MASTER

Electricity generation in remote areas in South Africa using stationary fuel cells adapting the technology roadmapping tool for R&D institutions

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Electricity Generation in Remote Areas in South Africa using Stationary Fuel Cells

Adapting the technology roadmapping tool for R&D institutions

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Electricity Generation in Remote Areas in South Africa using Stationary Fuel Cells

Adapting the technology roadmapping tool for R&D institutions

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Preface

After almost eight years of study of which about four years at Eindhoven University of Technology the time has come to conclude my studies with a master thesis study. During my exchange programme with the University of Pretoria in South Africa I decided to search for an assignment at a company in Pretoria, South Africa. I especially would like to thank Dr. A.C. Brent for his help in finding a suitable assignment at the CSIR (Council for Scientific and Industrial Research). Also in the role of my co-supervisor in South Africa I would like to thank him.

Furthermore, I would like to thank Dr. S. Hietkamp as my direct supervisor in the energy and processes competency area of the CSIR. All his input during discussions has been very valuable. Prof. Dr. M.W. Pretorius from the University of Pretoria has given me fine details and firm background about the tool of Technology Roadmapping during my meetings with him. Also, a special word of thank to Dr. M. Rohwer who I shared an office with during my time at the CSIR. He provided me with lots of input and we had several discussions about the future of fuel cells (FCs), which were very helpful.

During my research I needed to talk to experts in specific fields to get input for the Technology Roadmap. A special word of thanks goes to everybody who provided input. Especially I would like to thank Dr. S. Hietkamp and Dr. M. Rohwer from CSIR's Material Science and Manufacturing unit, Mr. M. Mapako (MSc) and Dr. A.C. Brent from the Natural Resources and the Environment unit in the Sustainable Energy Future research group, and Mr. S. Szewczuk from the Built Environment unit as specialist in Rural Energy and Economic Development.

Also, I would like to thank my first tutor in the Netherlands: Dr. Ing. G.P.A. Mom for his support during my stay in South Africa. The long distance was sometimes a bit of a hassle when discussing my documents but we managed to overcome this very well thanks to e-mail and telephone contact. Last but not least I thank my second tutor, Dr. Ir. G.P.J. Verbong, for taking this responsibility and the great cooperation.

The next quote by Graca Machel-Mandela, current wife of former President Nelson Mandela, suits this report in that lots of people from South Africa dream of a better existence. One way of accomplishing this is that everybody in South Africa should be given the opportunity to use electricity. For lots of people living in e.g. the Netherlands this is regarded as something common and obvious to have. People in South Africa's rural areas have to struggle to get it, and if they do, to be able to pay their relative small bills. Therefore if you strive to really want something, some things might become reality, although it might take some time before it actually happens.

'If we have intelligence, imagination, and the ability to dream, things can happen"
Graca Machel-Mandela

Summary/ abstract

This research modified the Technology Roadmapping (TRM) tool in order to use it in R&D institutions and to discuss what aspects are useful and what are not. Specifically, this tool has been modified to be utilised in the fuel cell focus-group of the CSIR, a research institution in South Africa. The modified TRM tool is executed to develop a Technology Roadmap (TR) for the introduction of fuel cells (FCs) in remote areas of South Africa (SA) where no national electricity grid is available and it is discussed what the main drivers are for implementation.

The research starts with a descriptive overview of the population of South Africa with its 48.5 million people and about 13 million households. It becomes clear that in the year 2007 80% of the households are already connected to the national power grid which is above the world's average of about 72%. People are considered 'connected' when they at least can use the grid connection for lighting. Furthermore, literature shows that most of the population is 'black' and that lots of 'black African' people have very low incomes and therefore can hardly afford to buy electricity, which makes paying bills hardly possible, and cannot afford to live in a 'normal' house with electricity. They still use traditional fuels for cooking, heating, and lighting. For cooking and heating they mostly use paraffin or wood, and for lighting candles are used.

South Africa mostly uses coal for electricity generation because South Africa has large and economically mineable coal reserves. Renewables, however, are also becoming important because SA has to comply with emission regulations since they are willing to fulfil the requirements of the current Kyoto protocol and are signing up the follow up program in the year 2012. Secondly, the use of renewables makes South Africa less depended on fossil fuels in case these might run out or might become more expensive.

The rest of the report is of an explorative character using the case study of developing a TR for the introduction of FCs to electrify remote areas of SA that are not connected to the electricity grid. The standard TRM tool is modified for the CSIR and it is executed to set the path for developing FCs to electrify remote SA that is not yet connected to the national grid.

There already exists a tool to fast-start the process of TRM. This is the 'T-plan' developed by the University of Cambridge. Their tool however is considered to take too much time from specialists involved. Especially in the CSIR where TRM has been done on one specific technology the normal number of four half day workshops was considered too time consuming. Therefore it was decided to modify the existing tool to fit an R&D institution in which only a small number of people from multiple disciplines could take place. The result was that only one half day workshop was needed when pre-interviews and a literature research were done. These together with the specialists' knowledge formed the input for the workshop. After the workshop the specialists individually were asked to prioritize the results in a matrix. Then the TR was developed with the input from the prioritization, the literature review, and the results from discussions in the workshop. The TR itself is a diagram having three time slots: the years 2008-2013, 2014-2020, and 2021-2030. The trends and drivers are presented per theme and targets are set for one or multiple timeslots and when it considered more practical issues certain years could be set as targets. So, the modification of the T-plan tool resulted in that the whole contents of the tool could be utilised, except for the number of contact days between specialists involved. To compensate this, one-to-one open interviews were held in advance. This way all opinions were heard and taken into account while developing the TR. The consequence of reducing the number of contact hours that significantly was that one of the main goals of performing TRM was about to get lost: communication/knowledge transfer between specialists. However, thanks to the pre-interviews and good discussions during the workshop this was not the case. It is recommended in future to increase the number of contact moments to at least twice so that in between the workshop people can think about the matters discussed.

The outcome of the TR is done using five themes: society, economy, environment, technology, and policy. All these themes are interconnected and play a significant role in developing FCs to electrify the remote places of SA were no grid is available. The themes are discussed from two perspectives: on the one hand from the general side, from South African people or SA as a country; on the other hand from the CSIR's perspective per theme.

General trends and drivers from society show that the population and number of households are increasing. In order to make sure that by the year 2014 all households in SA can have electricity for at least lighting, the 'electricity for all programme' has been invented after the apartheid was abandoned in the year 1994. People in remote settings would like to use electricity for lighting, cell phone charging, small refrigerators, small TV, and a radio. From the CSIR's point of perspective it is important that society has awareness and that people are taught in using and maintaining the systems properly. Inside the CSIR the main focus considering society is to increase its intellectual property and to stimulate knowledge transfer considering FCs.

The second theme, economy, showed that the focus for South Africa should be on the platinum group of metals resources of the country. SA has the largest global resource of platinum and is hoping to export it in order to stimulate their economy. The economy in SA in remote settings can use a boost in order to stimulate further growth. People first need to earn money before they can pay (electricity) bills. The poverty allowance of free 50kWh monthly for poor households is a good start, but it is still considered not to be enough for people who cannot afford to pay their (electricity) bills. It is often forgotten that electrical appliances are expensive as well The CSIR should focus on developing a FC that is cheap in maintenance and efficient in use. If the developed technology is considered a success the knowledge should be sold next to a company in the value chain to further fine tune it and make an (end-) product of it. From the TR it furthermore becomes clear that the technology developed also should fit niche applications in order to make more money in selling technologies.

The environment is also becoming an issue in South Africa. The population keeps growing and more energy is used through which emissions increase. From both the CSIR's and general's point of perspective regulations such as the 'zero waste' and national air quality act should be followed. SA has agreed to participate in the follow-up program of the Kyoto protocol, so this means that emissions have to be decreased significantly in the coming years.

The technology of FCs is important for SA because SA would like that platinum (Pt) will be used in the new technologies of FCs as well. Therefore SA is trying to catch up with global developments and is hoping to do breakthrough research in new technologies, i.e. the Direct Alcohol Alkaline Fuel Cell (DAAFC), which is expected to be marketed by the year 2030 as becomes clear from the TR. DAAFCs and PEMFCs are the two FCs that can be used for small scale electricity generation because these can handle fluctuations in demand the best. Therefore the focus is only on those two. DAAFCs have the advantage that alcohol directly can be fed into the FC; furthermore the output voltage per cell will be higher than using the currently most developed technology: the Proton Exchange Membrane Fuel Cell (PEMFC). PEMFC in combination with a reformer can also be used in rural settings. The reformer is needed to reform alcohol into hydrogen. Alcohol is preferred in remote settings for these purposes because of transport issues. Both kinds of FCs need purity research in order for the system to become operable in remote settings; now they still are poisoned to fast by CO. The DAAFC needs breakthrough research in developing stable membranes that conduct hydroxy-ions optimally. The FC systems furthermore should be developed in a modular way so that systems can be expanded when demand increases over time. Another result from the TR was that the maintenance should be organised decentralised by local people who are trained to do this. The output voltage of a FC system was discussed during the workshop and it was agreed that it must meet grid specification: 220-240V AC, 50-60Hz. This means that the typical 50V DC generated by a FC-stack (multiple cells connected) needs to be converted to grid specifications.

Considering the policy theme it is discussed that SA has to comply with global regulations as the Kyoto protocol discussed above in ‘environment’, as well as with the ‘Polokwane declaration’ to produce zero waste by the year 2022, and also to fulfil requirements of the ‘National Air Quality Act’ set in 1994. The CSIR has to comply to these as well and further more to its mandate towards government to improve the life of the South African people.

These five drivers should be taken into account while developing a TR to electrify places in SA where no electricity grid is available (yet). It can be concluded that people living in remote settings would like to be connected to the national power grid or get electricity that has similar properties. They feel left behind if they don’t receive a similar service to that of the national power grid.

List of abbreviations

AFC	Alkaline Fuel Cell
CSIR	Council for Scientific and Industrial Research
CV	Calorific value an alternate term is “heating value”
DAAFC	Direct Alcohol Alkaline Fuel Cell
DEFC	Direct Ethanol Fuel Cell
DME	Department of Minerals and Energy
DMFC	Direct Methanol Fuel Cell
e	Electron
EC	Eastern Cape province
FC	Fuel Cell
GHG	Green house gasses
GHS	General Household Survey
GP	Gauteng Province
H^+	Proton
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
H_2	Hydrogen
H_2O	Water
IEA	International Energy Agency
IP	Intellectual Property
kW	Kilowatt, a unit of power: a thousand watts
kWh	Kilowatt-hour, a unit of energy
LPG	Liquid petroleum gas (usually butane and propane)
MJ	Mega joule (10^6 joules), a unit of energy
MCFC	Molten Carbonate Fuel Cell
MSM	Material Sciences and Manufacturing
MW	Megawatt: unit of power: a million watts
MWe	Megawatt of power in the form of electricity
MWh	Megawatt-hours, a unit of energy
NER	National Electricity Regulator
NOx	Gaseous nitrogen compounds such as nitrogen dioxide and nitrous oxide
NRE	Natural Resources and Environment
OECD	Organization for Economic Cooperation and Development (comprising of the world’s richest countries)
OH^-	Hydroxy-ion
PAFC	Phosphoric Acid Fuel Cell
PBMR	Pebble bed modular reactor
PEMFC	Proton Exchange Membrane Fuel Cell
PJ	Peta joule (10^{15} joules)
PV	Photovoltaic
R	Rand (Currency of SA; exchange rate R1.- = € 0.10)
R&D	Research and development
SOFC	Solid Oxide Fuel Cell
SHS	Solar Home System
TR	Technology Roadmap
TRM	Technology Roadmapping
TU/e	Eindhoven University of Technology, the Netherlands
UP	University of Pretoria, South Africa
W	Watt
WEC	World Energy Council

Table of contents

Preface i
Summary/ abstract ii
List of abbreviations v
1. Introduction 1
1.1 General introduction 1
1.2 Population of South Africa 2
1.2.1 The people 2
1.2.2 Households 5
1.3 Electricity in South Africa 6
1.3.1 General considerations on electricity in SA 6
1.3.2 Rural electrification of SA 8
National electrification programme 8
Electrification rate 9
Poverty tariff 11
Rural electrification example: Lucingweni 12
1.3.3 Alternative energy sources in SA for electricity 12
Gas 13
Nuclear energy 13
Renewable energies 14
Fuel cells 15
1.4 CSIR and its fuel cell research 16
1.5 Research questions 17
1.6 Research strategy 18
2. Technology Roadmap review 19
2.1 Basics of Technology Roadmapping 19
2.2 TR of non-mature technologies in R&D settings 21
2.3 Conclusions on Technology Roadmapping 23
3. Research methodology 24
3.1 The choice of research methodology 24
3.2 Fuel Cell focus group at CSIR 24
3.3 Technology Roadmapping at CSIR 25
3.3.1 The process at the CSIR 25
3.3.2 Specialists involved in TRM process 27
3.3.3 Research limitations 27
4. Results of Technology Roadmapping at CSIR 28
4.1 Trends and drivers 28
4.1.1 Perspectives of specialists 28
Specialists in fuel cells 28
Specialists in rural electrification 29
4.1.2 Five trends and drivers specified 30
Society trends and drivers 33
Economic trends and drivers 34
Environmental trends and drivers 35
Technology trends and drivers 36
Policy trends and drivers 37
4.2 Prioritization of market, business, and product/service drivers 38
4.2.1 The drivers matrix 38
4.2.2 Client needs as main driver 38
4.2.3 Other important drivers to focus on 39
4.3 Technology Roadmap to electrify rural areas of SA 40
4.4 SWOT analysis of the CSIR FC R&D programme 47

4.6 Reflection on TR process at CSIR 48
5. Conclusions and recommendations 50
5.1 Conclusions 50
5.1.1 Electrifying remote South Africa without grid connection using stationary fuel cells 50
5.1.2 Technology Roadmapping in R&D settings 53
5.2 Recommendations 54
5.2.1 Electrifying remote South Africa without grid connection using stationary fuel cells 54
5.2.2 Technology Roadmapping in R&D settings 55
References 56
Appendices 60
Appendix 1: Map of South Africa 60
Appendix 2: Conversion factors, Prefixes, and Calorific values 61
Appendix 3: Projections of electricity capacity by plant type in GW 62
Appendix 4: Households by dwelling and type of fuel for cooking, heating, and lighting 63
Appendix 5: Losses and transport of electricity 66
Appendix 6: Fuel Cells 69
Appendix 7: Fuels for Fuel Cells 75
Appendix 8: Technology Roadmap expound 76
Appendix 9: Interviews with specialists 85
Appendix 10: Prioritisations 94
Appendix 11: Social impact of electrification 96

1. Introduction

1.1 General introduction

This research was conducted in collaboration with the Material Sciences and Manufacturing (MSM) and the Natural Resources and the Environment (NRE) operating units of the CSIR (Council for Scientific and Industrial Research), and the Graduate School of Technology Management of the University of Pretoria in South Africa. The study aimed to complete a technology roadmap for stationary applications of fuel cells to generate and supply electricity in remote areas, from the perspectives of the CSIR. Furthermore, it aimed to compile a master thesis for the study Innovation Management at the Department of Industrial Engineering and Technology Management of the Eindhoven University of Technology, the Netherlands (TU/e).

