a fridge	False
Entertainment/ education	Entertainment/education appliance ownership (0.13)	Has a radio or television	False
Communication	Telecommunication means (0.13)	Has a phone land line or a mobile phone	False

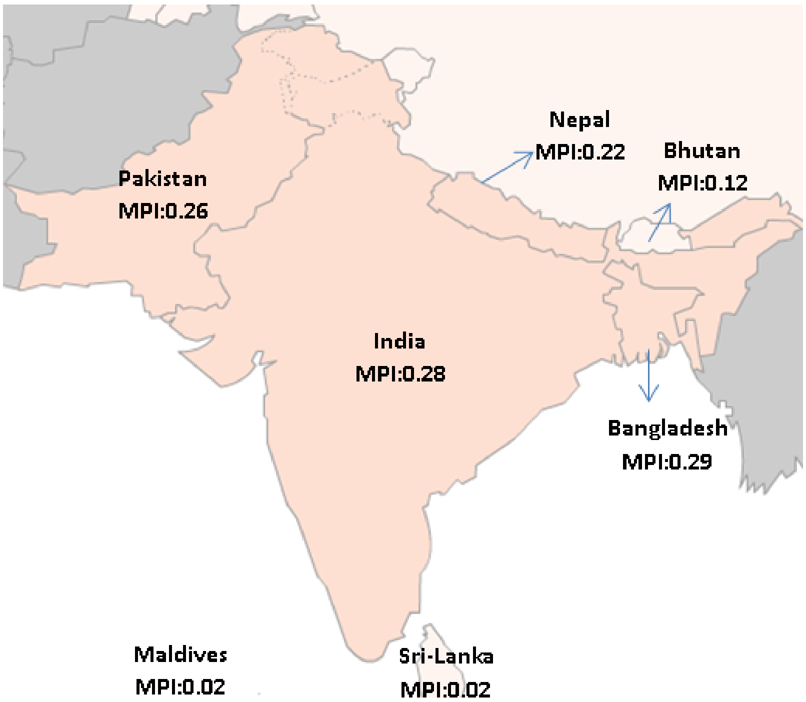


Figure 8-1: MPI for selected South Asia Countries [OPHI website]

National statistics most of the time hide the disparities in sub-national level. Nussbaumer et al. have applied the MEPI in district level for Bangladesh, India, Nepal and Pakistan.

3- TEIT: Total energy inconvenience threshold

In this research the composite index is developed to measure the energy poverty among rural households. The index accounts the inconvenience for households associated with use of different energy sources and energy consumption shortfall. A predefined basic minimum amount is used for comparison. The presented index supports to quantify the degree of energy poverty among rural households by measuring suffering inconveniences. Disadvantage is the need for accurate survey data that is sometimes hard to be achieved. 2 elements of excess inconvenience associated with the energy mix and lack of sufficient energy to fulfil the needs are based on the new indicator approach of energy poverty.

To measure energy inconvenience, indicators were defined such as frequency of buying or collecting a source of energy, distance from household travelled and means of transport used, household's member´s involvement in energy acquisition, time spent on energy collection per week, households' health and children's involvement in energy collection.

8.3. Survey for data input of MCDA

On the example of Borofsky an extract of how to approach decision makers with a survey to obtain insights for rural electrification planning is presented (Borofsky, 2015). For an application in this research specific survey questions would need to be defined for each of the devices and criteria accordingly.

Priorities for Rural Electrification Planning

Technology Factors

6. For each factor below, please indicate how influential you believe it to be to the initial adoption and long-term sustainability of a rural electrification plan. Please respond to all questions in this category to the best of your knowledge.

	Irrelevant	Not important	Important	Critically important
Ability to provide electricity to meet a level of demand that is beyond the most basic service (i.e., two lights and a mobile phone charger)	○	○	○	○
Local attitudes towards different rural electrification modes (e.g., perceiving solar-powered rural electrification modes to be a second-class option)	○	○	○	○
Convenience of procuring, storing, and preventing theft of diesel fuel	○	○	○	○
Consumer perception that quality of light provided by the rural electrification mode is superior to kerosene-powered light	○	○	○	○
Reliability (number of hours of electricity people consistently receive over a 24-hour period) of nearby existing grid connection	○	○	○	○
Location of the electricity generator (e.g., solar panel, diesel generation set, etc.) in the community (i.e., proximity to homes, places of worship, etc.)	○	○	○	○

Other technology factors (please specify)

Figure 8-2: Extract of rural electrification planning survey – technology factors (Borofsky, 2015)

Priorities for Rural Electrification Planning

Socioeconomic Factors

7. For each factor below, please indicate how influential you believe it to be to the initial adoption and long-term sustainability of a rural electrification plan. Please respond to all questions in this category to the best of your knowledge.

	Irrelevant	Not important	Important	Critically important
Proximity of the community to a public institution (e.g., school, hospital, community center, etc.) in need of electricity	○	○	○	○
Presence of a community development organization engaged in the provision of public services	○	○	○	○
Affordability of electricity and basic electricity-powered appliances	○	○	○	○
Religious differences among co-located households	○	○	○	○
Caste differences among co-located households	○	○	○	○
Ability of electricity service to enable economically productive activities (e.g., sewing, food processing, irrigation, etc.) that were not previously possible	○	○	○	○
Accessibility of financial institutions and financing	○	○	○	○
Local politics (e.g., grid extension as a campaign issue, corruption, political support, etc.)	○	○	○	○
Literacy of potential electricity customers	○	○	○	○

Figure 8-3: Extract of rural electrification planning survey – socioeconomic factors (Borofsky, 2015)

8.4. Data set for devices

Table 8-5: Overview of data for end-use devices

End-use	Device	Resource	Lifetime		Device cost [€]	O&M [cent/kWh]	Lumens [lm]	Efficiency [lm/Watt]	Power [W]	Average daily use [h]	Thermal eff [%]	Device efficiency [%]	x-factor
Cooking-DHW-AH	Typical open fire (3 stone)	Wood, Dung, residues/waste, woodchips, pellets	50	years	1	0,1			8000	7.0	12%	65%	2,00
	Well-tended open fire (3 stone)	Wood, Dung, residues/waste, woodchips, pellets	50	years	1	0,1			8000	3.5	25%	65%	2,00
	Rocket stove	Woodchips & pellets	20	years	20	0,1			3000	3.0	38%	78%	1,00
	Wood gas stove	Wood	20	years	15	0,1			3000	2.5	45%	72%	1,00
	LPG ring stove	LPG	20	years	30	12			3000	2.0	53%	83%	1,00
	Gas cooktop	LPG	20	years	5	12			1900	3.0	32%	40%	0,50
	Paraffin "Primus" stove	Paraffin	20	years	2,5	5			3000	4.0	35%	68%	1,25
	Kerosene stove	Oil	20	years	5	5			1000	8.0	45%	50%	1,00
	Improved liquid fuel stove	Kerosene, Ethanol, Methanol	20	years	10	4			1000	2.0	70%	82%	0,50
	Improved solid fuel stove	Wood, dung, coal, etc.	20	years	15	0,5			3000	3.0	43%	70%	1,00
	Coal stove	Coal	20	years	20	6			3000	8.0	2%	27%	1,50
Cooking-DHW	Solar cooker	Solar radiation	5	years	35	1			800	6.0	33%		0,50
	Coal brazier (Basa Njengo Magogo)	Coal & peat	20	years	2	6			4500	9.0	8%		1,00
	Electric induction stove	Power generator	20	years	20	PG			1500	1.5	84%		0,50
	Electric hotplate/cooktop	Power generator	14	years	10	PG			1200	2.0	74%		0,50
	Biolite	Wood	50	years	129	0,5			3400	2.0	50%		1,00
Domestic Hot Water	Electric geyser	Power generator	15	years	20	PG			2000	1.0	100 %		0,50
	LPG geyser	LPG	10	years	20	12			2000	1.0	85%		0,50
	Solar hot water heater	Solar radiation	20	years	80	1			1500	1.0	87%		0,50

Table 8-5 continued

End-use	Device	Resource	Lifetime		Device cost [€]	O&M [cent/kWh]	Lumens [lm]	Efficiency [lm/Watt]	Power [W]	Average daily use [h]	Thermal eff [%]	Device efficiency [%]	x-factor
Ambient Heating	Passive geothermal	Geothermal	100	years	0,1	0,1			0			100%	-
	Passive solar	Solar radiation	100	years	0,1	0,1			0			100%	-
	Geothermal (Ground source heat pump)	Geothermal	25	years	500	2			3000	2		300%	1,00
	Electric heater	Power generator	10	years	5	PG			1000	2		100%	1,00
	LPG heater	LPG	10	years	15	12			2800	3		50%	1,00
	Solar air heating system	Solar radiation	30	years	50	1			1000	2		90%	1,00
	Kerosene heater	Kerosene	10	years	10	4			2000	3		50%	1,00
Ambient Cooling	Wind passive	Wind	100	years	0,1	0,1			0			100%	-
	Solar PV fan	Solar	25	years	5	0,5			22	8		60%	1,00
	Electric fan	Power generator	25	years	10	PG			21	8		60%	1,00
	Evaporative cooling (air-water cooler)	Power generator	10	years	30	PG			100	8		75%	1,00
	Electric ventilation	Power generator	10	years	20	PG			100	8		90%	1,00
	Electric water cooler	Power generator	20	years	50	PG			100	8		90%	1,00
Food preservation	Passive geothermal	Geothermal	100	years	0,1	0,1			0			100%	-
	Passive wind	Wind	100	years	0,1	0,1			0			100%	-
	Zeer Pot or Pot-in pot (6-30 °C)	Wind	5	years	2	0,1			0	24		100%	-
	Electric - refrigerator (1-4 °C)	Power generator	10	years	100	PG			75	20		100%	1,00
	Medical refrigeration	Power generator	10	years	200	PG			165	24		100%	1,00
	Electric- freezer ((-18)- 0 °C)	Power generator	10	years	120	PG			150	20		100%	1,00
Lighting	Biolite + LED (4 W)	Wood	50	years	129	0,5	360	90	4	4			0,10
	Candles	Soild paraffin	0,0005	years	0,1	0,1	1	0,01	100	4			1,00
	Kerosene hurricane (lantern) (wick)	Kerosene	10	years	2	4	100	2	50	4			1,00
	High pressure (kerosene) lighting lamp	Solid paraffin	7	years	10	5	1300	2	650	4			1,00
	Oil lamp (mantle)	Oil	10	years	10	5	1000	1	1000	4			1,00
	Oil lamp (Wick)	Oil	7	years	4	5	10	1	10	4			1,00