The thesis will form a first-cut technology roadmap that the CSIR can use as reference point in developing stationary fuel cells in rural places of South Africa that are not connected to the national electricity grid. Furthermore, this thesis will discuss the use of a technology roadmap for this kind of technological development.

The report will first provide background information on South Africa. It starts with an overview of the population in which the contrasts between rich and poor, black, Indian, coloured, and the white population becomes visualized. The different type of housing will be presented and figures will be provided to support this. The second part will handle the electricity in South Africa (SA). First a general overview will be given and then the focus will be on rural SA. The focus of the report will be on fuel cells (FCs) as solution to electrifying rural areas of SA that are not connected to the national power grid. FCs are just one option for these areas, other options will be discussed shortly as well. The third part of the first chapter will provide background information on the CSIR and its research in FCs. Then the research questions are formulated and the chapter concludes with the research strategy followed during this research.

The second chapter will review the tool of technology roadmapping (TRM). The basics of a technology roadmap (TR) will be described and the use in R&D settings evaluated. The chapter finishes with a conclusion on what still needs to be investigated further.

Chapter three will address the research methodology that was utilized. In this chapter the research design based on the case study methodology will be presented with its strengths and weaknesses.

The results of the TR will be handled in chapter four and the TR itself will be given in a tabular format. First an overview of the trends and drivers is provided on five drivers: technology, economy, policy, society, and environment. Furthermore the process of TRM is evaluated by the participants in a reflection.

The report finishes with conclusion on both research questions and recommendations will be given for further research.

After the conclusions the appendices will be provided in order to support the main part of the report. The appendices will include among other things a map of SA to indicate the locations of the main cities and to provide an overview of the country considering provinces. Also the appendix will contain information on different kind of FCs and the elaboration on the tabular TR of as presented in chapter four.

1.2 Population of South Africa

1.2.1 The people

South Africa is a multi-cultural country of 48.5 million people (mostly dominated by 'Black[1] African' population as is tabulated in table 1.1. All the people in South Africa form the demand side for electricity. The supply side is (mostly) formed by the parastatal company Eskom as will be discussed later. Remarkable in table 1.1 is the high unemployment rate (28.6%) of the total population. The highest unemployment rate is found in the black African population with more than 34%. Partly this is because this group has the lowest educational level (GHS, 2006) which might be caused by a lack of sufficient funds for education as will become clear in table 1.3. So, in order to support these groups state involvement is critical.

	Male						Female						Total					
			Economically active						Economically active						Economically active			
	Total	Not economically active	Total	Workers	Unemployed	Unemployment rate	Total	Not economically active	Total	Workers	Unemployed	Unemployment rate	Total	Not economically active	Total	Workers	Unemployed	Unemployment rate
Population group	N (1 000)					%	N (1 000)					%	N (1 000)					%
All population groups	**14 511**	**5 151**	**9 360**	**7 131**	**2 228**	**23,8**	**15 419**	**8 007**	**7 412**	**4 849**	**2 563**	**34,6**	**29 935**	**13 161**	**16 774**	**11 982**	**4 792**	**28,6**
Black African	11 155	4 299	6 856	4 923	1 934	28,2	12 003	6 534	5 469	3 181	2 288	41,8	23 161	10 835	12 325	8 104	4 221	34,2
Coloured	1 341	395	946	761	184	19,5	1 436	646	790	610	180	22,8	2 777	1 041	1 736	1 371	365	21,0
Indian/Asian	431	98	333	276	57	17,2	403	229	174	136	38	21,7	836	327	509	414	95	18,7
White	1 568	354	1 214	1 161	53	4,3	1 570	595	974	917	57	9,6	3 138	950	2 188	2 078	110	5,0

* For all values of 10 000 or lower the sample size is too small for reliable estimates
Due to rounding numbers do not necessarily add up to totals.
Totals include other and unspecified population group and sex.

Table 1.1: Population characteristics in South Africa (GHS, 2006)

In South Africa not everybody can afford to live in a 'common' house. Therefore many people live in informal dwellings. Informal dwellings include shacks or shanties in informal settlements or in backyards. Formal dwellings on the other hand include a house on a separate stand, a flat or apartment in a block of flats, a townhouse, a room in a backyard, a room or flatlet on a shared property, or traditional African houses. For this research it is important to know in what situations inhabitants of South Africa are living. In the situation of living in a backyard it might be that this family is e.g. electrified via the owner of the premises instead of having a connection of their own.

[1] "Black" is here defined to include people classified as African, but excludes the "coloured" and Asian populations.

Type of dwelling	N (1 000)			
	1 - 3 rooms	4 - 5 rooms	6+ rooms	Total
Total	**5 901**	**3 889**	**2 625**	**12 972**
Dwelling/ house/ brick structure on a separate stand or yard or on farm	2 175	2 849	2 278	7 581
Traditional dwelling/ hut/ structure made of traditional materials	729	391	224	1 377
Flat/apartment in a block of flats	370	205	16	645
Town/ cluster/ semi-detached house (simplex/duplex/triplex)	88	149	26	278
Unit in retirement village	*	*	*	15
Dwelling/house/flat/room in backyard	437	63	44	592
Informal dwelling/ shack in backyard	652	54	*	745
Informal dwelling/ shack not in backyard	922	154	14	1 135
Room/flatlet	281	13	*	317
Caravan/tent	16	*	-	18
Other	212	*	*	245
Unspecified	11	*	*	24

* For all values of 10 000 or lower the sample size is too small for reliable estimates.
Totals include other and unspecified population group and those who do not have and unspecified rooms.
Due to rounding numbers do not necessarily add up to totals.

Table 1.2: Housing characteristics in South Africa (GHS, 2006)

People living in formal dwellings, i.e. the traditional African villages near the Wild Coast (figure 1.1), are not connected to the national power grid because of the wide open space between houses and remote situation of the village itself. Also the tradition to live without electricity and their style of living to foresee in their own need make it difficult to afford electricity, because they hardly make money.

Figure 1.1: Formal Dwellings: Traditional village, not electrified; Bulungula Village, Eastern Cape (Pierre Smits, 2007)

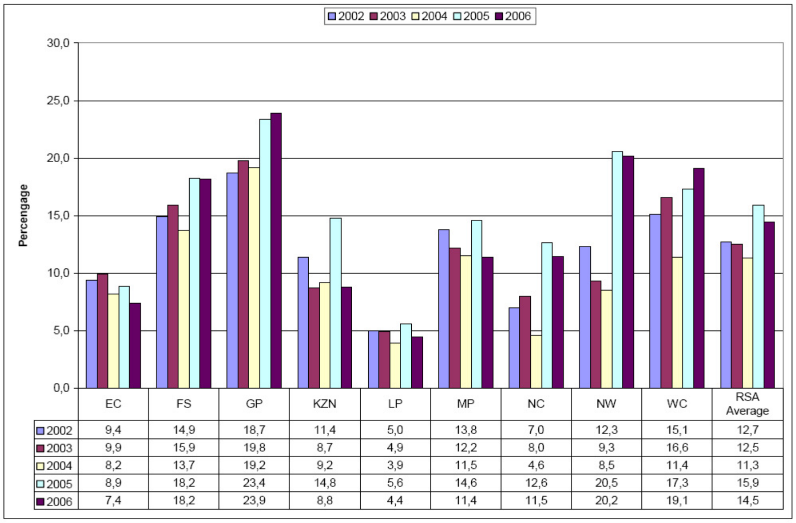


Figure 1.2: Percentage of households living in informal dwellings, per province (see appendix 1 for an overview of the provinces in SA) (GHS, 2006)

It is remarkable how many people live in an informal dwelling and the trend of more people living in such a situation (figure 1.2). It should be noted that many people are leaving the formal dwellings (as i.e. traditional villages presented in figure 1.1) to go to large cities hoping to find work. In the large cities they often end up in informal dwellings in suburbs as presented in figure 1.3.

Population group and sex of household head	N (1 000)									
	R0 - R399	R400 - R799	R800 - R1 199	R1 200 - R1 799	R1 800 - R2 499	R2 500 - R4 999	R5 000 - R9 999	R10 000 or more	Refused	Total
All population groups										
Total	**2 276**	**3 742**	**2 268**	**1 361**	**837**	**1 188**	**773**	**345**	**51**	**12 972**
Male	1 254	2 000	1 381	926	591	922	617	304	38	8 128
Female	1 022	1 742	887	436	245	267	156	42	13	4 843
Black African										
Total	**2 186**	**3 496**	**1 983**	**1 047**	**492**	**498**	**197**	**62**	*	**10 051**
Male	1 194	1 853	1 202	703	341	363	139	43	*	5 901
Female	992	1 643	781	344	151	135	58	19	*	4 150
Other**										
Total	**90**	**245**	**284**	**312**	**344**	**689**	**575**	**282**	**41**	**2 911**
Male	60	146	178	220	250	557	477	259	31	2 218
Female	29	99	107	92	94	131	97	23	*	692

** Other includes coloured, Indian/Asian, white and unspecified population groups. These groups are aggregated due to the small sample size.
* For all values of 10 000 or lower the sample size is too small for reliable estimates.
Totals include unspecified sex of the household head and the "don't know" and "unspecified" categories of monthly expenditure variable.
Due to rounding numbers do not necessarily add up to totals.

Table 1.3: Households by total expenditure in the month prior to the interview, population group and sex of the household head (GHS, 2006) [exchange rate about: €1.- = R10]

The fact that so many people have to live in such informal dwellings correlates with the income of a household which is given in table 1.3. This table presents lots of information: On the one hand the major differences between incomes in households in an average ‘Black African’ or ‘other’ population group. Most Black African households can spend only between R400 and R799 per month, while the others can spend much more per month. This is why in informal dwellings mostly Black African people are found rather than the white or coloured people. Furthermore the differences in income per household between a household run by women or by men are made clear. On average a household run by men earn more per month. So, from table 1.3 is becomes clear that on average the Black African population do not have much money to spend and electricity is considered as a luxury. An electricity bill could e.g. be the same amount as their income that month, or even more. This means that even when a household has a connection to the power grid, this does not automatically mean that they can afford to use electricity or buy electrical devices to connect to the grid.

Figure 1.3: Informal dwelling, electrified, near Cape Town (Pierre Smits, 2007)

1.2.2 Households

During the research the word ‘household’ will be used often. To make clear what this means in practice it will be explained in more detail now. Table 1.4 shows that the population of South Africa has increased from 45.53 million in 2002 to 48.5 million in 2007 (CS, 2007). This resembles an increase in population of about 6.5%. The largest increase in population has been in the province Gauteng where the large cities Johannesburg and Pretoria are located. The number of households grew from 11.48 million to 12.97 million in 2006 which is a net increase of 13%. These figures show that the increase in number of households is caused by three factors: migration to large cities, general population increase, and the trend that new households become smaller. When the average number of people per household in South Africa is calculated using table 1.4, it can be concluded that this would be 3.65 people per household in the year 2006, while this figure in the year 2002 was almost 3.97 people per household. In 2004 it was 3.80 people per household. Out of this it can be concluded that the trend is that households are becoming smaller every year.

Provinces	Total population (Thousand)					Number of households (Thousand)				
	2002	2003	2004	2005	2006	2 002	2 003	2 004	2 005	2 006
Western Cape	4 344	4 446	4 547	4 652	4 745	1 139	1 212	1 228	1 283	1 323
Eastern Cape	7 002	7 017	7 030	7 040	7 052	1 681	1 682	1 651	1 732	1 729
Northern Cape	885	891	897	903	911	236	235	236	243	240
Free State	2 929	2 939	2 947	2 953	2 959	795	822	844	858	849
KwaZulu-Natal	9 424	9 505	9 581	9 655	9 732	2 189	2 328	2 380	2 457	2 589
North West	3 747	3 775	3 801	3 825	3 858	975	989	1 022	1 033	1050
Gauteng	8 498	8 674	8 848	9 029	9 211	2 475	2 712	2 747	2 983	3 032
Mpumalanga	3 154	3 178	3 200	3 221	3 252	768	813	805	793	797
Limpopo	5 550	5 580	5 608	5 636	5 671	1 222	1 248	1 283	1 345	1 362
Total	**45 533**	**46 007**	**46 459**	**46 913**	**47 391**	**11 479**	**12 041**	**12 194**	**12 726**	**12 972**

Table 1.4: Population and households in South Africa per region (StatSA, 2006)

The future needs to be projected to get to know how many households will be living in certain conditions up to the year 2030, like urban or rural, high or low income, electrified or not-electrified.

	2001	2005	2010	2015	2020	2025	2030
UHE	4 074 438	4 319 029	4 624 768	4 930 508	5 236 247	5 541 987	5 847 726
ULE	1 255 728	1 416 680	1 617 870	1 819 060	2 020 250	2 221 440	2 422 629
ULN	1 349 240	1 174 661	956 436	738 212	519 988	301 763	83 539
RHE	1 181 279	1 268 071	1 376 561	1 485 050	1 593 540	1 702 030	1 810 520
RLE	1 095 449	1 256 511	1 457 839	1 659 167	1 860 494	2 061 822	2 263 150
RLN	2 249 571	2 001 717	1 691 899	1 382 082	1 072 265	762 447	452 630

Table 1.5: Projection of household numbers up to 2030 (Winkler et al., 2006)

Winkler et al. (2006) divided the South African population into 6 groups:

UHE = urban higher income electrified household
ULE = urban lower income electrified household
ULN = urban lower income non-electrified household
RHE = rural higher income electrified household
RLE = rural lower income electrified household
RLN = rural lower income non-electrified household

Table 1.5 indicates that the number of electrified households in both urban and rural areas will increase. So, the number of households without electricity will drop significantly. When the year 2001 is compared to the year 2030 it becomes clear that 6.68 million households live in *urban* areas where this number is expected to increase to 8.35 million households in 2030. In the *rural* areas in 2001 about 4.53 million rural households were habituated; this number is expected to stay about the same up to the year 2030 according to Winkler et al. (2006).

The trend for South Africa is expected to be that the population growth rate will stabilize and will not grow fast anymore because of the impact of the AIDS-virus. According to the data presented by Barings (1999), most AIDS-related deaths are likely to occur between the age of 25 to 45 years. As a result, AIDS not only lessens life expectancy and the rate of population growth, it will also increase the load on the working age population, who will be required to care for the young and the sick (Arndt & Lewis, 2000). Here it should be noted that three factors play a role in the increase of households: migration from rural to urban, decrease in size of households, and a small increase in population because of the AIDS-virus.

All of these factors play a role in the electrification of households. The number of rural houses without electricity will decrease thanks to the electrification programmes that will be discussed in paragraph 1.3.2 in this report.

1.3 Electricity in South Africa

1.3.1 General considerations on electricity in SA

Electricity consumption in South Africa has been growing rapidly since 1980 (www.eia.doe.gov, 2007). The generation is mostly coal-fired, and largely under the control of the parastatal company Eskom. Unfortunately, not all places in South Africa can be supplied with grid electricity yet; therefore alternatives are to be considered in those areas in order to fulfil the requirement of ‘electricity for all’ in 2014 (DME, 2006). These areas can, for example, be remote villages not connected to the national electricity grid (Carette et al., 2000). The community survey of 2007 indicated that 80% of the South African population is electrified. This means that in theory 80% of the population should be able to get connection to electricity but in practice lots of people cannot afford to use the electricity because their income is too low as discussed in paragraph 1.2.

South Africa generates over half the electricity used in Africa. This production is dominated by the parastatal company Eskom which generates 93.5% of the total production (NER, 2001). Municipal generators and certain industries like pulp mills, sugar refineries, Sasol, and Mossgas also generate small amounts of electricity. Eskom has a licensed capacity of 42011MWe which includes 3541MWe of non-operating (mothballed) coal power stations (Eskom Annual report, 2005). The mothballed stations are brought on stream now in order to be able to fulfil demand if necessary in the next few years (most likely necessary very soon). Table 1.6 shows the current licensed capacity of Eskom coal power stations. Appendix 2 will provide conversion factors on electricity. Furthermore SA has some renewable energy sources like hydropower. This one will be discussed in paragraph 1.3.3 on the renewable energy sources.

Coal-fired stations	*Number of units x unit capacity*	*Nominal Capacity (MWe)*	*Total net Capacity (MWe)*	*First unit commissioned*	*Cooling*
Arnot, Middelburg	6 x 350	2 100	1 980	1971	Wet
Camden, Ermelo	8 x 200	1 600	Mothballed	1966	Wet
Duvha, Witbank	6 x 600	3 600	3 450	1980	Wet
Grootvlei, Balfour	6 x 200	1 200	Mothballed	1969	Wet
Hendrina, Hendrina	10 x 200	2 000	1 895	1970	Wet
Kendal, Witbank	6 x 686	4 116	3 840	1988	Dry
Komati, Middelburg	5 x 100; 4 x 125	1 000	Mothballed	1961	Wet
Kriel, Bethal	6 x 500	3 000	2 850	1976	Wet
Lethabo, Sasolburg	6 x 618	3 708	3 558	1985	Wet
Majuba, Volksrust	3 x 657; 3 x 713	4 110	3 843	1996	Wet/Dry
Matimba, Ellisras	6 x 665	3 990	3 990	1987	Dry
Matla, Bethal	6 x 600	3 600	3 450	1979	Wet
Tutuka, Standerton	6 x 609	3 654	3 510	1985	Wet
Subtotal coal-fired stations		37 678	32 066		

Table 1.6: Eskom licensed capacity in coal (Eskom, 2005; Winkler et al., 2006)

By 2008/2009 regional electricity demand is expected to exceed supply capacity, and South Africa's power exports are already being shortened in order to be able to fulfil their own country's demand (DME, 2006). To produce electricity in a renewable way and provide extra energy, the 'White Paper on Renewable Energy' has been constructed in 2003. It sets a target of 10,000GWh of energy annually to be produced from renewable energy sources by the year 2013, which is 4% of the estimated generation in 2013, which would require 3 805MW capacity; assuming a 30% availability factor. This availability factor is important because renewables are not always available (e.g. wind power). The renewables will mainly consist of biomass, wind, solar and small-scale hydro, but the biomass usage by the residential sector will be excluded because of its negative impact on health and environment when this is used in a non-sustainable manner by mostly poor households.

The forecasted increase in electricity demand is shown in figure 1.4 by Haw & Hughes (2007). The forecasted increase in electricity demand is in line with that of the high growth rate scenario considered in the National Integrated Resource Plan (NER, 2004). The demand for electricity will increase the most in the industrial sector, even though all sectors see electricity demand double up to the year 2030. Electricity demand in the agricultural and commercial sectors is expected to go up by 144% and the industrial and commercial sectors demand is expected to increase by 200% over the period (Haw & Hughes, 2007).

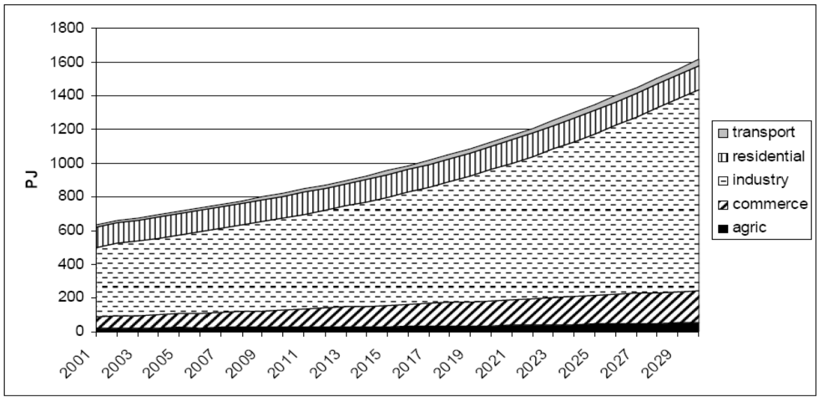


Figure 1.4 Electricity forecast by sector (Haw & Hughes, 2007)

Appendix 3 (Winkler et al., 2006) shows a forecast of electricity capacity per type of plant (in GW) up to the year 2030. In this table it seems like the capacity of coal decreases but this will be compensated with new coal through which the total amount will increase in time as can be viewed in appendix 3. The fifth appendix comprises the losses in electricity due to the great distance between the place of electricity generation and the demand. Also in this appendix the losses of electricity in switches and transformers are included which all have their own efficiency rate through which at the end considerable electricity losses can occur. (e.g. up to 40%, depending on the distance and the material of the cable which determines the Ohmic losses per meter and the number of switches used). Appendix 2 will provide basic formulas and discusses the use of DC versus AC. Furthermore appendix 5 discusses the use of high voltage DC lines that have a higher efficiency than high voltage AC power lines and it provides also a table that shows the different kind of power lines used in SA to transport electricity to all grid connections.

1.3.2 Rural electrification of SA

National electrification programme

During the apartheid period energy policies were generally centred on energy security due to the political isolation of the country. After the beginning of democracy in 1994, energy policies were concentrated on the injustices faced by the (mostly black) majority of the population who had previously been denied basic services; equity and justice were therefore the primary goals for that time period. Economic scenario studies in 1990 led to the identification of household electrification as a stimulus for national development (Gaunt, 2002). The concept was adopted by the national utility (Eskom) and the municipal electricity utilities as the “Electricity for All” programme in 1991, and given widespread support during the emerging political normalization after 1992. The new government adopted the programme as the “National Electrification Programme” (NEP) in 1994. Phase 1 of this programme was completed in 1999. The targets were to electrify 2.5 million households on top of the 3 million that already had been electrified. This would bring the national proportion of electrified households at that time up to 66%. The period after 2000 concentrates on trying to achieve targets set by the government after 1994. These targets concern e.g. job creation, economic security, and recognition of a sustainable manner to protect both local and global environments. Phase 2 of the National Electrification Programme has started to electrify every household up to the year 2014.

Up until the year 2000 the NEP was funded mainly by Eskom, either through internal subsidies or through transfers to an electrification fund that the National Energy Regulator (NER) allocated to municipalities. More than R8billion has been spent on the programme between 1994 and 1999. Per connection or household the average cost has been around R3,200 (NER, 2001). The electricity industry has been able to fund and cross-subsidize this massive electrification programme largely because there is a major industrial customer base that accounts for the main part of the electricity sales.

Electrification rate

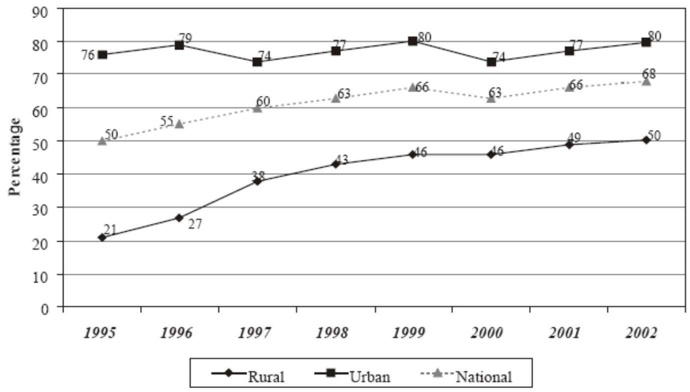


Figure 1.5: Trends in electrification of households in South Africa (NER, 2003)

Figure 1.5 shows that at the end of 2002, nationally 68% of the households in South Africa have been electrified. The trend of the graph is in accordance with the predictions from 2001 (NER, 2003). To determine the number of households connected to the electricity grid is not easy, mainly because of estimating the number of households. Figures on the number of households are provided by Statistics South Africa (Stat SA). The decrease in percentage of people electrified is explained by the transfer to another database by the General Household Survey (GHS) institution (GHS, 2006).

	Electrification rate	*Population without electricity*	*Population with electricity*
	%	*million*	*million*
South Africa	66.1	14.5	28.3
Africa	34.3	522.3	272.7
Indonesia	53.4	98.0	112.4
Developing countries	64.2	1 634.2	2 930.7
OECD	99.2	8.5	1108.3
World	72.8	1644.5	4 390.4

Table 1.6: Global electrification rates in 2000 (IEA, 2002)
OECD= Organization for Economic Cooperation and Development, (Well developed countries)

When South Africa is compared to other countries in the year 2000 it can be concluded that it was below the world average regarding electrification. In 2004 the electrification rate was already up to 71% (WBCSD, 2006) and in 2007 this went up to 80% for lighting (CS, 2007). Nowadays the rate of electrification in South Africa is already higher than the world's average electrification rate in 2000: 72.8%.

Figure 1.6 indicates where the rural and where the urban areas can be found. From this it becomes clear that the provinces Eastern Cape and some places of KwaZulu Natal are the ones with the most rural places (appendix one contains a map of SA where the provinces and main cities are indicated). In these dark colour areas the electrification rates are lowest.

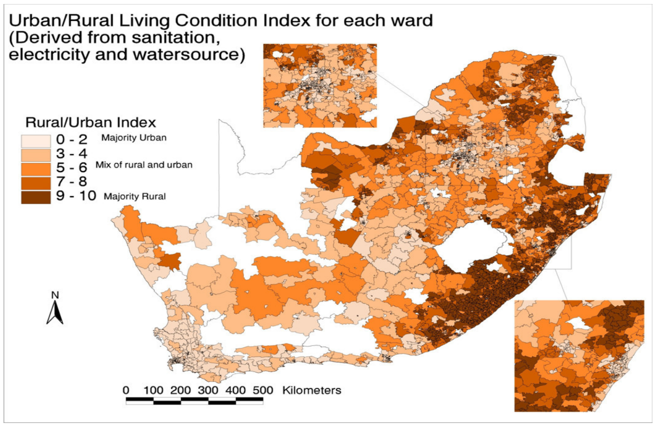
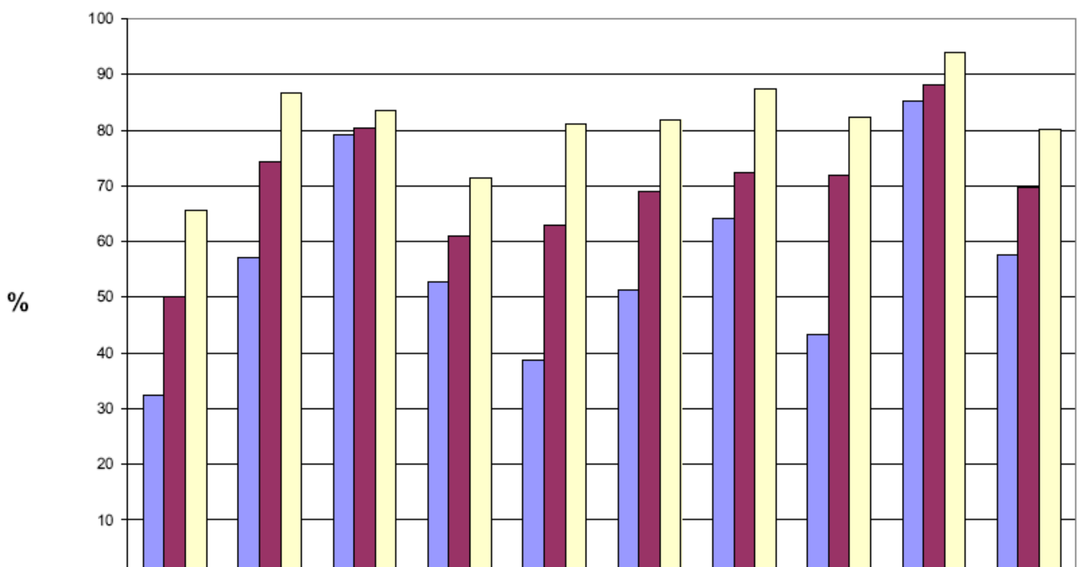


Figure 1.6: Urban/Rural living condition index (Hall, 2002)

The number of *rural* households electrified in South Africa has risen from 12% in 1994 to about 51% in 2004. According to available statistics by StatSA (2006) there are 12.97 million households in South Africa of which 7.5 million were electrified at the end of 2003, and 10.4 million by 2006. This brings the level of electrification in South Africa to about 80.2% by the year 2006. From figure 1.7 it furthermore becomes clear that the electrification of the Eastern Cape province is the lowest at this moment although progress is made rapidly. Remarkable is the slow growing number of connections in Gauteng province.



	Eastern Cape	Free State	Gauteng	KwaZulu-Natal	Limpopo	Mpumalanga	Northern Cape	North West	Western Cape	South Africa
Census 1996	32,4	57,1	79,1	52,6	38,7	51,3	64,2	43,3	85,2	57,6
Census 2001	50,0	74,4	80,4	60,9	62,9	68,9	72,4	71,8	88,0	69,7
CS 2007	65,5	86,6	83,5	71,5	81,0	81,7	87,3	82,3	94,0	80,0

Figure 1.7: Electrification for lighting per province over time (CS, 2007)

In order to provide electricity CGIS.gov.za (2007) states that the DME's policy is that electricity, for at least lighting, is to be attained by everyone by the year 2014 in whole South Africa. DME's (2007) main policies considering electricity are:

- Attaining universal access to electricity by 2014 (either grid or non-grid connection);
- Accessible, affordable and reliable electricity, especially for the poor;
- Diversifying primary energy sources and reducing dependency on coal;

- Good governance, which must also facilitate and encourage private-sector investments in the energy sector; and
- Environmentally responsible electricity provision.