Table 8-5 continued

End-use	Device	Resource	Lifetime		Device cost [€]	O&M [cent/kWh]	Lumens [lm]	Efficiency [lm/Watt]	Power [W]	Average daily use [h]	Thermal eff [%]	Device efficiency [%]	x-factor
Lighting	Filament lamp (40 W)	Power generator	1	year	1	PG	400	10	40	4			1,00
	Incandescent lighting (40 W)	Power generator	1	year	0,2	PG	450	11	40	4			1,00
	Fluorescent (10 W)	Power generator	1,5	years	0,3	PG	600	60	10	4			0,25
	Compact fluorescent (CFL) (10 W)	Power generator	5	years	0,4	PG	500	50	10	4			0,25
	Light emitting diodes (LEDs) (4 W)	Power generator	10	years	1	PG	360	90	4	4			0,10
	Small portable solar lantern + LED (4 W)	Solar radiation	5	years	1	0,1	360	90	4	4			0,10
	Medium portable solar lantern + LED (8 W)	Solar radiation	5	years	2	0,1	720	90	8	4			0,20
Lighting-Street Lamps	Mercury vapor (gas lamp) (80 W)	Power generator	10	years	1	PG	6000	75	80	4		100%	0,80
	LED+PV solar street lamps (100 W LED) +Battery	Solar radiation	3	years	65	0,5	9000	90	100	4		100%	1,00
ICT	Computer (desktop with monitor)	PV home system (PV-diesel)	5	years	120	PG			200	4		100%	1,00
	Copy machine	PV home system (PV-diesel)	5	years	20	PG			75	4		100%	1,00
	Rasberry Pie	PV home system (PV-diesel)	5	years	35	PG			5	4		100%	1,00
	OLPXXO-1 computer (laptop)	PV home system (PV-diesel)	5	years	100	PG			2	1		100%	1,00
	Modem & satellite	PV home system (PV-diesel)	5	years	3	PG			110	4		100%	1,00
	Portable radio with battery	Battery	5	years	1	0,25			11	5		100%	1,00
	Small radio	Power generator	5	years	2	PG			5	5		100%	1,00
	Mobile phone with battery and charger	Power generator	2	years	10	PG			11	3		100%	1,00
	TV	Power generator	5	years	40	PG			100	5		100%	1,00
	Other small electrical devices	Power generator	5	years	5	PG			100			100%	1,00
	Medical Sterilizator	Power generator	15	years	500	PG			500	1		100%	1,00
Water pumping	Mechanical pump	Human or animal power	15	years	5	1			0			100%	-
	Intermediate tech.: treadle pump	Human power	15	years	5	1			0			100%	-
	Intermediate tech.: vane-flapping turbine	Human or animal power	50	years	5	1			0			100%	-

Table 8-5 continued														
End-use	Device	Resource	Lifetime		Device cost [€]	O&M [cent/kWh]	Lumens [lm]	Efficiency [lm/Watt]	Power [W]	Average daily use [h]	Thermal eff [%]	Device efficiency [%]	x-factor
Water pumping	Electric pump	Power generator (150 liter/hour)	15	years	10	PG			60	Depends on demand		100%	1,00
	Solar PV DC pump	Solar radiation	15	years	100	PG			20			100%	0,33
	Choti Bijli (diesel genset)	Diesel (150 liter/hour)	15	years	100	PG			1000			60%	10,00
Agriculture machine work	Human & animal power	Human & animal power	50	years	0,1	0,1			0			100%	-
	Grain/food drying	Solar radiation	100	years	0,1	0,1			0			100%	-
	Electric Grinding mill	PV-diesel system	25	years	15	PG			1000	2		100%	1,00
	Electric Pulveriser	PV-diesel system	25	years	300	PG			500	2		100%	0,50
	Electric Skin pealing machine	PV-diesel system	25	years	500	PG			500	2		100%	0,50
	Electric Motor 0.01-100 kW (uses average of 1 kW)	PV-diesel system	25	years	50	PG			1000	4		100%	1,00

8.5. Survey for assessment of current situation

While the survey should follow a straightforward structure for the simplified assessment of the communities' general data (Santos Perez, 2015), (Gram Oorja Solutions Private Limited, 2014), (Borofsky, 2015) there are five key factors that need to be retrieved from the information obtained.

- Resource availability
- Per capita energy consumption
- Sectorial assessment
- End-use
- Devices

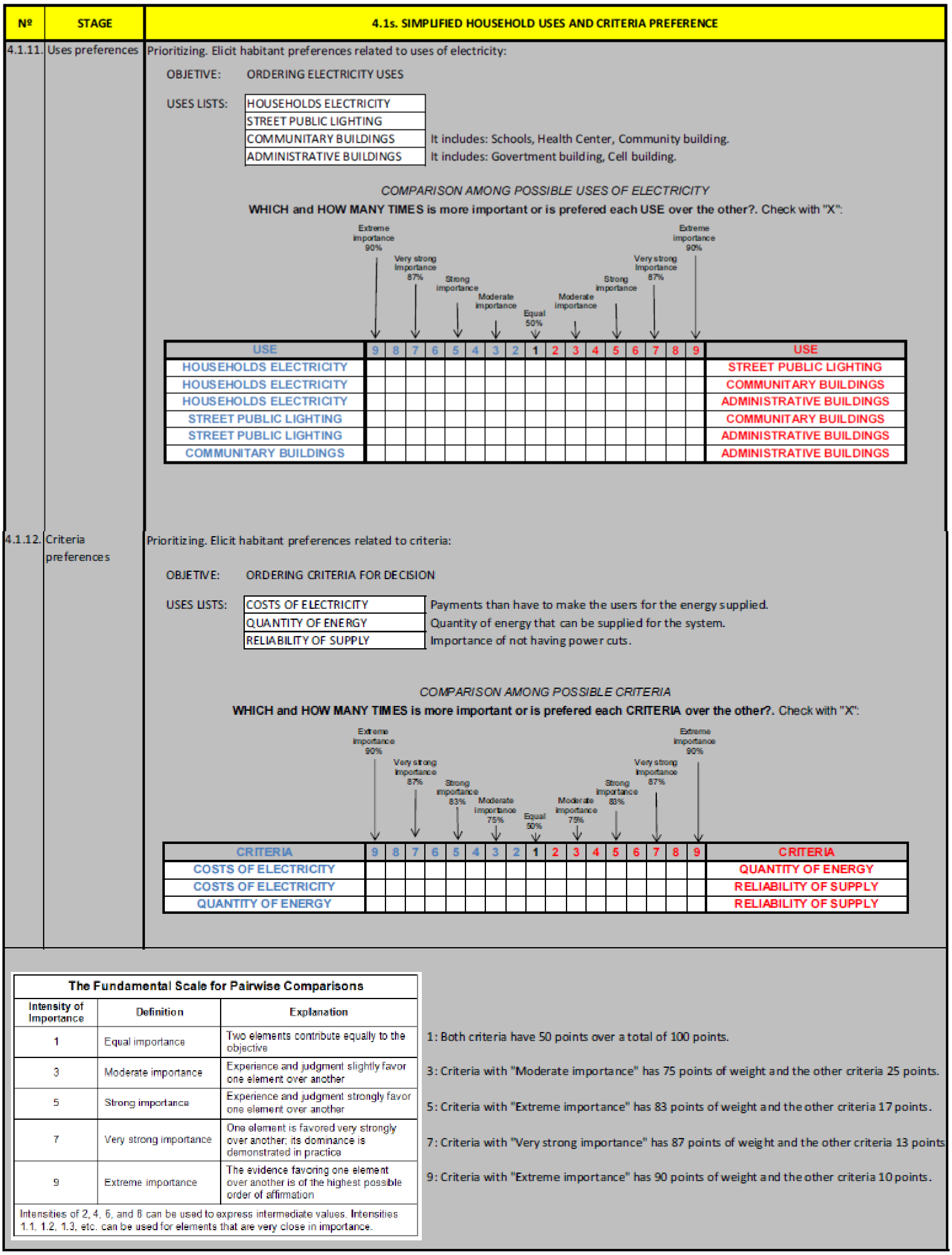
Extract of survey by (Santos Perez, 2015)

Nº	STAGE	4.1s. SIMPLIFIED HOUSEHOLD GENERAL DATA
4.1.1.	Introduction	Explain motivation and confidentialy of the work: *Describe the objective of the work is being performed: It is a study not project definition (at this moment there are not funds to execute it).* *Confidentiality of the data for each participant (their particular answers will not be distributed to anyone).* Date: ☐ Star time: ☐
4.1.2.	Identification	Household identification data. House number identification in map ☐ House photo: ☐ YES ☐ NO Name (local interviewee): ☐ Gender: ☐ Male ☐ Female Address or identification: ☐
4.1.3.	Education	Not applicable in simplified questionnaire
4.1.4.	Economic activity characterization	What is your family main activity?. In case of working in more than one activity, please refer to the main activity ☐ House keeping ☐ Professor, doctor, priest ☐ Agriculture ☐ Public service ☐ Cattle ☐ Small commerce ☐ Building, woodcraft, plumbing, transport ☐ Other. Indicate: ☐

Figure 8-4: Extract of simplified household general data survey – part 1 (Santos Perez, 2015)

4.1.5.	Inhabitants	How many people live is your home?: Adult women: ☐ Adult men: ☐ Girls: ☐ Boys: ☐
4.1.6.	Income	Family monthly income, related to the rest of the people in my community is: ☐ Much less than others ☐ A little less than others ☐ The same as others ☐ A little more than others ☐ Much more than others MONTHLY level of mean income: ☐ Less than 20.000 RWF/month (<30 $/month) ☐ Between 20.000 - 40.000 RWF/month (30 - 60 $/month) ☐ Between 40.000 - 100.000 RWF/month (60 - 150 $/month) ☐ Between 100.000 - 200.000 RWF/month (150 - 300 $/month) ☐ More than 200.000 RWF/month (>300 $/month).
4.1.7	House dimension	How many square meters is your home?: ☐ How many different spaces (rooms + kitchen + leaving room,...) are in your home?: ☐
4.1.8.	House services	Not applicable in simplified questionnaire
4.1.9.	Household / Energy	What is the lighting system of your household? ☐ Candles ☐ Kerosene lamps ☐ Disposable batteries lanterns ☐ Rechargeable lamps ☐ Grid connected ☐ Micro grid ☐ Solar home system ☐ Others: ☐ Do you have the following appliances at your home? ☐ Fan ☐ Radio ☐ Telephone ☐ TV ☐ Others: ☐ Do you have any of the following equipment? ☐ Diesel generator ☐ Solar panel ☐ Other Technical data (power, battery,...): ☐ Description (hours, uses,...): ☐
4.1.10.	Benefits and damages	How do you consider that an electrification HOUSEHOLD project in your community will affect you? If electricity price is high and it will be families that can not afford it, then in this case (check only one): ☐ In this case it is better to install small and cheaper systems with lower energy capacitiy but all the people can afford it. ☐ Does not matter and nothing will happen to have electricity only some families and no others. If electricity price is high and it will be families that can not afford it, then in this case (check only one): ☐ In this case it is better than the houses does not have electricity and install electricity systems only for communal buildings. ☐ Does not matter and nothing will happen to have electricity only some families and no others. I think that electricity can damage my interests, as detailed below: ☐

Figure 8-5: Extract of simplified household general data survey – part 2 (Santos Perez, 2015)



Nº	STAGE	4.1s. SIMPLIFIED HOUSEHOLD USES AND CRITERIA PREFERENCE
4.1.11.	Uses preferences	Prioritizing. Elicit habitant preferences related to uses of electricity:

OBJETIVE: ORDERING ELECTRICITY USES

USES LISTS:

HOUSEHOLDS ELECTRICITY	
STREET PUBLIC LIGHTING	
COMMUNITARY BUILDINGS	It includes: Schools, Health Center, Community building.
ADMINISTRATIVE BUILDINGS	It includes: Govertment building, Cell building.

COMPARISON AMONG POSSIBLE USES OF ELECTRICITY

WHICH and HOW MANY TIMES is more important or is prefered each USE over the other?. Check with "X":

Extreme importance 90% — Very strong importance 87% — Strong importance — Moderate importance — Equal 50% — Moderate importance — Strong importance — Very strong importance 87% — Extreme importance 90%

USE	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	USE
HOUSEHOLDS ELECTRICITY																		STREET PUBLIC LIGHTING
HOUSEHOLDS ELECTRICITY																		COMMUNITARY BUILDINGS
HOUSEHOLDS ELECTRICITY																		ADMINISTRATIVE BUILDINGS
STREET PUBLIC LIGHTING																		COMMUNITARY BUILDINGS
STREET PUBLIC LIGHTING																		ADMINISTRATIVE BUILDINGS
COMMUNITARY BUILDINGS																		ADMINISTRATIVE BUILDINGS

4.1.12.	Criteria preferences	Prioritizing. Elicit habitant preferences related to criteria:

OBJETIVE: ORDERING CRITERIA FOR DECISION

USES LISTS:

COSTS OF ELECTRICITY	Payments than have to make the users for the energy supplied.
QUANTITY OF ENERGY	Quantity of energy that can be supplied for the system.
RELIABILITY OF SUPPLY	Importance of not having power cuts.

COMPARISON AMONG POSSIBLE CRITERIA

WHICH and HOW MANY TIMES is more important or is prefered each CRITERIA over the other?. Check with "X":

Extreme importance 90% — Very strong importance 87% — Strong importance 83% — Moderate importance 75% — Equal 50% — Moderate importance 75% — Strong importance 83% — Very strong importance 87% — Extreme importance 90%

CRITERIA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CRITERIA
COSTS OF ELECTRICITY																		QUANTITY OF ENERGY
COSTS OF ELECTRICITY																		RELIABILITY OF SUPPLY
QUANTITY OF ENERGY																		RELIABILITY OF SUPPLY

The Fundamental Scale for Pairwise Comparisons

Intensity of Importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

Intensities of 2, 4, 6, and 8 can be used to express intermediate values. Intensities 1.1, 1.2, 1.3, etc. can be used for elements that are very close in importance.

1: Both criteria have 50 points over a total of 100 points.

3: Criteria with "Moderate importance" has 75 points of weight and the other criteria 25 points.

5: Criteria with "Extreme importance" has 83 points of weight and the other criteria 17 points.

7: Criteria with "Very strong importance" has 87 points of weight and the other criteria 13 points

9: Criteria with "Extreme importance" has 90 points of weight and the other criteria 10 points.

Figure 8-6: Extract of simplified household general data survey – part 3 (Santos Perez, 2015)

Nº	STEP	4.1s. SIMPLIFIED HOUSEHOLD ESTIMATION OF AFFORDABILITY / CAPACITY OF PAYMENT
4.1.13.	Income	Not applicable in simplified questionnaire
4.1.14.	LIGHTING uses before electrification	Currently appliances used for household LIGHTING (only related to illumination not for other uses):
4.1.15.	Lighting expenses before electrification	How often, how many and how much is the expenditure in lighting?

4.1.14. LIGHTING uses before electrification

Currently appliances used for household LIGHTING (only related to illumination not for other uses):

☐ Oil lamps or keronese (only for lighting not for cooking or heating).
Check the hours of use 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

☐ Candles
Check the hours of use 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

☐ Lantern with replaceable batteries
Check the hours of use 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

☐ Other (car batteries, solar panel, solar portable lamp, diesel genset, etc.). Specify:
Check the hours of use 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

☐ Another one (car batteries, solar panel, solar portable lamp, diesel genset, etc.). Specify:
Check the hours of use 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

☐ Another one (car batteries, solar panel, solar portable lamp, diesel genset, etc.). Specify:
Check the hours of use 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

4.1.15. Lighting expenses before electrification

How often, how many and how much is the expenditure in lighting?

	Quantity: How many you buy each time?	Frequency: How often you buy .....?	Cost: How much you spend each time?
Kerosene / oil **only lighting not cooking**			
Candles			
Batteries for lanterns			
Charge car battery			
Diesel / fuel for the genset			
Solar panel	Price for panel, battery and other expenses for the system. When they bought? And when they changed the battery and cost?:		
Other:			

Figure 8-7: Extract of simplified household general data survey – part 4 (Santos Perez, 2015)

4.1.16.	Other energy uses to be replaced	What equipment do you use that need electricity currently?: ☐ Radio. Check the hours of use: 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 Use your radio out of home (going to work or cultivate, attending the cattle,...)?: ☐ YES ☐ NO ☐ Cell phone: How many times per week you need to charge it?: ☐ ☐ TV: Check the hours of use 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 ☐ Other equipments that require drycells. Please detail: Check the hours of use 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 ☐ Another equipments that require electricity (fan, iron, washing machine). Please detail: Check the hours of use 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
4.1.17.	Other energy expenses to be replaced	What are the expenses in energy and the frequency of these expenses for your currently appliances:

	How many items needed?	Frequency?	Total costs
Batteries for the radio			
Cellphone charge			
Battery charge for TV			
Other:			
Other:			

Figure 8-8: Extract of simplified household general data survey – part 5 (Santos Perez, 2015)

Nº	STEP	4.1s. SIMPLIFIED HOUSEHOLD ESTIMATION OF WILLINGNESS TO PAY
4.1.18.	Expenditure decision	Not applicable in simplified questionnaire
4.1.19.	Willingness to pay	How much would you pay for having: 4 hours per day of lighting and phone charging (RWF per month)? ☐ RWF/month IF YOU WOULD RATHER PAY MORE AND HAVE MORE ELECTRIC ENERGY THEN ANSWER THIS QUESTION (OTHERWISE GO TO POINT 4.1.20): How much would you pay for: 8 hours per day of lighting and phone charging, or for 4 hours per day for lighting and phone charging + radio or television or small fan or lapto ☐ RWF/month IF YOU WOULD RATHER PAY MORE AND HAVE MORE ELECTRIC ENERGY THEN ANSWER THIS QUESTION (OTHERWISE GO TO POINT 4.1.20): How much would you pay for a full reliability 24 hours electric supply enough to power high power appliances (refrigerator,...)? ☐ RWF/month
4.1.20.	Preferred level of expenditure	Check your preferred option (payments in $ are orientative, should be replaced by sensible payments in local currency): ☐ 1.- Spend 5 $/month for 3 lights, a phone charger and one radio (4 hours a day). ☐ 2.- Spend 10 $/month for 3 lights, a phone charger, one radio, and TV or small laptop (4 hours a day). ONLY IN CASE YOU SELECTED BEFORE OPTION 2, please check the preferred supply from the following two: ☐ 2.- Spend 10 $/month for 3 lights, a phone charger, one radio, and TV or small laptop (4 hours a day). ☐ 3.- Spend 20 $/month for 3 lights, a phone charger, one radio, TV or small laptop and Other appliances (all day, 24 hours a day).
4.1.21.	Payment frequency	Frequency at which you want to make the necessary payments for electricity: ☐ Every week ☐ Every month ☐ Every 6 months ☐ Seasonal. Specify: ☐

Figure 8-9: Extract of simplified household general data survey – part 6 (Santos Perez, 2015)

Nº	STEP	4.1s. SIMPLIFIED HOUSEHOLD APPLIANCES DATA
4.1.22.	ELECTRIC equipment existed and expected	What electric equipment do you have? And when are you thinking buy the new equipments will be use in a few years? *Pay attention that this part is related to ELECTRIC appliances: LIGHTS are refer to electric lamps (not kerosen, oil,...).*

EQUIPMENTS	EXISTED	EXPECT BUY	WHEN WILL YOU COULD BUY IT?			IN CASE HIGH PRICE ELECTRICITY
	Nº of units	Nº of units	Short term (<1 year)	Medium term (2-4 years)	Long term (>5 years)	Are you continuing used it?
KITCHEN LIGHTS			☐	☐	☐	☐ YES ☐ NO
MAIN ROOM LIGHTS			☐	☐	☐	☐ YES ☐ NO
BEDROOM LIGHTS			☐	☐	☐	☐ YES ☐ NO
BATHROOM LIGHTS			☐	☐	☐	☐ YES ☐ NO
AMBIENT / SECURITY LIGHTS			☐	☐	☐	☐ YES ☐ NO
EXTERNAL HOUSE LIGHTS			☐	☐	☐	☐ YES ☐ NO
PORTABLE WALKING LAMP			☐	☐	☐	☐ YES ☐ NO
RADIO			☐	☐	☐	☐ YES ☐ NO
MUSIC EQUIPMENT - CD			☐	☐	☐	☐ YES ☐ NO
TELEVISION			☐	☐	☐	☐ YES ☐ NO
PARABOLIC			☐	☐	☐	☐ YES ☐ NO
DVD			☐	☐	☐	☐ YES ☐ NO
MOBILE TELEPHONE			☐	☐	☐	☐ YES ☐ NO
LAPTOP OR TABLET			☐	☐	☐	☐ YES ☐ NO
FAN			☐	☐	☐	☐ YES ☐ NO
BLENDER			☐	☐	☐	☐ YES ☐ NO
REFRIGERATOR			☐	☐	☐	☐ YES ☐ NO
WASHING MAQ. (cold water)			☐	☐	☐	☐ YES ☐ NO
IRON			☐	☐	☐	☐ YES ☐ NO
WATER PUMP			☐	☐	☐	☐ YES ☐ NO
Other:			☐	☐	☐	☐ YES ☐ NO
Other:			☐	☐	☐	☐ YES ☐ NO
Other:			☐	☐	☐	☐ YES ☐ NO
Other:			☐	☐	☐	☐ YES ☐ NO

Nº	STEP	
4.1.23.	Demand hourly and daily profile	Not applicable in simplified questionnaire
4.1.24.	Demand yearly profile	Not applicable in simplified questionnaire
4.1.25.	Closing	At the end of the questionnaire: It should be acknowledged their participation and time dedicated. *And it will be indicated that the results of work will be sent to the community including aggregated data (no one will know that results correspond to each family).* End time:

Figure 8-10: Extract of simplified household general data survey – part 7 (Santos Perez, 2015)

Extract of survey by (Gram Oorja Solutions Private Limited, 2014)

Survey done by__________________________ **Date:** __________

I. General Information:

(1) Name of Village: _________________ (2) Name of Gram panchayat: _____

(3) Tehsil: __________ (4) District: _______ (5) State: __________

(6) Census village/Grampanchayat Number: ____

(7A) Name of NGO: _____________

Contact numbers: ____

Email: ____

(7B) Name of contact person – ______________

Contact number: ___________

II. Village Information :

(1) Population: 170 (2) No. of houses: 30

(3) Attach photographs of houses which shows overall appearance from outside & inside

(4) Languages used: Marathi (5) Is the village inside reserved forest: No

(6) Distance from tehsil place: Around 25 km (7) Nearest bus stand & distance: Jawhar, 25 Km

(8) Nearest railway station: Palghar, 95 km (9) Nearest air port : Mumbai

(10) Is grid power available in the village: No (11) Is grid power available in the farms: No

(12) Remarks on 10/11: Grid has never reached the village.

(13) Water for domestic use: Well / River – lifting manually

(14) Water for agriculture use: Rain water

(15) Months of water scarcity: None (16) Farming: one time

(17) Crops, water requirement & revenue per year per acre: Rice and Nachni done on rain water, not sold. Used for self-consumption.

(18) Other sources of income generation & average annual income generation: Working as labor____

(19) Average no. of cattle per house: 2 (20) No. of cattle in the village: 60-70

(21) Is there a dairy in the village: No (22) Is there a Gaushala in the village: No

(23) Whether any biogas plants/solar systems installed in the village: Biogas - No, Solar – Yes

(24) Any remarks on 21/22/23: Solar street lights & some houses have solar home lighting systems

(25) Fuel used for cooking and lighting: Firewood / Dung cake / Kerosene

(26) Average consumption of fuel & cost: Firewood – 80-90 kg/month; Kerosene - 1.5-2 lits/month

(27) What are types of trades in the village? No. of people involved, power requirement, economics:

Mostly farming and labor work. No other trade being done.

____

____

____

(28) Name of school/college in the village: Zilla Parishad School upto 4th standard

(29) Name & activity of social groups formed by villagers: _________________________

____

(30) Name & activity of NGO working in the village: _____________________________

____

(31) Number of beneficiaries and demand of power for list of equipment, quantity & approximate usage hours

	Light	Charging point/ No. Mobile Phones	TV	Fan	Mixer	Other (Motor/ computer)
Number of beneficiary	30	20-25	10	12		1
Hours	5-6	3	4	3		

(32) Attach map of village showing scattering of houses, power usage points, directions, distances
(33) General observations:
There is a possibility for a second crop as there is river flowing near the fields.
____

Extract of survey by (Borofsky, 2015)
1. How many electric lights do you own?