Poverty tariff

Cassim and Jackson (2003) discuss that it has been national policy that the capital cost of new connections should be subsidized. However, there have also been unexpected disappointments in costs and revenues from operating costs. At the beginning of the electrification programme, it was estimated that the average monthly consumption of newly connected, low-income households would be around 350kWh per month (compared to a middle-income family in SA that consumes 750kWh per month). In practice however the average monthly consumption has been around 130kWh and some only consumed 50kWh. Prasad and Ranninger (2003) found in their research similar amounts of 100kWh per month on average for low-income households. This is why few of the new electrification schemes are financially viable; now, or even in the long term. Government has decided to grant 50kWh per month for free to poor consumers who accept load-limited supplies, this concept is also known as the 'poverty tariff'.

Many municipalities already introduced free monthly electricity between 20 and 100kWh since 2001 (Winkler et al., 2006; DME, 2003). The grant is made from South Africa's National Treasury and is allocated to local governments. The problem that remains in the electrification programme is that lots of people can neither afford the electricity use (on top of the 50kWh) nor the capital costs of electrical devices to be connected to it. If either (or both) of these would be subsidized this could mean that households could replace the coal or paraffin for electricity which actually will be cheaper for them on the long term, thus saving them money and also making the connection to the grid financially worthwhile for Eskom. But it is the question where the extra subsidy should come from. This shows that the supply side (mostly by Eskom) has different expectations than the end-users. The end-users do not have much money to spend on electricity; the money they do spend on electricity, they would like to get most effort out by using fuels they think have best efficiency. Appendix 4 shows us an overview of different types of housing and the fuel they use for three purposes: cooking, heating, and lighting. This overview shows indirectly how little electricity some people can afford. Therefore the poverty tariff was created.

Rural electrification example: Lucingweni

An example of the use of electricity in rural settings is provided by Rogers et al. (2007). This research used a case study approach focused on a mini-grid in Lucingweni, Eastern Cape, SA. Table 1.7 shows clearly where the electricity is used for and how much power is consumed. Furthermore, the distinction between AC and DC use is shown. The Lucingweni mini-grid is a solar and wind hybrid powered rural energy station. Solar panels and wind turbines generate DC electricity which needs to be converted to AC before it can be used for certain appliances. When DC can be used directly this is preferred because the transformation AC to DC has an efficiency of 85% as is shown in table 1.7:

Category and sub-category of power applications	No	Unit power (AC W)	Duration (hrs)	AC (kWh/day)	DC (kWh/day)	Sum per Category	
						AC kWh/day	DC kWh/day
Houses	220						
Lights	4	15	4	52.8	62		
Radio	1	10	10	22	26		
TV	1	70	5	77	91		
Decoders	1	40	5	44	52		
Cell charger	1	10	2	4.4	5	200.2	235.5
Street lights	70	26	7	12.74	15	12.7	15.0
Community centre	1						
Lights	10	15	8	1.2	1.41		
Telecom	3	40	5	0.6	0.71		
Plugs	10	200	8	16	19	18.8	22.1
Drinking water							
Pumping	3	2000	5	30	35	30.0	35.3
Power Generator System	1						
Logger	1	20	1	0.02	0		
Telecom	1	10	1	0.01	0.01		
Lights	3	45	1	0.135	0.16		
Security	1	10	24	0.24	0.28	0.4	0.5
Shops	4						
Lights	8	15	10	1.2	1.41		
Refrigeration	4	100	8	3.2	3.76	4.4	5.2
Total				**266.5**	**313.6**	**266.5**	**313.6**
Conversion efficiency from DC to AC						**0.85**	

Table 1.7: Lucingweni electricity use (Rogers et al., 2007)

1.3.3 Alternative energy sources in SA for electricity

Some of the alternative energy sources that could be considered as alternatives to coal are: nuclear energy, gas turbines, pumped storage, fuel cells, or renewables such as bio-fuels (for electricity), photovoltaic systems or wind- or hydropower. Table 1.8 indicates current amount of energy sources Eskom uses for electricity generation besides coal.

The data quality for some of the annual renewable energy consumptions is poor and the data presented are estimates since the accuracy cannot always be verified because they are not connected to the national grid (Winkler et al., 2006). DME (2006) estimates the current used wind energy to be around 32GWh and solar energy about 532GWh annually (see appendix 2 for conversion factors).

There are other sources of energy, which are distributed either directly or indirectly all over the country such as landfill gas with a potential of 7.2TWh of electricity generation, which is estimated, to grow to 10.8TWh by the year 2040 (DME, 2006).

Pumped storage systems are e.g. artificial lakes that will be filled using overcapacity. The electricity will be used to propel pumps and transport water to a higher place. When extra electricity is needed water from this lake can propel turbines to produce electricity.

Gas

Gas turbines use gas that e.g. is produced in Mozambique and transported via a pipeline or from Mossgas generated in Mosselbay, SA. South African companies do not produce much natural gas, therefore the use of natural gas is not stimulated. SA does not have a large gas pipe network as e.g. the Netherlands have. This is why it is not common to use natural gas for heating and cooking. However LPG, mostly sold in bottles, is used sometimes for these purposes. It is most common to use electricity for both when electricity is available and affordable.

Coal-fired stations	*Number of units x unit capacity*	*Nominal Capacity (MWe)*	*Total net Capacity (MWe)*
Gas turbine stations			
Acacia, Cape Town	3 x 57	171	171
Port Rex, East London	3 x 57	171	171
Subtotal gas turbine stations		342	342
Hydroelectric stations			
Colley Wobbles, Mbashe River	3 x 14	42	
First Falls, Umtata River	2 x 3	6	
Gariep, Norvalspont	4 x 90	360	360
Ncora, Ncora River	4; 1 x 1,3	2	2
Second Falls, Umtata River	2 x 5,5	11	11
Vanderkloof, Petrusville	2 x 120	240	240
Subtotal hydroelectric stations		661	600
Pumped storage schemes			
Palmiet, Grabouw	2 x 200	400	400
Drakensberg, Bergville	4 x 250	1 000	1 000
Subtotal pumped storage		1 400	1 400
Nuclear power station			
Koeberg, Cape Town	2 x 965	1 930	1 800

Table 1.8: Eskom licensed capacity other than coal (Eskom, 2005; Winkler et al., 2006)

Nuclear energy

The South African government has its intention to develop all available energy sources, including nuclear (Mlambo-Ngcuka 2002a, 2003, 2004). The country currently has one nuclear light-water reactor at Koeberg near Cape Town (1840 MW), but Eskom is also developing the pebble-bed modular reactor, which entails further development on an earlier German design (Loxton, 2004). The designers claim that it is ‘inherently safe’ since it uses helium as the coolant and graphite as the moderator (PBMR Ltd, 2002). It can be produced in small modular units of 165MW, thus overcoming redundancy constraints associated with large conventional nuclear stations (DME, 2006). Due to its modular design, construction lead times are expected to be shorter. The fuel consists of pellets of uranium surrounded by multiple barriers and embedded in graphite balls (‘pebbles’).
In February 2007 an announcement was made to build a second conventional nuclear system close to the existing one in Koeberg to keep up with the demand for electricity near Cape Town. The new plant is supposed to generate 1000MW and it is planned not to interfere the introduction of the

PBMR. Research around the PBMR will continue and it will take at least 8 years before the PBMR becomes commercialized (Campbell, 2007).

Renewable energies

Other energy sources applied in South Africa to produce electricity are solar energy systems like photovoltaic or wind powered, or other energy sources such as biomass or hydropower that could be used to produce electricity as well. These will be discussed one by one.

Biomass

Kenny (2006) states that the historical trend in both the world and South Africa is that more and more people use modern fuels as electricity and gas instead of traditional fuels like wood and dung. The trend in South Africa is that people move to urban areas searching for work. This would suggest that the use of biomass for households would decline but this is not (yet) the case. Often people who have moved to the city end up in poverty and still use biomass as their main source of energy for cooking. Kenny (2006) estimates that 87PJ of wood is used by the poor for cooking, mainly in rural areas and informal settlements. Appendix 4 gives an overview of which fuels are used in particular settlements for cooking, heating, and lighting. This appendix indicates that for cooking paraffin is used most often in informal dwellings and traditional dwellings. For heating these groups rather use wood than paraffin.

Industry uses a small but significant amount of biomass: about 2 million tons of sugar is made from 20 million ton sugar cane crops. About 7 million tons bagasse is produced from the 20 million tons sugar cane; some is used for paper but most is used in sugar refineries to produce steam for electricity generation and to process heat. Pulp mills use biomass to generate electricity while burning sawdust and bark to heat boilers and generate about 170MWe.

Solar

Another energy source to produce electricity is the use of solar energy systems like photovoltaic (PV)-systems. The southern African region, and in fact the whole of Africa, has sunshine all year round. DME (2007) states that the annual 24-hour solar radiation average is about 220 W/m2 for South Africa; compared to about 150 W/m2 for parts of the USA, and about 100 W/m2 for Europe. Most areas in South Africa average more than 2,500 hours of sunshine per year, and average solar-radiation levels range between 4.5 and 6.5kW/m2 (0.19-0.27kWh/m2) in one day. This makes South Africa's resource one of the highest in the world.

Solar power is not (yet) used to provide electricity to the national grid. Mainly this source of energy is used in rural areas that are not connected to the national power grid. In South Africa it is estimated that about 70,000 households, 250 clinics and 2,100 schools have photovoltaic panels (Kenny, 2006). Eskom is exploring the potential of grid electricity from solar and wind power. It initiated the South African Bulk Renewable Energy Generation (SABRE) programme in 1998, and in 2002, installed a 25kW solar dish with a Stirling engine at the Development Bank of Southern Africa premises in Midrand (Eskom, 2004). Eskom is studying the feasibility of building a 300MWe solar thermal power station near Upington in Northern Cape. If this one would be built, this station would have three 100MWe units (Eskom, 2004).

Several tryouts have been done in SA to electrify rural places using ‘solar home systems’ (SHS) but this was not always a success. Partly this was caused by neglecting to look at what customers would like to use the system for. Furthermore people just got the systems without being told what it was for or how it works.

Wind

Wind energy is a potential source of commercial energy in some parts of South Africa, but like other renewable energy technologies it is hard to compete to the lower costs basis of conventional electricity; in particular South Africa's cheap coal. Furthermore there are not that many places in SA where windmills can be used in an economical viable situation.

South Africa's best wind resources are to be found mainly in the coastal regions. So far, no electricity in the national grid is generated from wind. Wind always has been important as a traditional source of energy, and continues to be, for mechanically water pumping, and small-scale electricity on farms in rural areas. Most of the small windmills operate mechanically to pump water out of a well as fresh water for cattle or irrigation.
In 2003, Eskom installed two 660kW wind turbines and a 1.7MWe one at Klipheuvel in the Western Cape as part of its SABRE programme of demonstration and research. An independent group, Darling Independent Power Producer, proposed to develop a 5MWe Darling Wind Farm, also in the Western Cape. It has been licensed by the National Electricity Regulator and approved after an environmental impact assessment (EIA) had been performed recently.

Station	Maximum capacity (MW)	Location
Gariep	360	Orange River
Vanderkloof	240	Orange River
Colly Wobbles	42	Mbashe River
Second Falls	11	Umtata River
First Falls	6	Umtata River
Friedenheim	3	
Lydenburg	2	Ncora River
Ncora	2	Ncora River
Piet Retief	1	
Ceres	1	
Total hydro capacity	668	

Table 1.9: Conventional hydro electricity in South Africa (DME, 2006)

Hydropower

South Africa has 668MW of domestic installed conventional hydropower (table 1.9) and 1400MW pumped storage. Because of the scarcity of water, which is characterizing the country, some hydropower is imported from neighbouring countries. The amount of total hydropower equals to 2% of the national electricity supply in South Africa.

Hydropower is in lots of countries an important contributor to the amount of 'green' energy. However, SA is relatively dry and has only few rivers that can be used for generating electricity. Another option could be to use the waves produced by the sea. Several options to use e.g. waves or underwater turbines are currently in research. The potentials for these options are gigantic because waves and current could generate electricity continuously. Wave energy *potential* is estimated to yield up to 70TWh per year (DME, 2006). Especially the wave and current energy might be interesting for SA because SA has a large coastline.

Fuel cells

Fuel cells could contribute to the electrification of rural places in SA because they can operate locally in a decentralized way. Because it can be very expensive to set up grid connections it might be cheaper to use alternatives in these areas. Fuel cells can be used per household but even small local mini-grids can be accomplished. The bigger the demand for electricity the bigger the capacity needs to be. Appendix 6 will handle all sorts of fuel cells and provides information about what they are and appendix 7 specifies the fuels they use. Fuel cells are not always renewable energy sources because some produce carbon dioxide which is one of the GHGs. Some however only produce pure water as exhaust e.g. PEMFC. Appendix 6 will tell more about this.

Because FCs can contribute in bridging the gap between electrified and non-electrified houses in rural households in SA, FCs could fit into the power sector of SA. This will contribute to reaching the goal set by government to electrify all households by the year 2014. However, the use of electricity in South African households should be split for different purposes when analyzed because capacity plays a prominent role during the electricity generation. Some purposes demand a lot of energy e.g. cooking and heating. When electricity would be used for these two, demand grows significantly. It would be more efficient to use the fuel directly or to use other clean energy sources e.g. LPG. If for some reason it is decided to use a FC for these purposes it is recommended using a different kind of FC than PEM or AFC having a higher capacity (discussed in appendix 6 on fuel cells). This is because these purposes will significantly increase the amount of kW needed per household. So, the maximum number of households connected to one system will decrease significantly as well, or in the case of a FC per household the system should become significantly larger.

1.4 CSIR and its fuel cell research

CSIR is the abbreviation of Council for Scientific and Industrial Research. The CSIR is a parastatal company and it is situated in several places in South Africa; its largest site is located in Pretoria. Nationally, in 2007, the CSIR employed 2170 employees. At the Pretoria site 1821 people are working of which 1452 are staff members and 369 are temporary. The Pretoria site has eight research areas; one of the research areas is in Material Science and Manufacturing (MSM). This area has several competency areas and one of them is in Energy and Processes. The research in FCs is part of this focus group. As late as 2004 CSIR decided to start its research in FCs. It all started with a literature study and the first actual research is performed in 2005. The main interest at that moment is in Proton Exchange Membrane FCs (PEMFCs) because internationally these are developed farthest and these offer highest promise for commercial success. CSIR now also is becoming interested in another ‘new’ kind of FC based on hydroxy-ion exchange in an alkaline medium instead of proton exchange using alcohol as fuel. This new kind of Alkaline Fuel Cell (AFC) is fuelled directly by alcohol. This type will be called Direct Alcohol Alkaline FC (DAAFC) during this report because there is no official standard name for this type in the market or literature yet. In appendix 6 this (concept) type of FC will be explained further. Because the DAAFC is (globally) still in its infancy CSIR is hoping to contribute to achieve breakthroughs to put SA on the ‘map’ considering research in FCs.