___ Incandescent ___ Typical wattage

___ Fluorescent ___ Typical wattage

___ LED ___ Typical wattage

2. Do you own any other electric appliances:

APPLIANCE ____ Typical Wattage ____

APPLIANCE ____ Typical Wattage ____

APPLIANCE ____ Typical Wattage ____

APPLIANCE ____ Typical Wattage ____

3. Do you use any electric appliances in your business? How much do they contribute to your monthly business income?

____ APPLIANCE ____ MONTHLY ESTIMATE OF ADDED INCOME

4. Do you charge your mobile phone at home? 1 Yes 0 No

IF YES: how frequently? ___ TIMES A WEEK

5. Other than your home, where do you charge your mobile phone? __________

6. How frequently do you charge your mobile phone somewhere other than your home?

____

7. Which of the following do you use for lighting? [Check all that apply]

a. Electricity

b. Kerosene

c. Candles

d. Battery charged lamps

e. Solar panel

f. Off-grid electricity from Mera Gao Power

Other [SPECIFY]: ____________________________

INSTRUCTIONS: For all daily usage questions, please ask respondent to explain the time of day they most frequently use each appliance with respect to each of the three seasons enumerated in the table. Place a check mark next to each time of day and under each season that applies. If usage does not vary by season, check the appropriate box under "All Year".

1. LIGHTING:
   During what time of day are you most likely to use light inside or outside your home [insert each season]?

	Winter	Spring	Rainy Season	All Year
Morning: 6am - 12pm				
Midday: 12pm - 3pm				
Afternoon: 3pm - 7pm				
Evening: 7pm - 9:30pm				
Night: 9:30pm - 6am				

2. IF THE HOUSEHOLD OWNS A TV:

   2.a. How many televisions do you own? ___ COUNT

   2.b. During what time of day are you most likely to watch TV?

	Winter	Spring	Rainy Season	All Year
Morning: 6am - 12pm				
Midday: 12pm - 3pm				
Afternoon: 3pm - 7pm				
Evening: 7pm - 9:30pm				
Night: 9:30pm - 6am				

Figure 8-11: Extract of survey on usage pattern (Borofsky, 2015)

8.6. Data set for MCDA

Table 8-6: Overview of attribute scores for MCDA

		RE.1	RE.2	RE.3	RE.4	EN.1	EN.2	EC.1	EC.2	TC.1	TC.2	TC.3	TC.4	SO.1	SO.2	SO.3	SO.4
End-use	Energy system/device (Demand-Supply)	Minimize Import dependency	Minimize Conflict between resource usage	Minimize Land use to grow and store resource	Maximize Local resource use	Minimize Emission	Minimize indoor/local pollution	Minimize Investment cost	Minimize Operation and maintenance cost	Maximize Ease of use	Maximize Efficiency	Minimize implementation time for device/ technology	Maximize Level or degree of technology	Minimize human vulnerability, pollutant, disease	Maximize Social benefit	Maximize Social acceptability	Maximize Level of comfort
Cooking-DHW-AH	Typical open fire (3 stone)	0	6	9	9	9	9	0	0	9	0	0	0	9	0	9	0
	Well-tended open fire (3 stone)	0	6	9	9	6	6	0	0	9	3	0	0	6	3	9	3
	Rocket stove	0	6	3	9	6	6	3	3	9	6	0	3	6	0	6	0
	Wood gas stove	0	3	9	9	6	6	3	3	9	3	3	3	9	3	9	3
	LPG ring stove	9	3	3	0	3	6	6	9	6	9	6	6	3	9	3	9
	Gas cooktop	6	3	3	3	0	0	6	6	3	3	9	9	3	9	3	9
	Paraffin "Primus" stove	6	3	3	0	9	9	0	3	9	0	0	3	9	0	9	0
	Kerosene stove	6	6	3	0	9	6	3	3	9	0	3	3	9	3	6	0
	Improved liquid fuel stove	6	3	3	0	3	3	6	6	9	6	3	6	6	6	3	6
	Improved solid fuel stove	0	6	9	9	6	3	3	3	6	3	3	6	6	6	6	6
	Coal stove	9	0	3	3	3	9	3	3	9	0	0	0	9	0	6	0
Cooking-DHW	Solar cooker	0	0	0	9	0	0	9	0	6	3	6	9	0	9	3	6
	Coal brazier	9	0	3	3	9	9	6	3	6	3	6	6	6	3	6	6
	Electric induction stove	0	9	6	9	0	0	9	9	6	9	9	9	0	9	0	9
	Electric induction stove	9	3	3	0	3	3	6	6	6	9	9	9	0	9	3	9
	Electric hotplate/cooktop	0	9	6	9	0	0	9	9	6	9	9	9	0	9	0	9
	Electric hotplate/cooktop	9	3	3	0	3	3	6	6	6	9	9	9	0	9	3	9
	Biolite	0	6	6	9	3	3	3	3	9	6	3	6	3	6	3	6

Table 8-6 continued

End-use	Energy system/device (Demand-Supply)	RE.1	RE.2	RE.3	RE.4	EN.1	EN.2	EC.1	EC.2	TC.1	TC.2	TC.3	TC.4	SO.1	SO.2	SO.3	SO.4
DHW	Electric geyser	0	9	3	9	0	0	9	9	9	9	9	9	0	9	3	9
	Electric geyser	9	3	3	0	3	0	6	6	9	9	9	9	0	9	3	9
	LPG geyser	9	6	3	0	3	3	6	6	9	6	6	6	3	6	6	6
	Solar hot water heater	0	0	0	9	0	0	9	6	6	9	9	9	0	9	6	9
Ambient Heating	Passive geothermal	0	0	0	9	0	0	3	0	9	9	0	3	0	9	9	9
	Passive solar	0	0	0	9	0	0	3	0	9	9	0	3	0	9	9	9
	Geothermal (Ground source heat pump)	0	0	0	9	0	0	9	6	3	9	9	9	0	9	0	6
	Electric heater	0	9	3	9	0	0	6	6	6	9	9	9	0	9	3	9
	Electric heater	9	3	3	0	3	3	6	6	6	9	9	9	0	9	3	9
	LPG heater	9	6	3	0	3	3	6	9	6	9	6	6	3	6	6	9
	Solar air heating system	0	0	0	9	0	0	9	6	9	9	9	9	0	9	3	6
	Kerosene heater	6	3	3	0	6	6	6	9	9	3	3	6	6	0	6	3
Ambient Cooling	Wind passive	0	0	0	9	0	0	0	0	9	9	0	3	0	9	9	9
	Solar portable PV fan	0	0	0	9	0	0	6	6	6	6	6	9	0	9	6	9
	Electric fan	0	9	3	9	0	0	6	6	6	9	9	6	0	9	6	9
	Electric fan	9	3	3	0	3	3	9	9	6	9	9	6	3	6	9	9
	Electrical Evaporative cooling (air-water cooler)	0	9	3	9	0	0	9	6	3	9	9	9	0	9	3	9
	Electrical Evaporative cooling (air-water cooler)	9	3	3	0	3	3	9	9	3	9	9	9	3	6	6	9
	Electric ventilation	0	9	3	9	0	0	9	6	6	9	9	6	0	9	6	6
	Electric ventilation	9	3	3	0	3	3	9	9	6	9	9	6	3	6	9	6
	Electric water cooler	0	9	3	9	0	0	9	6	6	9	9	9	0	9	3	9
	Electric water cooler	9	3	3	0	3	3	9	9	6	9	9	9	3	6	6	9
Food preservation	Passive geothermal	0	0	0	9	0	0	0	0	9	3	3	3	0	9	9	9
	Passive wind	0	0	0	9	0	0	0	0	9	3	0	3	0	9	9	9
	Zeer Pot or Pot-in pot	0	0	3	9	0	0	3	0	9	3	3	3	0	6	9	6
	Electric - Refrigerator	0	9	3	9	0	0	9	9	9	9	9	9	0	9	3	6
	Electric - Refrigerator	9	3	3	0	3	3	9	9	9	9	6	9	3	9	3	6
	Electric- Freezer	0	9	3	9	0	0	9	9	9	9	9	9	0	6	3	9
	Electric- Freezer	9	3	3	0	3	3	9	9	9	9	6	9	3	6	3	9
Lighting	Biolite + LED	0	6	0	9	3	0	6	3	9	9	3	6	3	9	6	6
	Candles	3	0	0	0	3	3	3	0	9	0	0	3	9	0	9	0
	Kerosene hurricane	6	3	3	0	6	6	6	6	6	3	3	6	6	3	9	6
	High pressure lighting lamp	6	3	3	0	6	6	6	6	6	3	3	6	6	3	9	6

Table 8-6 continued

End-use	Energy system/device (Demand-Supply)	RE.1	RE.2	RE.3	RE.4	EN.1	EN.2	EC.1	EC.2	TC.1	TC.2	TC.3	TC.4	SO.1	SO.2	SO.3	SO.4
Lighting	Oil lamp (mantle)	6	6	3	0	6	6	6	9	6	3	3	6	6	3	9	6
	Oil lamp (Wick)	6	6	3	0	6	6	6	9	6	0	3	3	6	3	9	3
	Filament lamp	0	9	3	9	0	0	3	6	9	6	6	6	3	9	9	6
	Filament lamp	9	3	3	0	0	3	3	6	9	6	6	6	3	9	9	6
	Incandescent lighting	0	9	3	9	0	0	3	6	9	6	6	6	3	9	9	6
	Incandescent lighting	9	3	3	0	0	3	3	6	9	6	6	6	3	9	9	6
	Fluorescent	0	9	3	9	0	0	6	6	9	9	6	9	3	9	6	9
	Fluorescent	9	3	3	0	0	3	6	6	9	9	6	9	3	9	6	9
	Compact fluorescent	0	9	3	9	0	0	6	3	9	9	6	9	3	9	6	9
	Compact fluorescent	9	3	3	0	0	3	6	3	9	9	6	9	3	9	6	9
	Light emitting diodes	0	9	3	9	0	0	9	3	9	9	6	9	0	9	6	9
	Light emitting diodes	9	3	3	0	0	3	9	3	9	9	6	9	0	9	6	9
	Small portable solar lantern + LED	0	0	0	9	0	0	6	0	9	9	9	9	0	9	3	9
	Medium portable solar lantern + LED (8 W)	0	0	0	9	0	0	9	0	9	9	9	9	0	9	3	9
Lighting-Street Lamps	Mercury vapor (gas lamp) with electricity function	6	9	3	0	6	6	6	6	9	6	9	9	6	6	6	9
	LED+PV solar street lamps (100 W LED) +Battery	0	0	3	9	0	0	9	0	9	9	9	9	0	9	3	9
ICT	Computer	0	9	3	9	0	0	9	9	3	9	9	9	0	9	0	9
	Computer	9	3	3	0	0	3	9	9	3	9	9	9	0	9	0	9
	Copy machine	0	9	3	9	0	0	9	9	3	9	9	9	0	9	0	9
	Copy machine	9	3	3	0	0	3	9	9	3	9	9	9	0	9	0	9
	Rasberry Pie	0	9	3	9	0	0	9	9	3	9	9	9	0	9	0	9
	Rasberry Pie	9	3	3	0	0	3	9	9	3	9	9	9	0	9	0	9
	OLPXXO-1 computer	0	9	3	9	0	0	9	9	3	9	9	9	0	9	0	9
	OLPXXO-1 computer	9	3	3	0	0	3	9	9	3	9	9	9	0	9	0	9
	Modem & satellite	0	9	3	9	0	0	9	9	3	9	9	9	0	9	0	9
	Modem & satellite	9	3	3	0	0	3	9	9	3	9	9	9	0	9	0	9
	Portable radio with battery	3	3	0	3	0	0	3	9	9	9	3	3	0	9	9	9
	Small radio	0	9	3	9	0	0	6	3	9	9	3	3	0	9	9	9
	Small radio	9	3	0	0	0	3	6	3	9	9	3	3	0	9	9	9
	Mobile phone with battery and charger	3	3	0	3	0	0	6	6	6	9	3	6	0	9	6	9