CSIR would like to continue its research in FCs in the future because FCs might be one of the pathways to a more sustainable energy use in the future of South Africa. FC systems are already produced in other countries by lots of companies; large companies are for example in Canada ‘Ballard Power Systems’ and in the USA ‘Plug Power’. In South Africa there are a few companies in maintaining and distributing FCs i.e. the ‘IST Holding’ and ‘Intelligent Energy’. Furthermore there are several research companies active in optimizing and finding new technologies for better performing FCs. CSIR is one of those research companies. In order to get an idea where to aim for in the future, the idea came to develop a first-cut Technology Roadmap. The concept of Technology Roadmapping will be discussed in chapter two.

Because CSIR is parastatal it has a certain obligation towards government. The CSIR formulated a mandate to keep up with this obligation: "The objects of the CSIR are, through directed and particularly multi-disciplinary research and technological innovation, to foster, in the national interest and in fields which in its opinion should receive preference, industrial and scientific development, either by itself or in co-operation with principals from the private or public sectors, and thereby to contribute to the improvement of the quality of life of the people of the Republic [of South Africa], and to perform any other functions that may be assigned to the CSIR by or under this Act." (http://www.csir.co.za/csir_mandate.html, December 2007). This indicates clearly the drive of the CSIR to comply with the needs of government. Government demands in its national electrification programme that all households of SA should be able to use electricity for at least lighting by the year

2014. CSIR is contributing to fulfil the requirements set by government by researching the options of electrification using local fuel cells.

The CSIR is mostly active in R&D. When a certain technology is tested in labs and proven to be valuable, the technology will be sold to other companies for further development by companies in the value chain or by spin-offs of CSIR. The goal of the CSIR in FCs is to develop new or improved technologies that will result in better performing FCs. When a breakthrough is done, CSIR will try to get a patent to protect other companies from copying it. Furthermore, CSIR will publish a paper in a well known magazine to promote and share their findings. CSIR eventually will try to sell the new or improved technology to FC manufacturers.

When a (new) technology is to be developed as is the case at the CSIR, a certain strategy is to be followed while developing. The tool of Technology Roadmapping (TRM) is a general tool for such an introduction. It is a flexible tool which is often used in product development and some times in technology development, more about this will be handled in chapter two. Because the tool is very flexible it is researched whether it could be utilized in an R&D institution as would be the case at the CSIR. However, the research group in FCs has no experience in utilizing this tool. This might be because the tool has not (often) been used in R&D settings before as becomes clear from literature. The properties the tool possesses like the use knowledge of multiple disciplines (see chapter two and three) could be one of the reasons to investigate the added value of using the tool of TRM in the FC focus group. The overall goal of the tool will remain to set a path for (further) developments of FCs into the future.

1.5 Research questions

South Africa has about 12.5 million households and about 20% of these households (2.5 million households) are not yet connected to the electricity grid (Community Survey (CS), 2007). By the year 2014 every household in SA should have access to electricity due to the National Electrification Programme started in 1994. It is very costly to get every household connected to the national power grid and therefore alternatives to grid electricity are considered in some rural areas. This is why alternatives like local stationary FC stations fuelled by hydrogen or alcohol to produce electricity should be considered as alternatives to connection to the power grid. This research will focus on the electrification of households not yet connected to the power grid.

Furthermore, it will be researched whether the research and forecasting tool of Technology Roadmapping (TRM) can be applied in R&D settings. The tool will be discussed and evaluated for its use in this research.

Therefore the main research questions that underpin this report are:

1) *What are the main considerations for implementing fuel cells for stationary applications in remote areas of South Africa and what would be the technology roadmap for such implementation?*
2) *What are the benefits and constraints of utilising the Technology Roadmapping tool in the context of an R&D institution, which considers technologies for remote market settings; what aspects are considered to be useful and what not?*

The first question implies the view from a national perspective as well as the view internally from the CSIR to implement FCs in remote areas. The second question is made from an academic point of view, to evaluate the tool of TR in R&D settings. It is to be evaluated what 'good' and what 'bad' aspects the tool possesses when it is used in a R&D perspective and modify the tool for usage in a R&D institution context.

1.6 Research strategy

The research started with a literature review. From this it became clear that hardly, if any, studies have been performed in electrifying remote areas using FCs. However, alternative energy sources like solar systems have had pilot projects; see paragraph 1.3.2 and 1.3.3.

The tool used during this research is the tool of TRM. The tool has been modified to fit a first time use in a R&D institution, the CSIR, as will be handled in chapter three. There it will be discussed that the number of contact days is reduced to only half a day. To be able to discuss all subjects during the workshop the strategy was to pre-interview all and afterwards set individual prioritizations. The outcomes of all of these three formed the input for the final TR.

After the literature review on the tool of TRM, the tool was adapted to be used in the CSIR context as is shown in figure 1.8. This literature research formed input for multiple stages in the process: the pre-interviews, the workshop, and the TR.

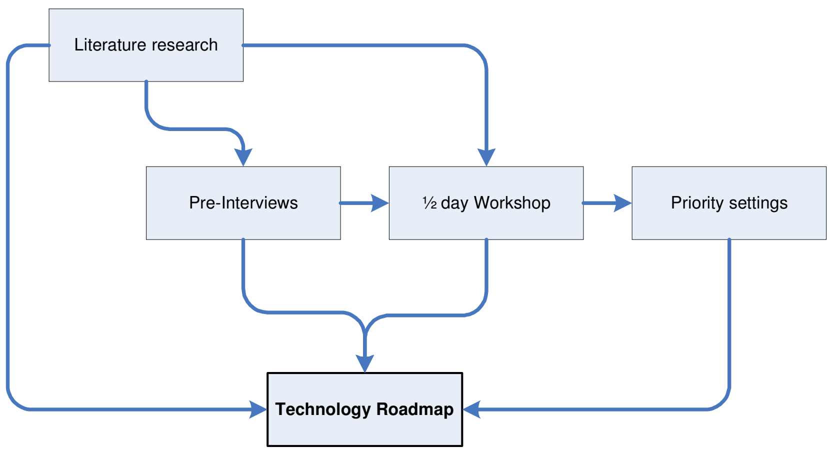


Figure 1.8: Research strategy of modified TRM process

2. Technology Roadmap review

2.1 Basics of Technology Roadmapping

Technology Roadmapping (TRM) is an extremely flexible and powerful technique for supporting strategic planning and can be adapted to many strategic situations. This flexibility can be considered as both a strength and a weakness in that it can be applied in many contexts but often has to be customized in order to fit particular applications. This tool is so much customizable that it can be applied in almost any company. The tool was originally developed in the 1970s by Motorola, and later the University of Cambridge developed the T-plan to fast-start the process of TRM in a cost effective manner (Phaal et al., 2001c). The TRM-process aims to make maximum use of time committed by senior management and participants to rapidly produce a first-cut Technology Roadmap (TR) that clearly links technology development and acquisition to business drivers and strategy.

Roadmapping is different than other modern graphically based management tools as e.g. the Programme Evaluation Review Technique or PERT network (Wiest and Levy, 1977). A PERT network can be used for scheduling complex projects. The software will calculate diverse time estimates for completing project activities, and is very sophisticatedly built. Unlike roadmapping, Petrick and Echols (2004) state that PERT-networks are not a forecasting or enterprise integration tool. PERT-networks and Gantt-charts are used in the technology roadmap tool, so the process of TRM comprises this and other management tools.

TRM offers a solid framework to integrate market, product, and technology evolution. Firms can use it to collect information from a wide variety of sources. With these resources they can develop dynamic near-, mid-, and long-term plans for R&D investments as well as new product and process developments. Petrick and Echols (2004) argue that within a company, this tool could integrate what is known at all levels of the firm into a framework that supports strategic initiatives and tactical decisions. In general, roadmaps identify technologies underlying current and planned products and highlight the known technology developments that are expected, and the elements that will be needed to successfully develop these in new products. TRs also identify the underlying R&D investments needed to develop the technologies and to integrate them into a new product and/or system (Petrick and Echols, 2004).

An alternative to the TR-tool could be ‘smaller’ tools to predict the future (forecasting) or tools to reorganize or organize a company (product development, TQM.) The strategic context can be described in terms of a number of dimensions such as the organization’s nature, its goals, the existing processes and procedures, and the available information and resources. In order to fit particular circumstances the approach should match the company needs. The only tool that is slightly similar is the SAILS-tool (Standards, Architectures, Integration, Linkages, and Substitutions). This tool is argued to be specifically suitable in introducing disruptive innovations (Vojak and Chambers, 2004).

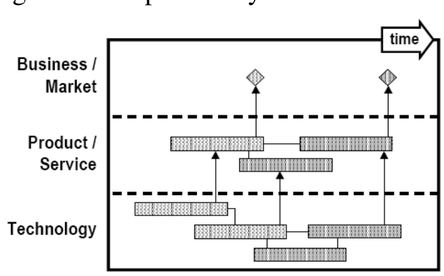


Figure 2.1: Schematic TR, showing typical layers (Phaal et al., 2001)

Phaal et al. (2001) have identified 16 different formats of roadmaps at use in companies. However, all company-based roadmaps possess some common elements which can be seen in figure 2.1: the three layers of market, service, and technology in time. Figure 2.2 is discussed to be the most basic type of TR, relating to the insertion of technology into manufactured products, often including more than one generation of products (Phaal et al., 2001b). Philips for example uses this TR to link planned technology and product developments.

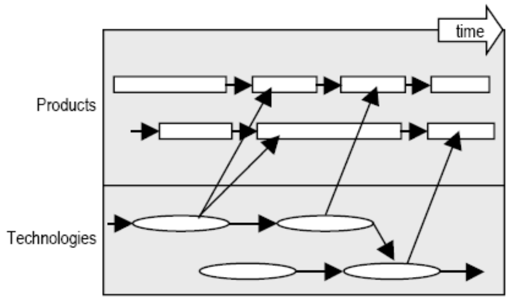


Figure 2.2: Product planning TR (Phaal et al., 2001b)

The University of Cambridge developed the T-plan as a tool to support the rapid initiation of roadmapping in firms in a cost effective manner The TR was developed from the T-plan process and differs through the adoption of a more structured first module and in application to even smaller companies with typically less than 200 people. The TR-process aims to make maximum use of time committed by senior management and participants to rapidly produce a first-cut TR that clearly links technology development and acquisition to business drivers and strategy.

Figure 2.3 represents all steps of a T-plan for a fast start TR developed by the University of Cambridge. A management guide has been written to support the application of the T-plan approach (Phaal et al., 2001c), which aims to:

- Support the start-up of company-specific TR processes.
- Establish key linkages between technology resources and business drivers.
- Identify important gaps in market, product and technology intelligence.
- Develop a 'first-cut' technology roadmap.
- Support technology strategy and planning initiatives in the firm.
- Support communication between technical and commercial functions.

To get all people involved in the same direction the T-plan uses four facilitated workshops. The basis of each TR consists of four sessions of half a day each where standard brainstorming, theming, and prioritizing techniques are used to address the three key layers of the roadmap: Market Environment and Objectives, Product Offering, and Technology. The first three will focus on the three key layers of the roadmap (market / business, product / service, and technology), while the final workshop will bring the layers together on a time-basis to construct the chart, (see figure 2.3).

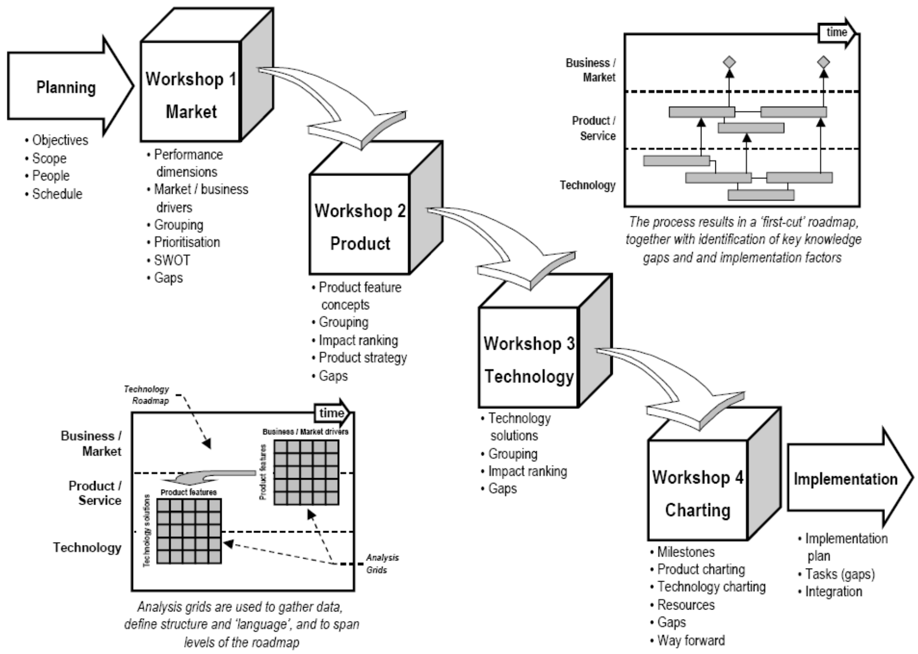


Figure 2.3: T-plan: standard process steps showing linked analysis grids (Phaal et al., 2001b)

After the TR process is performed it is necessary 'to keep the TR alive'. Information is to be updated on a frequent basis in order to keep up with new developments and to prevent having to do the whole, time consuming process, again. At least once a year the TR should be updated thoroughly. Another important aspect is that the TR should be communicated through the department or company so that everybody is aware about the developments and future goals.

The main obstacles in conducting successful TRM as discussed by Lee and Park (2005) are often related to limited resources and the need to have various departments interacting. Interaction between several disciplines within a company is the heart of TR; simple communication between the departments might already improve the whole process and solve minor problems. Customization of roadmapping techniques is one of the solutions suggested by Lee and Park (2005) because every company has its own working habits.

Groenveld (1997) describes TRM as terms of activities of the (usually iterative) way and specification of goals and the 'roads' to get there. TRs mostly try to capture the future of mature technological options, where products, product (and technology) drivers, and the regulation environment are known. There is by now a wealth of literature on TRM of incremental innovation (Albright and Kappel 2003; Barker and Smith 1995; Kappel 2001; Kostoff and Schaller 2001; McCarthy 2004; Phaal et al 2004, 2001a,b,c; Probert and Radnor 2003; Rinne 2004). TRs are in all literature studies notified to be maintained and updated frequently in order to keep their effectiveness in business. When this is done frequently, roadmaps become a powerful tool for creating alignment around technological and product options and to help accelerating their development. There have been earlier attempts at modifying the existing techniques of TR to become better applicable to emerging, enabling technologies, both at industry and research level in science and policy (Walsh, 2004).

2.2 TR of non-mature technologies in R&D settings

Walsh and Elders (2002) argue that most roadmaps today focus on high-tech, dynamic sustaining technologies with a *mature* (sales) base. Few, if any (Walsh and Elders, 2002), TR processes are available for technologies that either have the potential to radically change the way products are currently being produced, or are the foundation for products that might create entirely new industries i.e. future disruptive technologies (Walsh and Linton, 2000).

Lynn et al. (1996) and Walsh (1996) argue that disruptive technologies enable discontinuous innovations, processes, or services to provide exponential improvements in the value received by the customer. While disruptive technologies promise considerable opportunities for early and strong entry into existing and new markets, they also involve a high risk of failure, due to customer resistance (Walsh, 2004). Disruptive technologies are sometimes considered an increasingly costly endeavour with uncertainty of success in a rapidly changing technological environment. However, it is the resulting discontinuous innovations aspect of disruptive technologies and their importance to economic progress that is perhaps more important in modern businesses nowadays. Schumpeter (1934) describes capitalism as an economic system that finds its competitive strength in innovation that creates new demands in new markets while destroying old, existing markets based on older technology. This product innovative activity, which Schumpeter calls 'creative destruction', is clearly driven by what is called disruptive technologies in this report.

Technology roadmapping however *is* done on emerging technologies as becomes clear from literature (Walsh, 2003). Emerging TRs often focus on a single technology that might become disruptive but not necessarily. They describe the way the technology is expected to develop, and they may include project plans to support these developments. Walsh (2004) argues that emerging TRs mainly focus on:

- the development and commercialization of a new or emerging technology
- the competitive position of an organization with respect to that technology forecasting
- how the emerging technology and the organization's competitive position will develop

The result of an emerging TR may be a decision to allocate additional resources to develop the technology to improve a competitive position. The implication in this is that as the technology develops, uses will be found for it. So, along the path into the future the TR needs to be updated frequently in order to stay accurately. Also, literature shows that the main goal of the emerging TR is to secure the competitiveness of the company.

The most common TR however is the product TR. This particular TR is as its name already says, focused on products and the introduction of these in the future. Because this TR is more focused on the introduction of a product, R&D departments are often more involved. This TR identifies, as a function of these needs:

- critical supporting technology areas and their drivers
- technology gaps that must be filled to meet targets
- technology alternatives and information needed to make trade-off decisions
- a plan to develop and deploy appropriate technology alternatives

Although the product TR is the roadmap used most often, several TRs have been constructed for emerging technologies. Mostly these are constructed for the semiconductor industry. TRs have been constructed in nanoelectronics (TR for nanoelectronics: Microelectronics Advanced Research Initiative, 1999) and for the whole sector of semiconductors: ITRS (International Technology Roadmap for Semiconductors, 2003), the NEMI-TR ((National Electronics Manufacturing Initiative TR done in the USA) and the SIA roadmap ((Semiconductor Industry Association, 2003). One of the problems that the 'International Industrial Microsystems and Top-Down Nanosystems Roadmap' (IIMTDNR) group faced while developing their TR was the basic difference between an emerging and disruptive technology which affected the roadmapping process. The emerging TR focuses on a single technology competing against a *single traditional* technology where *disruptive* technologies tend to be a *cluster* of technologies competing against a variety of traditional technology solutions. Walsh (2004) reports in his TR research how in the top-down nanotechnology certain requirements of traditional TR approaches could *not* be met:

- definition of the scope and boundaries of the technology
- specification of technology drivers and their targets for the future
- identification of the (specific) future product that would be the focus of the roadmap

Myers et al (2002) remain sceptical about how disruptive technologies could be forecasted. They find that a disruptive technology acquires maturity by moving through the three stages of proof of concept, establishment of a limited application, and widespread application. Because of the high risk of failing each transition, forecasting the next disruptive technology remains 'an elusive ambition' (Myers et al., 2002, pp. 322-327).

Besides the semiconductor industry emerging TRs have been constructed in the renewable energy sector as well. These TRs mainly function to set targets for the use of renewable energies. Examples of these are the EREC (European Renewable Energy Council, 2007) and the SHERPA (Small Hydro Energy Efficient Campaign Action, 2007). These renewable energy roadmaps set targets for emissions and furthermore provide information on impacts of use of renewables on environment. These roadmaps are mostly large TRs that are constructed over a few years time and include lots of companies' and government's input.

Fortunately for companies who seek to gain competitive advantage, the future is not stable and deterministic. So, in addition to technology improvements that are evolutionary, sustaining and incremental, another, more competitively powerful set of disruptive, radical, and emergent improvements can be expected (Bindito and Frohman, 1981; Martino, 1993). The real challenge for TRM and forecasting, then, is identifying when the discontinuous, the unexpected and the disruptive will occur (Vojak and Chambes, 2004).

2.3 Conclusions on Technology Roadmapping

This literature overview on TRM shows that TRM for mature products is relative normal however to make a TR for a non-mature product is much more complicated. The focus of chapter two was on emerging markets and technologies. For this purpose it is shown that several attempts have been performed in developing TRs but it should be noted that these TRs have been constructed for complete markets; not single companies. These involve all companies active in that market segment in a certain region or country in order to set common goals for further development. How the standard methodology of TRM has been modified in order to involve all parties from all regions is however not discussed in literature. Only the result is provided: the TR itself; not the process.

The literature on emerging TRs discusses the next difficulties:

- defining boundaries of the technology and scope
- setting targets for the future
- identification of the future product properties
- filling technology gaps
- technology alternatives
- company's competitive position

In order to overcome these issues the standard TRM tool needs to be modified. If a TR should be developed on an emerging or disruptive single technology, the TR process needs to be adapted because then the issues provided above are to be overcome as well as the addition of even more uncertainties regarding future unstable developments. However no relevant literature has been found in adapting the 'normal' process of TRM in this case. The *process* of adapting the 'normal process' of TRM into a modified version of TRM for a single and radical technology needs to be investigated further in order to become more reliable. Next chapter will provide details of the modifications to the standard TRM process to be able to use the tool of TRM in developing a first-cut TR in a R&D institution.

3. Research methodology

3.1 The choice of research methodology

The research performed was conducted using an explorative case study methodology as described by Yin (2003). Most of the research is explorative; however it started with a descriptive character in the beginning of the introduction. Yin (2003) argues that research not necessary needs to be solely descriptive or explorative; therefore it was chosen to first provide some more feedback on the electricity supply and population of SA. The rest of the research is considered explorative because the main goal was to explore how the path of introducing of FCs was to be set. Secondly it was to be explored how the tool of TRM was to be modified in order to become useful in R&D settings. A case study is defined by Yin (2003, pp. 13-14):

> "..an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident…[It also] copes with the technically distinctive situation in which there will be many more variables of interest than data points, and as one result relies on multiple courses of evidence, with data needing to converge in a triangulating fashion, and as another result benefits from the prior development of theoretical proposition to guide data collection and analysis".

This definition fits the research as the main aspects in this definition are covered in this research. This case study has focused on a single case study because it solely aimed at the CSIR and their goal in introducing FCs in rural SA. CSIR is a single research institution and there was no other company to focus on or other documents that handled similar cases. This single case study used multiple sources of evidence as Yin (2003) suggested in order for it to be objective:

- relevant literature
- open interviews
- workshop
- direct observation at CSIR
- direct observation in rural area

These multiple sources of evidence make sure that the research is performed from multiple points of perspective in order to prevent biasing by the researcher while e.g. asking questions in an open interview and guiding him in a certain direction through which the researcher only gets out what he would like to hear. The strength of the case study approach is in its ability to examine a "full variety of evidence – documents, artifacts, interview, and observations" (Yin, 2003, p. 8).

Besides the advantages mentioned above this concept of case study on a single case has also negative issues that should be noted. Yin (2003) argues that case studies might lack methodological rigor. This means that it is not performed in a systematic way through which e.g. the researcher might bias the interviewee in a certain direction instead of staying neutral. Furthermore this evidence might be equivocal or misinterpreted. A second negative issue considering this approach offered by Yin (2003) is that it provides little basis for scientific generalization because it only is based on a single case.

3.2 Fuel Cell focus group at CSIR

The research was performed for the FC focus group of the CSIR in collaboration with the research group in Sustainable Energy Futures and the Built Environment. The case study is designed to fit these groups. The FC focus group of the CSIR is mostly active in research in PEMFCs. Because CSIR only started in 2005 with its first experiments in FCs they are trying to keep up with global developments and understand new concepts. The goal is to also be able to develop competitive FCs to put SA on the ‘map’ considering FCs. Furthermore CSIR monitors developments in other kinds of FCs besides the PEMFCs. Since a while a new kind of concept FC is monitored and explored: the DAAFC. Because this is a new concept CSIR is interested and willing to invest in this FC hoping to do breakthrough research besides its research in development in the PEMFCs.

The FC focus group currently consists of only eight people that fulltime work on experiments and monitoring literature. This groups consists of five researchers including one post-doctorate; furthermore one research assistant is present, one PhD student and one who is doing an internship and gets in-service training in order to become a researcher in FCs. In another centre (the Manufacturing Science and Technology group at the CSIR) two more researchers have started a project on micro fuel cells in collaboration with the FC focus group of MSM. So, in total ten people are working in FCs at the CSIR. The researchers closely work together with other focus groups in sustainable energies and other disciplines of the CSIR. Besides the knowledge in the CSIR there is cooperation with universities and companies in SA and abroad. All research groups and units together possess a large amount of knowledge.

The FC focus group did not have experience with the tool of TRM before but it became interested in it and willing to try to get familiar with it. If it will be evaluated as a success it might be used more often and tried by other focus groups as well.

3.3 Technology Roadmapping at CSIR

3.3.1 The process at the CSIR

The FC research group of CSIR is mainly active in R&D and did not have experience with the concept of TRM. Only few members outside the FC group had experience in TRM through earlier projects. When TRM is experienced as valuable the concept might be used more often.

During this research the T-plan developed by the University of Cambridge to ‘fast-start’ Technology Roadmapping has been modified in order to further speed up the process and minimize the contact hours of the specialists involved. Four half a day workshops at CSIR are considered to take a too large amount of time which is costly. Therefore it was decided to shorten this contact time to only half a day. The workshop was the only time that all participants, the experts in a particular field, were together in one room around a big table. In the stage of adjusting an adapting the common approach a specialist in TRM was contacted to discuss and approve the modified approach. To be able to cover all subjects normally covered in a TR as discussed in chapter two, it was decided to pre-interview all participants in order to gain information and get their thoughts about certain future technology developments, and have them think about the questions and matters to be handled during the workshop. The interviews discussed the market, business, and performance dimensions, the product feature drivers, and the technology drivers. So, by pre-interviewing the TR-process speeded up and it was less time consuming for the participants. Only the person responsible for the TR had to perform all the interviews, evaluate and cross-reference them, and compare the results later to be presented as input for discussion during the workshop. During the workshop the results were discussed and eventually one opinion had to be formulated and written down on the white board and flip over. Afterwards, the participants most familiar with FCs were asked to prioritize the outcomes of all market and business drivers and product features in a matrix. After cross referencing and levelling the main priorities from all participants, the focus points for the CSIR became clear and the TR could be constructed (see figure 3.1 for the modified TR-process). The focus points generated during prioritizing will be discussed in more detail in paragraph 4.3.

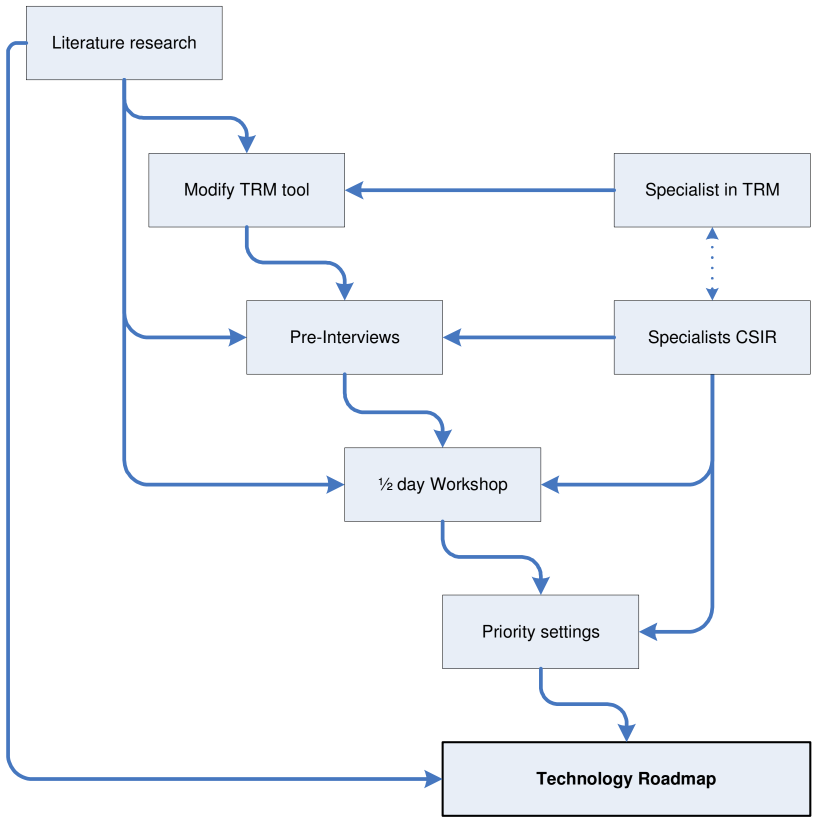


Figure 3.1: Modified Technology Roadmapping at CSIR and the interaction process of specialists involved

Furthermore it was decided in the beginning of the workshop to use the concept of ‘back casting’. This means that at the beginning of setting up the TR a certain year was set for the actual introduction of FCs in rural areas in SA. First, it was discussed what kind of product was supposed to be introduced and general specifications were set, then the year of introduction was defined for the product DAAFC: the year 2030. For PEMFCs using reformers to make hydrogen from alcohol the year of introduction in rural areas was expected earlier: the year 2020.

The strength of modifying the TRM process to the particulars for the CSIR is that it is less time consuming for the participants. The modified version of the TR is designed especially to be used for generating a first-cut TR and to minimize contact hours during the workshop. Especially because for some it was the first time they participated in a TRM process. On the other hand, the minimal number of contact hours for discussion between the participants can have a negative influence when the preparations are not organized well enough. When people e.g. are unprepared at the beginning of the workshop lots of time might be lost in explaining what will be expected from them. The purpose of the workshop is to have optimal communication/interaction between the specialists. When they come unprepared the chance is rather large that creativity might lack because then they are only trying to catch up with the discussions and their contribution will be minimal. So, in order to prevent this from happening during this research the pre-interviews were be done not long before the actual workshop day was so that the participants had fresh memories on the subjects discussed then. To give the workshop a head start the results from the pre-interviews were used to set statements on paper that needed to be discussed in the workshop.

A last remark is that TRM is originally performed in large scale settings to set targets for a whole industry on e.g. environmental level or international operating companies. The use of the TRM tool during this research in the CSIR is to set a path for a single focus-group in FCs. This concerns less people interacting during the workshop which speeds up the process. In combination with the pre-interviews this is expected to result in the same outcome as in the 'traditional' approach; the T-plan by the University of Cambridge. The T-plan proposes all kinds of concepts to present the final TR. Most often the visualization is chosen as in figure 2.1 but during this research this is not an option because of its complexity. Also, this is not preferred because this research concerns setting a target for a technology that is still in development and parts are only in its infancy (e.g. DAAFC). To set rather general targets it is chosen to present the TR in three timeslots for all the different drivers involved.