Table 8-6 continued

End-use	Energy system/device (Demand-Supply)	RE.1	RE.2	RE.3	RE.4	EN.1	EN.2	EC.1	EC.2	TC.1	TC.2	TC.3	TC.4	SO.1	SO.2	SO.3	SO.4
ICT	Mobile phone with battery and charger	9	3	3	0	0	3	6	6	6	9	3	6	0	9	6	9
	TV	0	9	3	9	0	0	9	9	6	9	3	6	0	9	6	9
	TV	9	3	3	0	0	3	9	9	6	9	3	6	0	9	6	9
	Other small electrical devices	0	9	3	9	0	0	6	9	6	9	6	9	0	6	3	9
	Other small electrical devices	9	3	3	0	0	3	6	9	6	9	6	9	0	6	3	9
	Electrical Medical Sterilizator	0	9	3	9	0	0	9	9	3	9	9	9	0	9	6	9
	Electrical Medical Sterilizator	9	3	3	0	0	3	9	9	3	9	9	9	0	9	6	9
Water pumping	Mechanical pump	0	0	0	9	0	0	0	0	9	9	0	0	0	6	9	6
	Treadle pump	0	0	0	9	0	0	6	0	6	9	0	3	3	6	9	3
	Vane-flapping turbine	0	0	0	9	0	0	6	0	6	9	0	3	3	6	9	3
	Electric pump	0	9	3	9	0	0	9	6	3	9	9	9	0	9	3	9
	Electric pump	9	3	3	0	3	3	9	6	3	9	9	9	3	9	6	9
	Solar PV DC pump	0	0	0	9	0	0	9	3	6	9	6	9	0	9	6	9
	Choti Bijli (diesel genset)	6	6	6	0	6	6	9	9	3	6	9	6	6	9	6	6
Agriculture machine work	Human & animal power	0	0	0	9	0	0	0	0	9	9	0	0	0	6	9	3
	Grain/food drying	0	0	0	9	0	0	0	0	9	6	0	0	0	6	9	6
	Electric Grinding mill	0	9	3	9	0	0	6	6	6	9	9	3	3	3	6	6
	Electric Grinding mill	9	3	3	0	3	6	6	6	6	9	9	3	3	3	6	6
	Electric Pulveriser	0	9	3	9	0	0	9	9	3	9	9	6	3	6	3	6
	Electric Pulveriser	9	3	3	0	3	6	9	9	3	9	9	6	3	6	3	6
	Electric Skin pealing machine	0	9	3	9	0	0	6	6	3	9	9	6	3	3	3	6
	Electric Skin pealing machine	9	3	3	0	3	6	6	6	3	9	9	6	3	3	3	6
	Electric Motor 0.01-100 kW (uses average of 1kW)	0	9	3	9	0	0	9	9	6	9	9	9	3	9	6	9
	Electric Motor 0.01-100 kW (uses average of 1kW)	9	3	3	0	3	6	9	9	6	9	9	9	3	9	6	9
Electricity generation units	(Micro-) Diesel generator	9	6	3	0	9	9	6	9	9	9	3	6	9	6	9	6
	(Micro-) PV-diesel system	6	6	3	3	6	6	6	6	6	9	6	9	6	6	6	9
	(Micro-) Gas generator	0	3	6	9	3	3	9	6	6	6	3	9	3	9	9	3
	(Micro-) Hydro generator (>5kW)	0	3	3	9	0	0	9	3	9	6	6	6	0	9	9	9
	(Micro-) Wind turbine	0	0	3	9	0	0	9	3	3	3	9	6	0	9	3	9
	Solar Residential system (250-4000 W)	0	0	3	9	0	0	6	3	3	3	6	9	0	9	3	9
	PV home system (up to 250W)	0	0	3	9	0	0	6	0	3	3	6	9	0	9	3	9
	(Pico-) PV Pico system (1-10W)	0	0	0	9	0	0	0	0	6	3	3	6	0	9	6	9

Table 8-6 continued																	
End-use	Energy system/device (Demand-Supply)	RE.1	RE.2	RE.3	RE.4	EN.1	EN.2	EC.1	EC.2	TC.1	TC.2	TC.3	TC.4	SO.1	SO.2	SO.3	SO.4
Electricity generation units	(Micro-) Biomass power generator	0	3	0	9	3	3	3	3	6	3	0	3	3	9	9	6
	Pumped storage	0	3	9	9	0	0	6	3	3	6	9	6	0	9	6	6
	(Pico-)Wind Pico system	0	0	3	9	0	0	3	0	6	3	6	6	0	9	3	6
	(Pico-) Hydro system (<5kW)	0	3	3	9	0	0	0	0	9	6	3	6	0	9	9	9

8.7. Results of MER options

In the following sections the results for the MER options, except for MER 1, are presented. For each MER the overview of devices used as well as the target-performance comparison is provided.

8.7.1. Results of MER 2

Table 8-7: # of End-use devices by service and sector for MER 2

Sector	Service (end-use)	Device	# per device and end-use	# should be per end-use	lack by end-use	additional or comfort end-use devices
Domestic	Cooking	Biolite	34	34	-	-
	DHW	Biolite	34	34	-	-
	AH	Electric heater	34	34	-	-
	AC	Electric fan	34	34	-	-
	FP	Refrigerator	34	34	-	-
	Lighting	Medium portable solar lantern + LED (8 W)	34	34	-	-
	ICT	Small radio	34	34	-	-
		Mobile phone with battery and charger	34	34	-	-
		TV	34	34	-	-
Education	Cooking	-	-	-	-	-
	DHW	Biolite	1	1	-	-
	AH	Electric heater	1	1	-	-
	AC	Electric fan	1	1	-	-
	FP	-	-	-	-	-
	Lighting	Medium portable solar lantern + LED (8 W)	4	3	-	1
	ICT	Computer (desktop with monitor)	4	4	-	-
		Copy machine	1	1	-	-
		Modem & satellite dish	1	1	-	-
		Mobile phone with battery and charger	1	1	-	-
Health center	Cooking	-	-	-	-	-
	DHW	Biolite	1	1	-	-
	AH	Electric heater	1	1	-	-
	AC	Electric fan	1	1	-	-
	FP	Refrigerator	1	1	-	-
	Lighting	Medium portable solar lantern + LED (8 W)	3	3	-	-
	ICT	Computer (desktop with monitor)	2	2	-	-
		Copy machine	1	1	-	-
		Modem & satellite dish	1	1	-	-
		Mobile phone with battery and charger	4	4	-	-
		Sterilization	1	1	-	-
Community center	Lighting	Medium portable solar lantern + LED (8 W)	1	1	-	-
	ICT	Computer (desktop with monitor)	1	1	-	-
		Mobile phone with battery and charger	1	1	-	-
Small businesses	Lighting	Medium portable solar lantern + LED (8 W)	4	4	-	-
	ICT	Mobile phone with battery and charger	4	4	-	-
Public Illumination	Lighting	LED+PV solar street lamps (100 Watt LED) +Battery	4	4	-	-

Table 8-7 continued						
Sector	**Service (end-use)**	**Device**	**# per device and end-use**	**# should be per end-use**	**lack by end-use**	**additional or comfort end-use devices**
Water pumping	Water pumping	Solar PV DC pump	2	2	-	-
Agriculture	Agriculture	Electric grinding mill	1	5	-	-
		Electric pulveriser	1			
		Electric skin pealing machine	1			
		Electric motors (average 1 kW)	2			

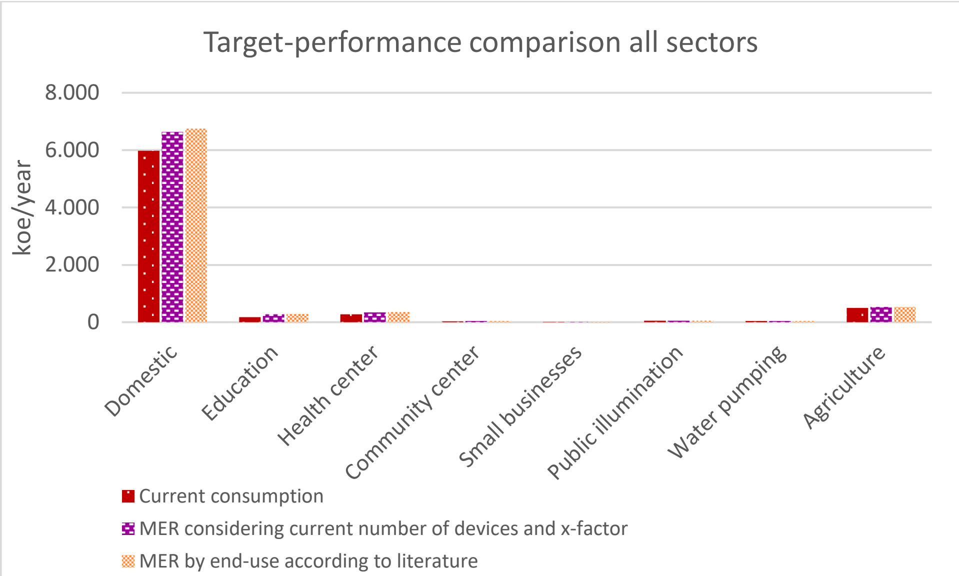


Figure 8-12: Target-performance comparison for MER 2 across all sectors

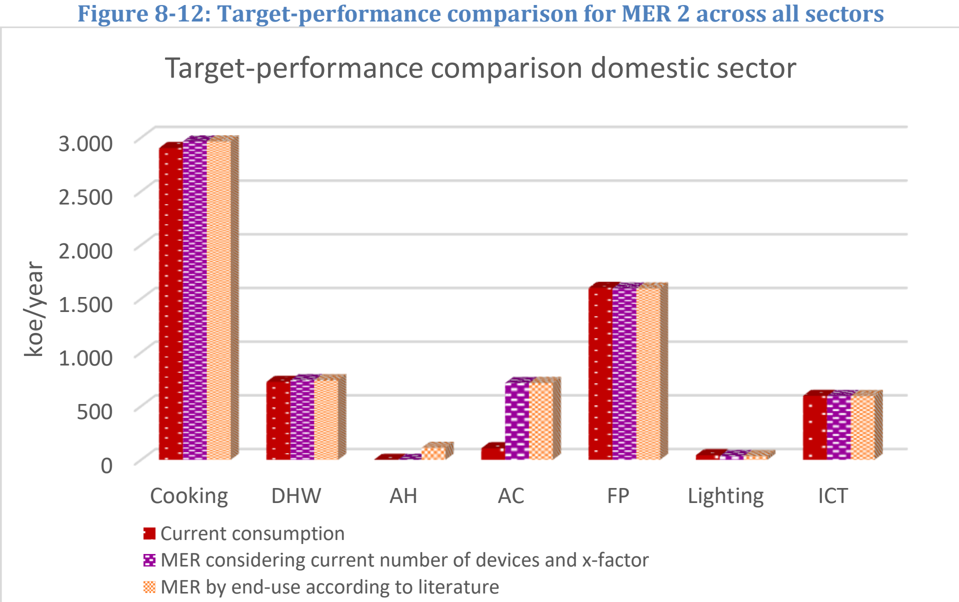


Figure 8-13: Target-performance comparison for MER 2 in domestic sector

8.7.2. Results of MER 3

Table 8-8: # of End-use devices by service and sector for MER 3

Sector	Service (end-use)	Device	# per device and end-use	# should be per end-use	lack by end-use	additional or comfort end-use devices
Domestic	Cooking	Gas cooktop	34	34	-	-
	DHW	Gas cooktop	34	34	-	-
	AH	Electric heater	34	34	34	34
	AC	Electric fan	34	34	-	-
	FP	Refrigerator	34	34	-	-
	Lighting	Light emitting diodes (LEDs) (4 W)	34	34	-	-
	ICT	Portable radio with battery Mobile phone with battery and charger TV	34 34 34	34 34 34	- - -	- - -
Education	Cooking	-	-	-	-	-
	DHW	Gas cooktop	1	1	-	-
	AH	Electric heater	1	1	1	1
	AC	Electric fan	1	1	-	-
	FP		-	-	-	-
	Lighting	Light emitting diodes (LEDs) (4 W)	4	3	-	1
	ICT	Computer (desktop with monitor) Copy machine Modem & satellite dish Mobile phone with battery and charger	4 1 1 1	4 1 1 1	- - - -	- - - -
Health center	Cooking	-	-	-	-	-
	DHW	Gas cooktop	1	1	-	-
	AH	Electric heater	1	1	1	1
	AC	Electric fan	1	1	-	-
	FP	Refrigerator	1	1	-	-
	Lighting	Light emitting diodes (LEDs) (4 W)	3	3	-	-
	ICT	Computer (desktop with monitor) Copy machine Modem & satellite dish Mobile phone with battery and charger Sterilization	2 1 1 4 1	2 1 1 4 1	- - - - -	- - - - -
Community center	Lighting	Light emitting diodes (LEDs) (4 W)	1	1	-	-
	ICT	Computer (desktop with monitor) Mobile phone with battery and charger	1 1	1 1	- -	- -
Small businesses	Lighting	Light emitting diodes (LEDs) (4 W)	4	4	-	-
	ICT	Mobile phone with battery and charger	4	4	-	-
Public Illumination	Lighting	Mercury vapor (gas lamp) (80W)	4	4	-	-
Water pumping	Water pumping	Electric pump	2	2	-	-
Agriculture	Agriculture	Electric motors (average 1 kW)	5	5	-	-