3.3.2 Specialists involved in TRM process

At the CSIR specialist were selected in the field of rural electrification and FCs. One of the workshops participants was the research group leader for sustainable energy futures another was research group leader for rural energy and economic development. A third research group leader came form the research group in renewable energy. Furthermore a senior researcher in FCs, and a senior energy specialist from the sustainable energy futures research group participated in the workshop. The author participated as 'objective' participant and guided the workshop in cooperation with the research group leader in sustainable energy futures. The combination of these specialists' expertises was considered a valuable mix to get multiple viewpoints in developing a TR on the introduction of FCs in non-electrified places of SA.

3.3.3 Research limitations

This research is done to develop a first-cut TR. This means that the outcome, the TR, is rather to set a general path for future development; more specific targets should be set in specific TRs. For example, the general targets for the DAAFC are set in the first-cut version. The specific targets for developments in DAAFCs should be set in a specific TR. This specific TR should however fit the general, first-cut, TR.

During this research the focus considering the 'system hierarchy' consisted mainly on the product: the FC. However, the user-system interaction also was part of the discussion in the workshop. It became clear that the customer is too often left out while developing technologies. Because the customer is that important their requirements should be noted already in the beginning of the process of development. Yet, in the beginning of developing a new technology only general customer demands should be taken into account. Further in the process when the CSIR is selling the technology to the next company in the value chain the customer requirements are becoming more and more important. The same goes for the rest of the system hierarchy like the exact materials to be used and exact costs involved. This is because it considers a first-cut TR here. It will not be investigated in great detail how the product should be implemented in remote areas. This is because the CSIR will not sell the product themselves but they develop the technology and then sell this technology to the next company in the value chain. This company will then also decide what kind of materials to use for the product as part of the 'systems hierarchy', therefore this will not be handled in detail in this report.

The limitation to South Africa has been chosen because in this country many people still live without electricity. The restriction to small scale electricity was chosen because of the focus on remote areas in South Africa where no power grid is available. Because they are not that familiar with the use of it, at first they will use electricity for lighting and other small kind of devices like battery chargers, small TV, small refrigerator. Cooking and heating are to be done on other kinds of fuels (e.g. LPG). What the definition of small scale generation is could not be retrieved from literature therefore during this research small scale electricity generation will be defined as electricity generation up to 50kW. This should be enough to electrify several households and satisfying then their first need which is lighting. Using conventional lighting a typical household would need only a 200W capacity fuel cell to light 3 light bulbs of about 60W. This would mean that 277 households could be electrified by this one system. In practice however a typical household demands more electricity for options such as cell phone charging, radio, and small fridge use and maybe even a small TV in colour or black and white. Therefore a typical household will need a capacity of about 1kW. So, when a 50kW fuel cell would be used, about 50 households could be electrified using one system; then a kind of local mini-grid is established. Another option could be to develop smaller systems that electrify only one or a few houses. These systems should be designed to generate around 1kW. Especially in rural settings this might be more convenient because distance between houses might be quite large. More about this is discussed in paragraph 1.3.2 where table 1.7 is presented to provide information on how much electricity a mini-grid in a pilot project in electrifying a rural village in the Eastern Cape was using.

4. Results of Technology Roadmapping at CSIR

This chapter will flow according to figure 3.1, the modified version of the TRM process at the CSIR. This figure also forms the backbone of this report. The tool of TRM has been modified to shorten the contact hours of specialists involved as discussed in chapter 3.3. This modification was performed in accordance with a specialist in TRM. The next step was to select people to participate in the workshop and pre-interview them to get their viewpoints. Their input was used to set up the workshop and to speed up the process. Furthermore the results from the literature research and the specific knowledge in a certain field of expertise by the specialists formed input during the half day workshop. After the workshop the participants were asked to prioritise the results and when this was completed the TR could be developed using some additional information from the literature research.

4.1 Trends and drivers

4.1.1 Perspectives of specialists

Specialists in fuel cells

Appendix 9 provides the complete interviews with all the specialists involved in developing the TR. One senior researcher in fuel cells participated in developing the TR. From his point of view he did not expect FCs to actual become active in remote areas of SA within the next 10 years. The main problem he foresees is the costs involved. He suggested installing other kinds of systems that generate 240VAC and can handle fluctuation and can be put on easily when demand is needed. One example he provided was to install small diesel generators that would generate e.g. 5kW. These could be used to electrify a few households in their basic needs. These diesel generators will be cheaper in capital costs than FCs. Only when the price of the diesel becomes competitive to the fuel needed for the FC and government will pay the initial capital costs, only then he argues that FCs become a competitor to diesel generators. The technology group leader of FCs, argues about the same. He also argues that diesel generators might be easier and cheaper in maintenance.

An alternative to the diesel generators suggested by the senior researcher in FCs could be the use of solar energy or the use of advanced battery systems. These should be developed further before the introduction in rural areas.

Furthermore he thinks that people in these rural places cannot afford to pay for the devices that need to be connected e.g. a radio, small TV, fridge. Only when they will be helped financially to buy these they will be able to actually use electricity. But then the problem arises that people in these areas cannot pay the electricity bill. So, he concludes that people are too poor to afford electricity. Only by (almost full) government support they can use electricity. The technology group leader of FCs agrees on most of this. He states that the main driver for energy security will be the government. Both researchers agree on that the price of FC systems should come down significantly. Partly this will be done by economies of scale but the research in cheaper materials plays a major role as well.

The main problems he foresees in the use of FCs is that FCs generate about 50VDC. Normal appliances do not work on this. The power needs to be converted to 220-240VAC. This conversion is necessary to be able to connect normal devices to it. The conversion itself is quite expensive and in the process energy in the form of heat is lost. Both the technology group leader in FCs and the senior researcher in FCs argue that FCs should not be implemented to address all energy needs. An additional fuel or direct use of this fuel is recommended for heat generation and for cooking because FCs (PEM) have a maximum efficiency of about 50%.

In terms of technical features of the FC the senior researcher in FCs stresses that it is important to research in the use of solid and liquid fuels to feed the FC. Alcohols are good options and should be researched further in order to be used in a stable way. These fuels are also more convenient in distribution than gaseous fuels. However he states that radical developments are necessary to make FCs possible that use liquid fuel directly. In order to do so he argues that the number of researchers should become much more as is also mentioned in the TR in paragraph 4.2 and appendix 8. The CSIR has a lot of research groups each with its own expertise and these should be used more optimally. Where necessary the help should come from outside CSIR. This is done already but should be done more often in the future. The technology group leader in FCs agrees that Human Resources should be a main driver in the process of developing FCs.

Both do think that there is a future in FCs but the senior researcher in FCs does not (yet) believe in successful implementation in rural settings. Both think that FCs should be used in niche applications e.g. in hospitals as backup generators or in telecommunication towers because they normally operate on 50VDC. Actually FCs can replace all batteries. Even the use in cars is still a viable option; certainly when liquids (room temperature) can be used as fuel. The technology group leader in FCs stresses that ‘green’ hydrogen is not an easy objective because SA does not have many renewable options to make this. The only current environmental option is to use solar energy to make hydrogen. See appendix 9 for more on this.

Specialists in rural electrification

Two people in the workshop are specialists in rural electrification. Appendix 9 will provide the whole interviews. One interviewee is specialized in rural infrastructure implementation and the other in rural electrification. Both argue that costs are the main problem. The costs involve the systems’ costs in purchase and the maintenance caused by using the system. Just as the technology group leader in FCs and the senior researcher in FCs argue that people do not earn enough to be able to pay their electricity bills.

The specialist in rural electrification states that the free electricity, the 50kWh monthly, should become better organized. Too often, he states, that people who need this free amount do not get it in practice due to bad local government. Everybody can apply for this free amount although it has load restrictions.

The specialist in rural electrification has experience with the introduction of Solar Home Systems (SHS) in rural places in SA. He stresses that the CSIR (and government) should learn from earlier mistakes in implementation. The settings of these rural places have not changed much therefore earlier projects should be considered. Most importantly, he states, is to include customer requirements; the rural infrastructure implementation specialist agrees on this as well. If they don’t like the system they will keep on using the traditional fuels for cooking and candles for lighting. One of the most important drivers from customers is the price in using the systems. So, fuel price and maintenance costs should be low. Furthermore reliability and efficiency are agreed by both to be major drivers in using the future FCs. If the system is not reliable and breaks down too often they stress that the local people will abandon the use of the FC. Even if the FC is too difficult in use they will quickly abandon using it.

Both argue that the electricity offered should be the same as electricity from the grid: 220-240VAC. This is necessary to be able to connect standard devices to it. People would like to connect the next main appliances:

- Radio
- Small TV
- Light bulbs (at least 3, preferable more)
- Small refrigerator
- Chargers for e.g. phone or computer.

Both do agree that multiple energy sources are needed in these rural areas because heating and cooking should not be done on electricity generated in a FC. The rural infrastructure implementation specialist prefers the use of Small Gas Turbines (SGTs) over FCs because the SGTs generate heat that can be used for heating e.g. water or air. Furthermore he argues that these will be sooner ready to be marketed.

The introduction of the FCs should be well organized otherwise the same will happen as with the introduction of the SHS. People should be made aware of what the FC is capable of and how to use the system. Furthermore should it be considered whether it is cheaper to install FCs per household or a few households together (kind of small mini-grid). The last option is by both the rural infrastructure implementation specialist and the specialist in rural electrification considered being cheaper. The technology group leader in FCs and the senior researcher in FCs also agree on this. However, this is only possible if houses are situated in a dense way. If the houses are spread too far from each other then this will not be an option because then expensive cables and constructions need to be used to connect the houses to the central FC system. The specialist in rural electrification adds to this that the fuels for the FC should be supplied within walking distance as is the case now with e.g. paraffin or diesel. He argues that certain local energy centres should be set up. These centres should supply cheap fuels otherwise people cannot afford using these systems as stated before. Furthermore, he argues, these centres should have spare parts that people can put in there selves. If the FC is somehow not working anymore people from this ‘energy centre’ should be able to fix the system. So maintenance should be organized decentralized. Local people should be educated in repairing the FC systems in order to prevent that people from ‘the big city’ need to come and repair the system, which implies that the system might be out of service for quite a while and people need to use the traditional ways. All interviewees agree upon the fact that maintenance should be organized in a decentralized manner in order for the FC to become a success.

4.1.2 Five trends and drivers specified

Based on the pre-interviews discussed above and the literature research five groups/themes of trends and drivers are distinguished, see figure 4.1. The aim is to relate technology and research requirements to the trends and drivers that define the future needs of FCs. Five themes have been used to structure the information of this roadmap as is visualised in figure 4.1. The format of this chapter has been presented in the same way as the Foresight Vehicle TR version 2.0 (2004) because of its clear way of presenting trends and drivers. The contents of the trends and drivers are to a large extent according the findings in their research. Their findings were verified, modified, and new information added where necessary. The trends and drivers will be presented in five themes that are all interrelated.

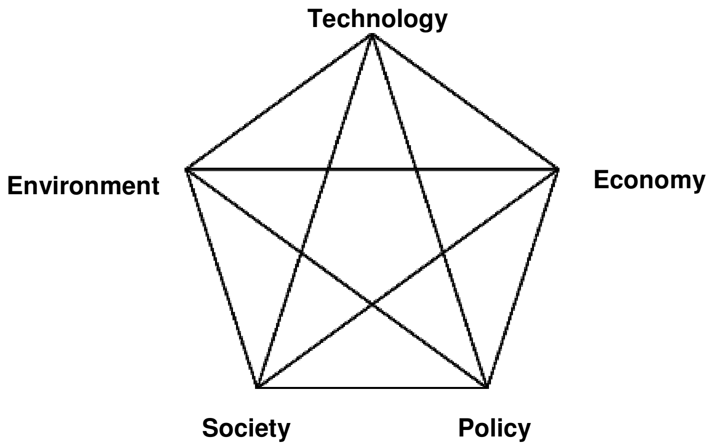


Figure 4.1: Five trends and drivers that influence introduction of FCs in remote areas in SA.

Social, economic, and the environmental drivers of figure 4.1 reflect the main three aspects of sustainable development in FCs. The other two: technology and policy are different from the other three because activities can either enable or constrain progress towards the primary social, economic and environmental goals.

1. *Technology* trends and drivers relate to how technology affects the way South African people live. This also includes the development of new energy systems and the fuel this technology uses, the electronics around this, the materials used, and the manufacturing and business processes involved.

2. *Economy* trends and drivers relate to the financial aspects that affect people's lives. This includes global, national, corporate, and personal economic considerations. However, the focus will be on SA.

3. *Policy* trends and drivers relate to the systems that govern people, including political, regulations, legislations, and the political processes in SA that lead to them.

4. *Society* trends and drivers relate to the social system people in SA live in. This also includes demographics, life style, working patterns, and desire for health, safety, and security.

5. *Environment* trends and drivers relate to the physical environment in which people live. This includes energy production and consumption, waste, pollution and emissions, and the health impacts as a result of this. The environment is focused on from South African point of perspective but also globally.

All these five themes are interdependent as visualized in figure 4.1. The CO_2 emissions for example relate to technology, economy, policy, society, and environment. The trends and drivers identified during this research are presented in table 4.1 and specified for the FC market. The contents have been retrieved from three sources: the literature, the pre-interviews, and the workshop and put in this table.