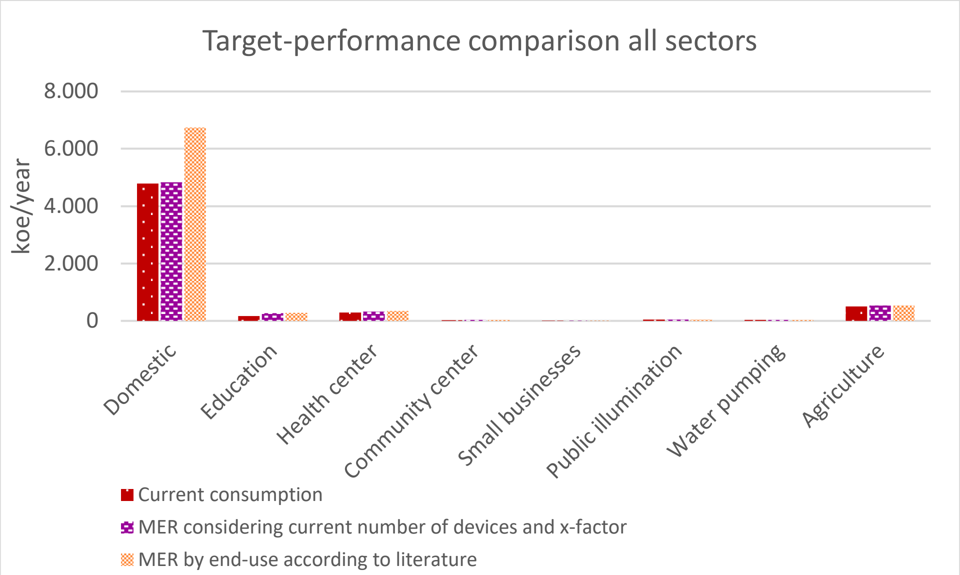


Figure 8-14: Target-performance comparison for MER 3 across all sectors

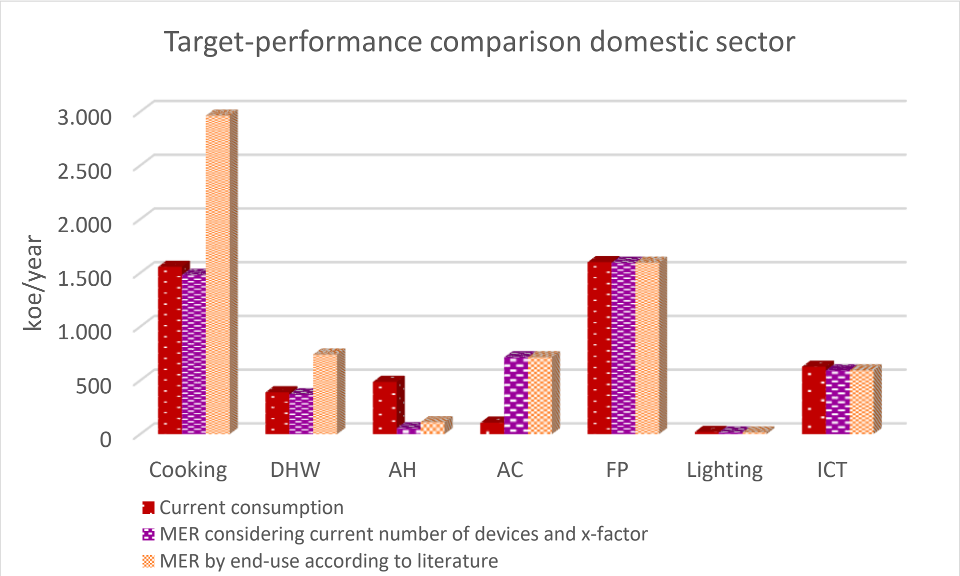


Figure 8-15: Target-performance comparison for MER 3 in domestic sector

8.7.3. Results of MER 4

Table 8-9: # of End-use devices by service and sector for MER 4

Sector	Service (end-use)	Device	# per device and end-use	# should be per end-use	lack by end-use	additional or comfort end-use devices
Domestic	Cooking	Wood gas stove	34	34	-	-
	DHW	Wood gas stove	34	34	-	-
	AH	LPG heater	34	34	-	34
	AC	Electric water cooler	34	34	-	-
	FP	Refrigerator	34	34	-	-
	Lighting	Compact fluorescent (CFL) (10 W)	34	34	-	-
	ICT	Portable radio with battery	34	34	-	-
		Mobile phone with battery and charger	34	34	-	-
		TV	34	34	-	-
Education	Cooking	-	-	-	-	-
	DHW	Wood gas stove	1	1	-	-
	AH	LPG heater	1	1	-	1
	AC	Electric water cooler	1	1	-	-
	FP		-	-	-	-
	Lighting	Compact fluorescent (CFL) (10 W)	4	3	-	1
	ICT	Computer (desktop with monitor)	4	4	-	-
		Copy machine	1	1	-	-
		Modem & satellite dish	1	1	-	-
		Mobile phone with battery and charger	1	1	-	-
Health center	Cooking	-	-	-	-	-
	DHW	Wood gas stove	1	1	-	-
	AH	LPG heater	1	1	-	1
	AC	Electric water cooler	1	1	-	-
	FP	Refrigerator	1	1	-	-
	Lighting	Compact fluorescent (CFL) (10 W)	3	3	-	-
	ICT	Computer (desktop with monitor)	2	2	-	-
		Copy machine	1	1	-	-
		Modem & satellite dish	1	1	-	-
		Mobile phone with battery and charger	4	4	-	-
		Sterilization	1	1	-	-
Community center	Lighting	Compact fluorescent (CFL) (10 W)	1	1	-	-
	ICT	Computer (desktop with monitor)	1	1	-	-
		Mobile phone with battery and charger	1	1	-	-
Small businesses	Lighting	Compact fluorescent (CFL) (10 W)	4	4	-	-
	ICT	Mobile phone with battery and charger	4	4	-	-
Public Illumination	Lighting	Mercury vapor (gas lamp) (80W)	4	4	-	-
Water pumping	Water pumping	Choti Bijli (diesel genset)	2	2	-	-
Agriculture	Agriculture	Electric grinding mill	1	5	-	-
		Electric pulveriser	1			
		Electric skin pealing machine	1			
		Electric motors (average 1 kW)	2			

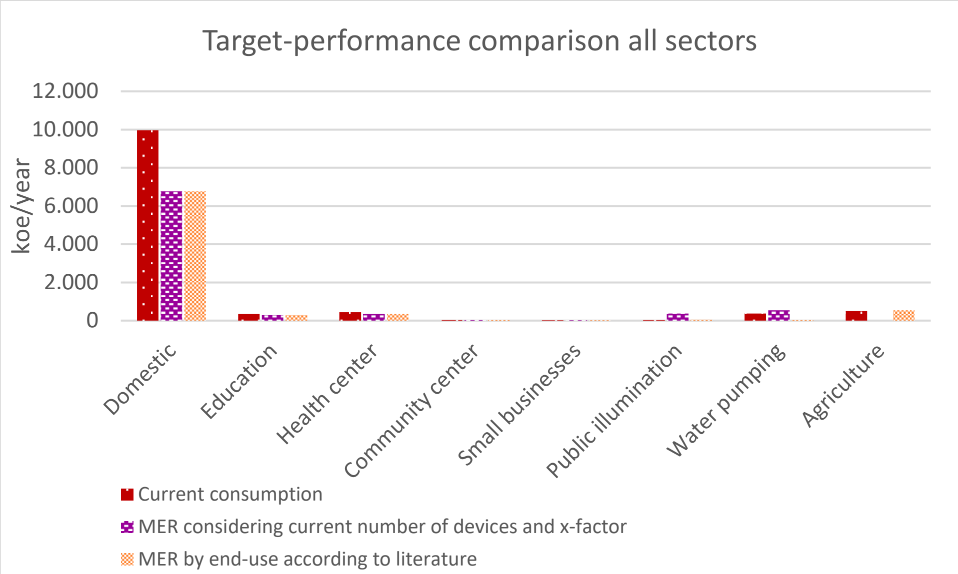


Figure 8-16: Target-performance comparison for MER 4 across all sectors

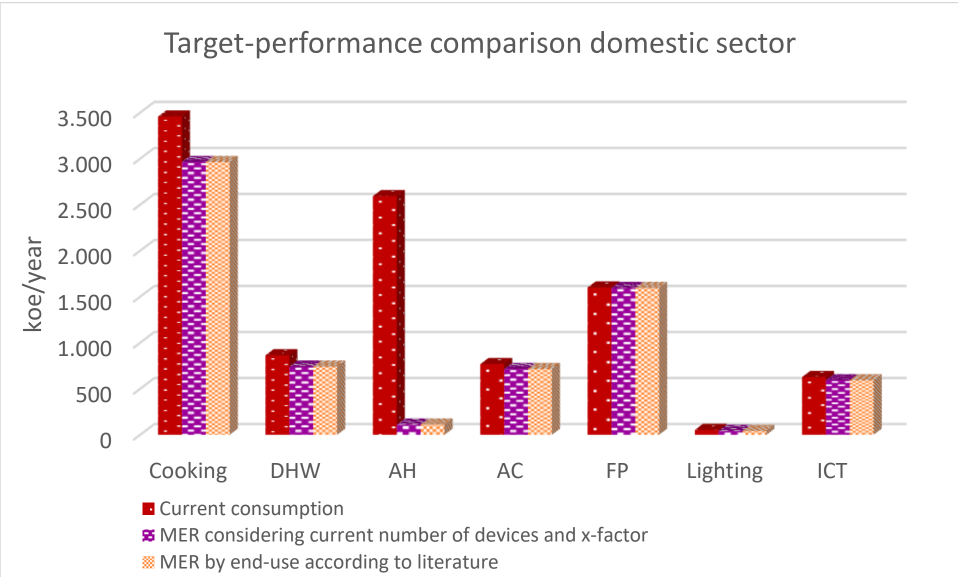


Figure 8-17: Target-performance comparison for MER 4 in domestic sector

8.7.4. Results of MER 5

Table 8-10: # of End-use devices by service and sector for MER 5

Sector	Service (end-use)	Device	# per device and end-use	# should be per end-use	lack by end-use	additional or comfort end-use devices
Domestic	Cooking	Improved solid fuel	34	34	-	-
	DHW	Improved solid fuel	34	34	-	-
	AH	Kerosene heater	34	34	-	34
	AC	Electric fan	34	34	-	-
	FP	Refrigerator	34	34	-	-
	Lighting	Kerosene hurricane (lantern) (wick)	34	34	-	-
	ICT	Portable radio with battery	34	34	-	-
		Mobile phone with battery and charger	34	34	-	-
		TV	34	34	-	-
Education	Cooking	-	-	-	-	-
	DHW	Improved solid fuel	1	1	-	-
	AH	Kerosene heater	1	1	-	1
	AC	Electric fan	1	1	-	-
	FP		-	-	-	-
	Lighting	Kerosene hurricane (lantern) (wick)	4	3	-	1
	ICT	Computer (desktop with monitor)	4	4	-	-
		Copy machine	1	1	-	-
		Modem & satelite dish	1	1	-	-
		Mobile phone with battery and charger	1	1	-	-
Health center	Cooking	-	-	-	-	-
	DHW	Improved solid fuel	1	1	-	-
	AH	Kerosene heater	1	1	-	1
	AC	Electric fan	1	1	-	-
	FP	Refrigerator	1	1	-	-
	Lighting	Kerosene hurricane (lantern) (wick)	3	3	-	-
	ICT	Computer (desktop with monitor)	2	2	-	-
		Copy machine	1	1	-	-
		Modem & satelite dish	1	1	-	-
		Mobile phone with battery and charger	4	4	-	-
		Sterilization	1	1	-	-
Community center	Lighting	Kerosene hurricane (lantern) (wick)	1	1	-	-
	ICT	Computer (desktop with monitor)	1	1	-	-
		Mobile phone with battery and charger	1	1	-	-
Small businesses	Lighting	Kerosene hurricane (lantern) (wick)	4	4	-	-
	ICT	Mobile phone with battery and charger	4	4	-	-
Public Illumination	Lighting	Mercury vapor (gas lamp) (80W)	4	4	-	-
Water pumping	Water pumping	Choti Bijli (diesel genset)	2	2	-	-
Agriculture	Agriculture	Electric grinding mill	1	5	-	-
		Electric pulveriser	1			
		Electric skin pealing machine	1			
		Electric motors (average 1 kW)	2			

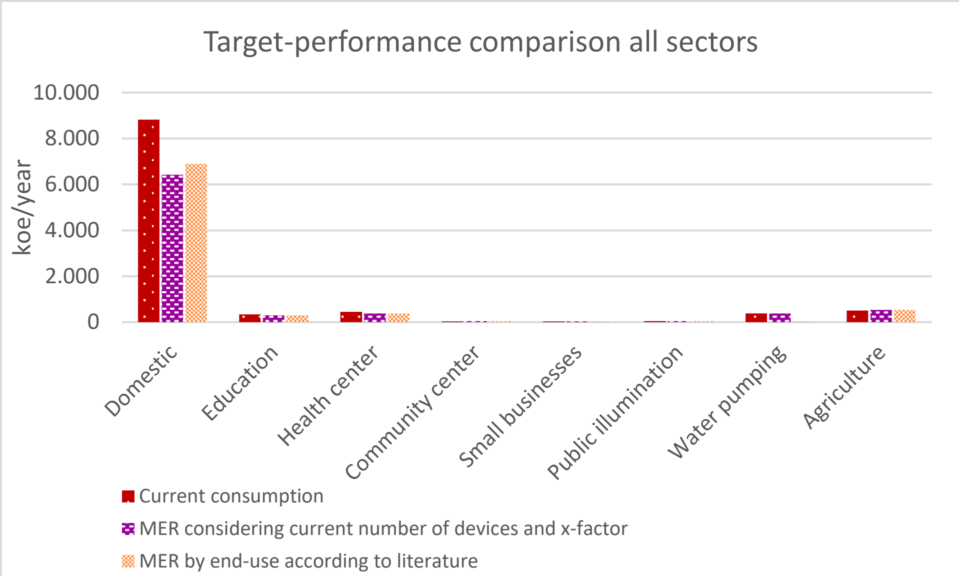


Figure 8-18: Target-performance comparison for MER 5 across all sectors

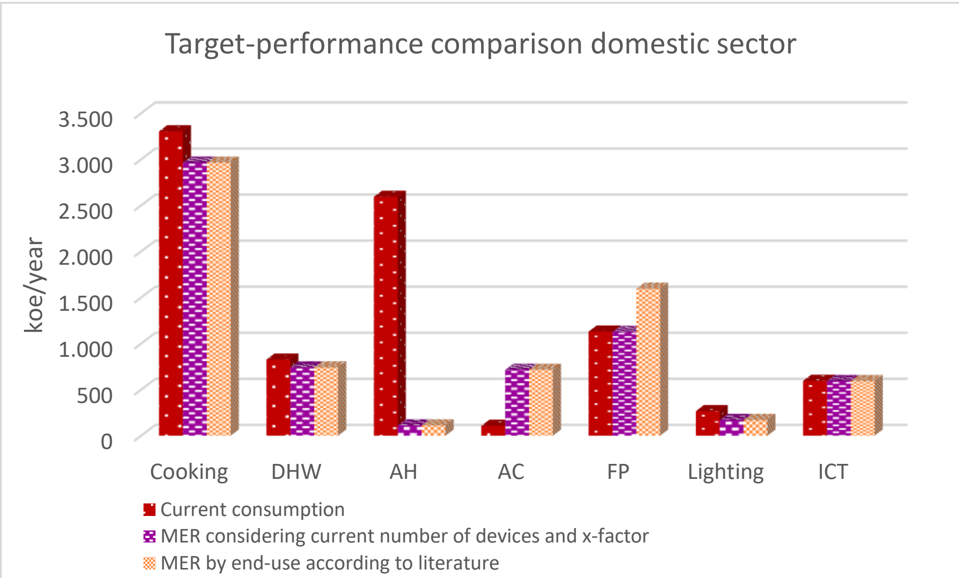


Figure 8-19: Target-performance comparison for MER 5 in domestic sector

8.8. Device cost and operation and maintenance cost of non-electrical devices

Table 8-11: Overview of device costs and O&M of non-electrical devices for "MER 1"

End-use	Device	# of Device									Consumption of non-electrical devices [kWh]								
		Domestic	Service - Education	Service – Health*	Service – Community*	Service - small businesses	Public illumination	Water pumping	Agriculture	Subtotal cost devices [€]	Domestic	Service - Education	Service – Health*	Service – Community*	Service - small	Public illumination	Water pumping	Agriculture	O&M of non-electrical devices [€]
Cooking	Solar cooker	34	1	1						152.32	15,726								125.81
Domestic hot water	Solar cooker	34	1	1						12.21	3,931	289	289						9.02
Ambient heating	Solar air heating system	34	1	1						60.00	22,338	657	657						236.52
Ambient Cooling	Solar PV fan	34	1	1						7.20	1,310	39	39						
Food preservation	Refrigerator	34								340.00									
	Medical refrigeration			1						20.00									
Lighting	Small portable solar lantern + LED (4 W)	34	4	3	1	4				9.20	248	18	35	6	23				0.33
Public Illumination	LED+PV solar street lamps (100 Watt LED) +Battery						4			86.67						584			2.92
ICT	Computer (desktop with monitor)		4	2	1					168.00									
	Copy machine		1	1						40.00									
	Modem & satellite		1	1						1.20									
	Sterilization			1						33.33									
	Small radio	34								13.60									
	Mobile phone with battery and charger	34	1	4	1	4				220.00									
	TV	34								272.00									
Water pumping	Solar PV DC pump							2		13.33									
Agriculture	Electric motors (average 1 kW)								4	8.00									
Total device cost without comfort requirements										1,397.17									145.01
Total device cost resulting from comfort										60.00									236.52

Table 8-12: Overview of device costs and O&M of non-electrical devices for "MER 2"

End-use	Device	# of Device									Consumption of non-electrical devices [kWh]								
		Domestic	Service - Education	Service – Health*	Service – Community*	Service - small businesses	Public illumination	Water pumping	Agriculture	Subtotal cost devices [€]	Domestic	Service - Education	Service – Health*	Service – Community*	Service - small	Public illumination	Water pumping	Agriculture	O&M of non-electrical devices [€]
Cooking	Biolite	34	1	1						56.14	33,755								135.02
Domestic hot water	Biolite	34	1	1						4.54	8,439	621	621						9.68
Ambient heating	Electric heater	34	1	1						18.00									
Ambient Cooling	Electric fan	34	1	1						14.40									
Food preservation	Refrigerator	34								340.00									
	Medical refrigeration			1						20.00									
Lighting	Medium portable solar lantern + LED (4 W)	34	4	3	1	4				18.40	496	35	70	12	47				0.66
Public Illumination	LED+PV solar street lamps (100 Watt LED) +Battery						4			86.67						584			2.92
ICT	Computer (desktop with monitor)		4	2	1					168.00									
	Copy machine		1	1						40.00									
	Modem & satellite		1	1						1.20									
	Sterilization			1						33.33									
	Small radio	34								13.60									
	Mobile phone with battery and charger	34	1	4	1	4				220.00									
	TV	34								270.00									
Water pumping	Electric pump							2		1.33									
Agriculture	Electric devices (average 1 kW)								5	36.60									
Total device cost without comfort requirements										1,3260.21									148.28
Total device cost resulting from comfort										18.00									

Table 8-13: Overview of device costs and O&M of non-electrical devices for "MER 3"

End-use	Device	# of Device									Consumption of non-electrical devices [kWh]								
		Domestic	Service - Education	Service – Health*	Service – Community*	Service - small businesses	Public illumination	Water pumping	Agriculture	Subtotal cost devices [€]	Domestic	Service - Education	Service – Health*	Service – Community*	Service - small	Public illumination	Water pumping	Agriculture	O&M of non-electrical devices [€]
Cooking	Gas cooktop	34	1	1						5.44	18,109								1,738.43
Domestic hot water	Gas cooktop	34	1	1						0.44	4,527	444	666						135.28
Ambient heating	Gas cooktop	34	1	1						-	5,659	111	166	(wasted heat as byproduct)					712.36
	Electric heater	34	1	1						18.00									
Ambient Cooling	Electric fan	34	1	1						14.40									
Food preservation	Refrigerator	34								340.00									
	Medical refrigeration			1						20.00									
Lighting	Light emitting diodes (LED) (4 W)	34	4	3	1	4				4.60									
Public Illumination	Mercury vapor (gas lamp) (80 W)						4			0.40									
ICT	Computer (desktop with monitor)		4	2	1					168.00									
	Copy machine		1	1						40.00									
	Modem & satellite		1	1						1.20									
	Sterilization			1						33.33									
	Portable radio with battery	34								6.80	683								1.71
	Mobile phone with battery and charger	34	1	4	1	4				220.00									
	TV	34								272.00									
Water pumping	Electric pump							2		1.33									
Agriculture	Electric motors (average 1 kW)								4	8.00									
Total device cost without comfort requirements										1,135.95									2,587.78
Total device cost resulting from comfort										18.00									-

Table 8-14: Overview of device costs and O&M of non-electrical devices for "MER 4"

End-use	Device	# of Device									Consumption of non-electrical devices [kWh]								
		Domestic	Service - Education	Service – Health*	Service – Community*	Service - small businesses	Public illumination	Water pumping	Agriculture	Subtotal cost devices [€]	Domestic	Service - Education	Service – Health*	Service – Community*	Service - small	Public illumination	Water pumping	Agriculture	O&M of non-electrical devices [€]
Cooking	Wood gas stove	34	1	1						16.32	40,208								32.17
Domestic hot water	Wood gas stove	34	1	1						1.32	10,052	1,478	1,478						2.60
Ambient heating	Wood gas stove	34	1	1						-	30,193	887	887	(wasted heat as byproduct)					31.93
	LPG heater	34	1	1						54.00	52,122	1533	1533						6622.56
Ambient Cooling	Electric water cooler	34	1	1						90.00									
Food preservation	Refrigerator	34								340.00									
	Medical refrigeration			1						20.00									
Lighting	Compact fluorescent (CFL) (10 W)	34	4	3	1	4				3.60									
Public Illumination	Mercury vapor (gas lamp) (80W)						4			0.40									
ICT	Computer (desktop with monitor)		4	2	1					168.00									
	Copy machine		1	1						40.00									
	Modem & satellite		1	1						1.20									
	Sterilization			1						33.33									
	Portable radio with battery	34								6.80	683								1.71
	Mobile phone with battery and charger	34	1	4	1	4				220.00									
	TV	34								272.00									
Water pumping	Choti Bijli (diesel genset)							2		13.33									
Agriculture	Electric motors (average 1 kW)								5	36.60									
Total device cost without comfort requirements										1262.91									68.41
Total device cost resulting from comfort										54.00									6622.56

Table 8-15: Overview of device costs and O&M of non-electrical devices for "MER 5"

End-use	Device	# of Device									Consumption of non-electrical devices [kWh]								
		Domestic	Service - Education	Service – Health*	Service – Community*	Service - small businesses	Public illumination	Water pumping	Agriculture	Subtotal cost devices [€]	Domestic	Service - Education	Service – Health*	Service – Community*	Service - small businesses	Public illumination	Water pumping	Agriculture	O&M of non-electrical devices [€]
Cooking	Improved solid fuel stove	34	1	1						16.32	38,421								153.69
Domestic hot water	Improved solid fuel stove	34	1	1						1.32	9,605	1,413	1,413						12.43
Ambient heating	Improved solid fuel stove	34	1	1							30,156	887	887	(wasted heat as byproduct)					159.65
	Kerosene heater	34	1	1						36.00	37,230	1,095	1,095						236.52
Ambient Cooling	Electric fan	34	1	1						14.40									
Food preservation	Refrigerator	24								240.00									
	Zeer pot	34		1						14.00									
	Medical refrigeration			1						20.00									
Lighting	Kerosene hurricane lantern	34	4	3	1	4				9.00	3,103	219	438	73	292				1576.80
Public Illumination	Mercury vapor (gas lamp) (80W)						4			0.40									
ICT	Computer (desktop with monitor)		4	2	1					168.00									
	Copy machine		1	1						40.00									
	Modem & satellite		1	1						1.20									
	Sterilization			1						33.33									
	Small radio	34								13.60									
	Mobile phone with battery and charger	34	1	4	1	4				220.00									
	TV	34								272.00									
Water pumping	Choti Bijli (diesel genset)							2		13.33									
Agriculture	Electric motors (average 1 kW)								5	36.60									
Total device cost without comfort requirements										1113.51									490.75
Total device cost resulting from comfort										36.00									1576.80

8.9. Size and consumption for cost definition of electricity generating system

Table 8-16: Size and consumption of electricity generating system for “MER 2”

End-use	Device	Power of all electrically driven devices [kW]									Consumption of all electrically driven devices [kWh]								
		Domestic	Service - Education	Service – Health*	Service – Community*	Service - small businesses	Public illumination	Water pumping	Agriculture	Subtotal Power kW	Domestic	Service - Education	Service – Health*	Service – Community*	Service - small businesses	Public illumination	Water pumping	Agriculture	Total Consumption kWh
Cooking	Biolite																		
Domestic hot water	Biolite																		
Ambient heating	Electric heater	34.00	1.00	1.00						36.00	24,820	730	730						26,280
Ambient Cooling	Electric fan	0.71	0.02	0.02						0.76	1,251	37	37						1,325
Food preservation	Refrigerator	2.55	-		-					2.55	18,615	-		-					18,615
	Medical refrigeration			0.17						0.17			1,445						1,445
Lighting	Medium portable solar lantern + LED (4 W)																		
Public Illumination	LED+PV solar street lamps (100 Watt LED) +Battery																		
ICT	Computer (desktop with monitor)	-	0.20	0.20	0.20	-				0.60	-	1,168	584	292	-				2,044
	Copy machine	-	0.08	0.08	-	-				0.15	-	27	27	-	-				55
	Modem & satellite	-	0.11	0.11	-	-				0.22	-	161	120	-	-				281
	Sterilization			0.50						0.50			183						183
	Small radio	0.85	-	-	-	-				0.85	310	-	-	-	-				310
	Mobile phone with battery and charger	1.12	0.01	0.01	0.01	0.04				1.20	410	16	64	16	64				570
	TV	17.00	-	-	-	-				17.00	6,205	-	-	-	-				6,205
Water pumping	Electric pump							0.06		0.06							438		438
Agriculture	Electric devices (average 1 kW)								3.00	3.00								5,840	5,840
	minimum requirements									27.05									37,311
	additional requirements									36.00									26,280

* While the overview of the community found no health and no community center, devices to meet the energetic requirements for those sectors and end-uses need to be considered. This is essential to meet convergence within the structuring method. Costs associated to the construction of buildings are not considered. It may also be that other buildings or empty ones will be used for alternative purposes.

Table 8-17: Size and consumption of electricity generating system for "MER 3"

End-use	Device	Power of all electrically driven devices [kW]									Consumption of all electrically driven devices [kWh]								
		Domestic	Service - Education	Service – Health*	Service – Community*	Service - small businesses	Public illumination	Water pumping	Agriculture	Subtotal Power kW	Domestic	Service - Education	Service – Health*	Service – Community*	Service - small businesses	Public illumination	Water pumping	Agriculture	Total Consumption kWh
Cooking	Gas cooktop																		
Domestic hot water	Gas cooktop																		
Ambient heating	Electric heater	34.00	1.00	1.00						36.00	24,820	730	730						26,280
Ambient Cooling	Electric fan	0.71	0.02	0.02						0.76	1,251	37	37						1,325
Food preservation	Refrigerator	2.55	-		-					2.55	18,615	-		-					18,615
	Medical refrigeration			0.17						0.17			1,445						1,445
Lighting	Light emitting diodes (LED) (4 W)	0.68	0.01	0.01	0.01	0.02				0.71	248	18	35	6	23				330
Public Illumination	Mercury vapor (gas lamp) (80 W)						0.08			0.08						467			467
ICT	Computer (desktop with monitor)	-	0.20	0.20	0.20	-				0.60	-	1,168	584	292	-				2,044
	Copy machine	-	0.08	0.08	-	-				0.15	-	27	27	-	-				55
	Modem & satellite	-	0.11	0.11	-	-				0.22	-	161	120	-	-				281
	Sterilization			0.50						0.50			183						183
	Portable radio with battery																		
	Mobile phone with battery and charger	1.12	0.01	0.01	0.01	0.04				1.20	410	16	64	16	64				570
	TV	17.00	-	-	-	-				17.00	6,205	-	-	-	-				6,205
Water pumping	Electric pump							0.06		0.06							438		438
Agriculture	Electric motors (average 1 kW)								1.00	1.00								5,840	5,840
	minimum requirements									24.99									37,798
	additional requirements									36.00									26,280

* While the overview of the community found no health and no community center, devices to meet the energetic requirements for those sectors and end-uses need to be considered. This is essential to meet convergence within the structuring method. Costs associated to the construction of buildings are not considered. It may also be that other buildings or empty ones will be used for alternative purposes.

Table 8-18: Size and consumption of electricity generating system for "MER 4"

End-use	Device	Power of all electrically driven devices [kW]									Consumption of all electrically driven devices [kWh]								
		Domestic	Service - Education	Service – Health*	Service – Community*	Service - small businesses	Public illumination	Water pumping	Agriculture	Subtotal Power kW	Domestic	Service - Education	Service – Health*	Service – Community*	Service - small businesses	Public illumination	Water pumping	Agriculture	Total Consumption kWh
Cooking	Wood gas stove																		
Domestic hot water	Wood gas stove																		
Ambient heating	LPG heater																		
Ambient Cooling	Electric water cooler	3.40	0.10	0.10						3.60	8,935	263	263						9,461
Food preservation	Refrigerator	2.55	-		-					2.55	18,615	-		-					18,615
	Medical refrigeration			0.17						0.17			1,445						1,445
Lighting	Compact fluorescent (CFL) (10 W)	1.70	0.01	0.01	0.01	0.04				1.77	621	44	88	15	58				825
Public Illumination	Mercury vapor (gas lamp) (80W)						0.08			0.08						467			467
ICT	Computer (desktop with monitor)	-	0.20	0.20	0.20	-				0.60	-	1,168	584	292	-				2,044
	Copy machine	-	0.08	0.08	-	-				0.15	-	27	27	-	-				55
	Modem & satellite	-	0.11	0.11	-	-				0.22	-	161	120	-	-				281
	Sterilization			0.50						0.50			183						183
	Portable radio with battery																		
	Mobile phone with battery and charger	1.12	0.01	0.01	0.01	0.04				1.20	410	16	64	16	64				570
	TV	17.00	-	-	-	-				17.00	6,205	-	-	-	-				6,205
Water pumping	Choti Bijli (diesel genset)							1.00		1.00							438		4,380
Agriculture	Electric motors (average 1 kW)								3.00	3.00								5,840	5,840
	minimum requirements									31.83									50,371
	additional requirements									-									-

* While the overview of the community found no health and no community center, devices to meet the energetic requirements for those sectors and end-uses need to be considered. This is essential to meet convergence within the structuring method. Costs associated to the construction of buildings are not considered. It may also be that other buildings or empty ones will be used for alternative purposes.

Table 8-19: Size and consumption of electricity generating system for "MER 5"

End-use	Device	Power of all electrically driven devices [kW]									Consumption of all electrically driven devices [kWh]								
		Domestic	Service - Education	Service – Health*	Service – Community*	Service - small businesses	Public illumination	Water pumping	Agriculture	Subtotal Power kW	Domestic	Service - Education	Service – Health*	Service – Community*	Service - small businesses	Public illumination	Water pumping	Agriculture	Total Consumption kWh
Cooking	Improved solid fuel stove																		
Domestic hot water	Improved solid fuel stove																		
Ambient heating	Kerosene heater																		
Ambient Cooling	Electric fan	0.71	0.02	0.02						0.76	1,251	37	37						1,325
Food preservation	Refrigerator	1.80	-		-					1.80	13,140	-		-					13,140
	Medical refrigeration			0.17						0.17			1,445						1,445
Lighting	Kerosene hurricane lantern																		
Public Illumination	Mercury vapor (gas lamp) (80W)						0.08			0.08						467			467
ICT	Computer (desktop with monitor)	-	0.20	0.20	0.20	-				0.60	-	1,168	584	292	-				2,044
	Copy machine	-	0.08	0.08	-	-				0.15	-	27	27	-	-				55
	Modem & satellite	-	0.11	0.11	-	-				0.22	-	161	120	-	-				281
	Sterilization			0.50						0.50			183						183
	Small radio	0.85								0.85	310								310
	Mobile phone with battery and charger	1.12	0.01	0.01	0.01	0.04				1.20	410	16	64	16	64				570
	TV	17.00	-	-	-	-				17.00	6,205	-	-	-	-				6,205
Water pumping	Choti Bijli (diesel genset)							1.00		1.00							438		4,380
Agriculture	Electric motors (average 1 kW)								3.00	3.00								5,840	5,840
	minimum requirements									27.32									36,245
	additional requirements									-									-

* While the overview of the community found no health and no community center, devices to meet the energetic requirements for those sectors and end-uses need to be considered. This is essential to meet convergence within the structuring method. Costs associated to the construction of buildings are not considered. It may also be that other buildings or empty ones will be used for alternative purposes.