	Trends and Drivers	Queries	Vision
Society	- growing demand for electricity - demand of electricity is almost at maximum for current active power stations - changing working and living patterns - smaller households - continued growth of cities and towns - increasing concern for health, safety, and security	Social attitude on environment?	Cheap, convenient, safe, secure, reliable, and clean electricity
Economy	- growth in economy and consumption - larger amount of public money needed to electrify rural areas - energy costs rise every year - instability of oil price - increasing gap between wealthy and poor	Will economy and consumption keep growing? Will rural electrification ever become viable for private companies to invest in? What will be the top-price of oil?	Successful and sustainable electricity generation in rural areas in SA using multiple energy sources optimally
Environment	- increasing (global) population and associated economic development - increasing energy consumption and exhaust of greenhouse gasses - reducing emissions (transport and industry) - pressure to utilize materials and energy more efficiently - opportunity to use (cleaner) alternative energy sources	Impact of global warming; is response adequate? How long will oil, gas, and coal supplies last? Social attitudes on environment in business and government policy	Environmentally sustainable electricity generation in rural SA
Technology	- opportunity for innovation in Fuel Cells: • Fuels to fuel the fuel cells • Electronics around FCs • Materials used	Which fuel cell will succeed in long-term for rural electrification with opportunities to expand and fulfil client needs	Effective and appropriate technological innovation to generate electricity in rural SA
Policy	- CSIR recommendations to government - CO_2, energy, and emissions legislation - social expectations for electrification of rural areas	Legislations in correspondence with foreign countries?	Effective, sustainable, and integrated electricity generation using Fuel cells in remote areas in SA according to international standards for environment

Table 4.1: Trends and Drivers of the FC market in SA (Adapted from Foresight Vehicle TR, 2004)

Society trends and drivers

Vision	Cheap, convenient, safe, secure, reliable, and clean electricity
Growing demand for electricity	There is a growing demand for electricity in SA stimulated by the economic growth and development. The Community Survey 2007 showed that the population is still growing and the households become smaller at the same time. This implies that the number of households grows even faster. Furthermore the government programme 'Electricity for all' stimulates the number of people electrified. This programme stands up for rural electrification among other things.
Demographics	There is a need to anticipate on demographic changes like the increase in ageing of the SA population and the growth of industrial and urban areas. This increase entails the increase in housing especially in the urban regions as Cape Town, Pretoria, and Johannesburg where lots of people try to find jobs. Gauteng (main cities Pretoria and Johannesburg) had an increase of population of 13.9% compared to 2001 and the Western Cape an increase of 16.7% since 2001 (StatSA, 2007). The population is expected to grow further but because of the AIDS-virus the rate of growth declines and takes mostly the lives of the young adults between 25 and 45 years (ING Barings, 1999). Life expectancy of the average South African is decreasing due to AIDS. The number of people without any schooling is substantially decreasing. The global trend is that the total number of people is increasing, as well as the growth of economies and the negative impact on environment caused by these.
Health, safety, and security	20% Of SA is not yet using electricity for lighting (StatSA, 2007). This means that 20% is not yet connected to the power grid. Most of these people live in rural areas where no connection to the power grid is possible. Every year 5.2% (StatSA, 2005) of all unnatural deaths are caused due to the use of candles, paraffin, and firewood inside the house causing carbon monoxide poisoning or burning down of the house with death as result. This trend is slowly increasing from 5% in 1999. Social demand for improved health will eventually encourage the efforts of SA to reduce emissions and particulates. The trend in energy security is becoming more and more of an issue due to the rise of the oil price and the question how long and to what price oil can still be exploited in SA.
Lifestyle and attitude	Electricity is supposed to be accessible to everyone in SA; this is the main goal of the 'Electricity for All' programme started in 1994. Electricity is supposed to making life easier and healthier as will be discussed in the health, safety, and security part of this section. The role of CSIR and government is to satisfy the needs and aspirations of SA people; to improve living standards, economically and with minimal impact on environment. Living and working patterns are changing and requiring (more) electricity; especially in rural areas these changes are significantly. Electricity in the poorest parts of SA is still seen as luxury, but more

and more people have it because it is part of the modern society. Electricity is part of the 'modern' world with lots of opportunities where the people still living without electricity would like to be part of. Appendix 11 will describe in more detail the social impact of electrification. It will be discussed that people feel treated unfair when they are not able to be connected to the grid or get inferior electricity supply (as they see it). Additionally, the use of multiple fuels is discussed and the appliances that will be connected to the electricity grid.

Economic trends and drivers

Vision	Successful and sustainable electricity generation in rural areas in SA using multiple energy sources optimally.

National economics

The South African consumption is increasing which stimulates the economy to grow. More and more people are connected to the power grid. This means also that the new connected people buy appliances like bulbs, radios, TVs, fridges, etc. Al these purchases stimulate economic growth. But the very rural areas without any grid will need government support in starting up a (mini-)grid. It is expected that if these areas are electrified the economy in those areas will start and small businesses will be established. So, the 20% of SA not yet electrified can in future contribute in the growth of SA's economy through which the gap between the poor and the wealthy may become smaller.
The use of Platinum (Pt) on electrodes as catalyst is a great stimulant for SA because SA has one of the biggest resources in this precious metal. The exploitation of Pt will contribute significantly to SA's wealth. Therefore it is important for SA to keep using Pt in FCs.

Fuel price

The high price of oil is at this moment, 2007, a big concern and the trend of price increase is expected to continue in the long term. The use of alternative energy sources reduces the dependency on oil and might level the price. Appendix 11 provides more information on this. Also a cost calculation is presented to show that the use of electricity is cheaper than e.g. paraffin.

Business

For private companies the trend seems to be that it is too costly to electrify rural areas. This is because people living in these areas cannot pay (any) bills or the maintenance of these systems and therefore government support is needed to start these areas up. After a while small companies are set up and people earn money to pay their bills. The initial costs of the electricity systems will be too high and will take a long time before they are earned back.

Consumer

Every year the energy prices are rising; partly caused by the annual inflation (5.7% in 2007, IMF – World Economic Outlook Databases), the rise of oil prices because of scarcity and the slightly increasing costs of mining in SA.
Furthermore the population growth in combination with economic development will provide commercial opportunities as well as pressure

on political systems and impact on environment. The trend from consumer perspective is to demand variety, performance, good quality, and service.
Last but not least is the trend of a wealth gap that is increasing although government is trying with programmes to minimize this gap.

Environmental trends and drivers

Vision	Environmentally sustainable electricity generation in rural SA
Environmental burden	The trend is that the population of SA is still increasing; the rate of this however is declining slowly but is still positively. This and the increase of wealth result in the increased use of electricity. The result of this is a greater impact on the environment by Greenhouse gasses (GHG) and other emissions by industry and transport. Furthermore the burden by depletion of coal for electricity generation and the (new) mining areas needed to keep up with growing demand which is expected to continue to grow.
Global warming	South Africa is the number 13 of 178 countries most polluting countries of the world with 344,590 thousand tons of CO_2 per year (World Resources Institute, 2003). CO_2 is one of the main GHG that cause global warming. SA is striving to set up regulations to better being able to control and reduce emissions mostly caused by transport and industry in electricity production.
Energy	DME (2006) states that 44.2% of coal in SA is used for electricity generation and 16.5% for liquefaction to make e.g. petrol. The price of oil has gone up significantly in the last few years. This is because the production is at the top and some oil fields are about to be finished. The demand for oil is still very large and growing. Because the rise of the oil price and the scarcity of oil is becoming a fact, alternatives as bio-fuel, electric, fuel cell, or hybrid engines are researched to reduce the dependency to oil. Also the alternative energy generation like wind, ocean wave, hydro, solar, and geothermal power are more often considered to be valuable alternatives. This trend provides an opportunity to actually apply renewable energy sources on a large scale.
Pollution	Pollution can influence the daily quality of life because this can have an impact on people's health. Pollution can be in the form of very small particles in the air but also the harmful gasses as the GHG. South Africa has only since 2004 an air quality act to improve air quality and reduce air pollution. SA furthermore has agreed to sign the follow up programme of Kyoto Protocol in the Washing Declaration in 2007. By 2012 the Kyoto Protocol is over and the follow up will be presented. SA is willing to meet the requirements to participate in this new policy and until that time the pollution is reduced by setting targets every year. A trend in SA as a result of this is the pressure to utilize materials and energy in a more efficient manner.
Waste	South Africa is becoming aware that waste is problem for its country.

Programmes are started to recycle as much as possible and reduce the amount of landfills. The policy is set for South Africa to produce zero-waste in 2020 in the 'Polokwane Declaration'.

Technology trends and drivers

Vision	Effective and appropriate technological innovation in FCs to generate electricity in rural SA
Energy and power	Electricity generation in SA in mainly depended on coal as primary fuel. The trend is that the current amount of electricity used annually in SA is growing. This asks for more use of coals through which the mines in SA will be depleted earlier than expected if this continues. The use of renewables like hydro, solar, wind, and wave power are expected to become important in producing significant amount of power. Hydrogen may also play an important role in that it can reduce the amount of electricity made by non-renewables; that is if the hydrogen is produced in a sustainable way. It is expected that the FCs will be implemented in rural areas in 2020 earliest. The trends in fuel for the FC will depend on the amount of research performed in the future. The hydrogen FC is expected to function in combination with a reformer to make hydrogen from an alcohol. Another technology is still in its infancy: the direct alcohol alkaline FC which will use alcohol directly as a fuel.
Materials used	The use of Platinum (Pt) on electrodes as catalyst is a great stimulant for SA because SA has one of the biggest resources in this precious metal. The exploitation of Pt will contribute significantly to SA's wealth. Therefore it is important for SA to keep using Pt in FCs. Furthermore the trend is that the number of materials used in products like a FC are tried to be minimized in order to reduce the cost price. This also saves environment. The membrane determines a lot in the output of the FC. Lots of research is going on in optimizing the membrane.
Electronics	The electronics around the fuel cell make sure that e.g. temperature is regulated and hydrogen is pumped optimally through the system along other things. The trend in electronics around the FC is that everything becomes monitored by one single computer providing the total status. The computer makes sure that the right components are activated. The trend in price of the electronics around FCs will be that the price is expected to decrease because of mass production.

Policy trends and drivers

Vision	Effective, sustainable, and integrated electricity generation using FCs in remote areas in SA according to international standards for environment
Energy and CO_2 reduction	The amount of energy use in SA is growing significantly and so is the amount of CO_2 and other GHG emissions. SA is striving to meet the standards of the Kyoto Protocol and eventually to sign the follow-up programme in 2012. Furthermore, SA is striving to improve indoor air quality in rural areas by introducing electricity by which candles can be replaced by bulbs.
Government	Government is becoming aware that global warming is really happening and the effects are noticeable earlier than expected. Therefore government is making regulations and legislations for pollution of air, land, and water. Furthermore, the government of SA is aware that globally the global warming should be reduced and therefore it is willing to participate in the follow-up programme of Kyoto and is now striving already to reduce pollution step by step.
Social expectations	People in rural areas expect government to take care of them in a certain way. This includes electrification of rural areas. Furthermore, people expect government to set up regulations and legislations to improve their living conditions. Appendix 11 will discuss more about people feeling treated unfair when they do not get national power grid connections. Regulations and legislations include national air quality acts, water, and waste management so that health safety and security are guaranteed. As a result is for example the zero-waste production set in the 'Polokwane Declaration' by 2020, and the National Air Quality Act in 2004 with lots of strict guidelines for companies to apply to.

4.2 Prioritization of market, business, and product/service drivers

4.2.1 The drivers matrix

After the workshop the results were collected and written down as can be viewed in table 4.2: the matrix of all main drivers. The higher the score the more correlation there is among the two drivers in the table. The individual correlations provided by the participants can be found in appendix 10. The scores are calculated in the next way:

- Reverse the individual priority scores of the market, business, and product drivers provided by participants.
- Multiply per participant their priority setting (the reversed one) with the number of 'ticks' provided. The number of 'ticks' indicates the correlation (between 0 and 3 ticks with 3 as highest correlation) between the two drivers.
- All participants' outcomes were added up cell by cell and written in the corresponding cell in table 4.2

The cell with the highest number indicates the highest correlation between two drivers. These drivers correspond with aspects that CSIR should try to take into account when developing (new) technologies. These are the main focus points.

Name: Overall

Market perspective / Business (CSIR) perspective

= Very Strong correlation
= Strong correlation
= Medium correlation
= Weak correlation
– = No correlation
1 = Highest priority driver

Priority	Product / Service	CSIR mandate to meet national needs	Beneficiation Pt	Niche applications	Price increase conventional fuels	Electricity capacity expansion potential	SA's growing economy	Awareness	HR development	IP development	Knowledge transfer	Client needs	Personal value Points (PVP)	CSIR Mandate	Total
2	Capacity 1-20kW	61	93	46	42	111	66	42	24*	81	24	147	12*	40	789
1	Response to load change	44	-	116	72*	158	90*	44	22	124	4*	204	20	30	928
3	Simplicity maintenance	26	-	102	42*	130	25*	52	18	61	62*	186	-	30	734
5	Modular systems	10	-	79	48*	96	48	32	8	57	25*	84	8*	20	515
6	Liquid fuels	9	52	86	88	34	25	27	12*	20	9*	101	2*	23	488
4	Efficiency	39	37	53	44	82	47	15	-	96	26	83	4*	45	571
	Total:	189	182	482	336	611	301	212	84	439	150	805	46	188	
	(Priority of Market driver 1-7)	6	7	2	3	1	4	5							
	(Priority of Business driver 1-6)								5	2	4	1	6	3	

(Priority of product driver 1-6)

*=input gained by 1 person only

Table 4.2: Matrix of drivers

4.2.2 Client needs as main driver

Table 4.2 shows that the most important driver the 'client needs' is in combination with the ability of the FC to be able to respond to load changes. This is the most important ability of the FC to look at;

especially in combination with the driver to make the FC able to change loads easily. The characteristics of the PEMFC or the AFC are in favour of this compared to the use of SOFC. PEMFC and AFC can handle fluctuations better than e.g. the AFC; appendix 6 shows more about FCs.

As becomes clear from the table it is very important that client needs are taken into account right from the beginning of the project. Eventually the end-user determines where they would like to use the FC for in practice. The interviews held before the workshop also made this clear (see appendix 9). Client needs are more important than perhaps is realized inside the CSIR at the moment. Obtaining these requirements is a process in which customers provide their requirements towards manufacturers and at the same time technology is pushed onto the market to make clear to customers what technology has to offer, also visualized in figure 4.2.

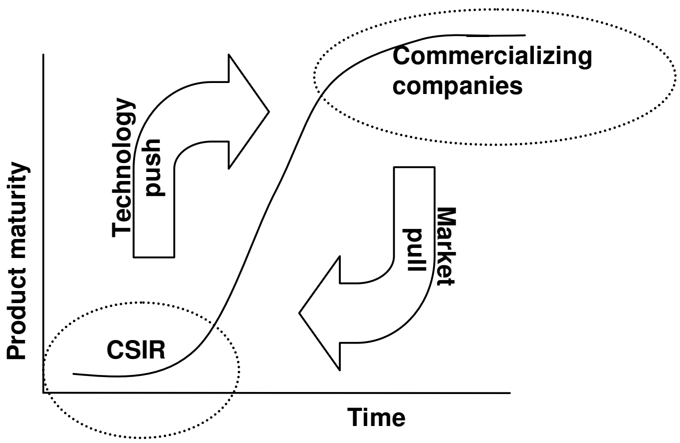


Figure 4.2: Positioning of CSIR in Product development over time

Technology push and pull
This particular TR for the CSIR is focusing on the introduction of a new technology of FCs for the use in rural areas. This implies the introduction of a new technology not yet mature (see figure 4.2). To include both a customer and a developer perspective it is suggested during pre-interviewing and during the workshop to acquire client needs during all stages of development. On the one hand clients provide information about their needs towards developers. This is called ‘Market Pull’. The concepts of technology-push and market pull (also called need-pull) were introduced by Schon (1967) as the underlying motivations and driving forces behind the innovation of a new technology (Chidamber & Kon, 1994). These two concepts propose and support two different arguments. The technology push suggests that innovation is driven by science, and thus drives technology and application: scientific discovery triggers the sequence of events which end in diffusion or application of the discovery (Munro & Noori, 1988).

The technology push stems from recognition of a new technological means for enhancing performance. Porter and Millar (1985) argued that, using appropriate structure and strategy, adoption of new technology could create substantial and sustainable competitive advantages. Appendix 8 where the TR will be further expounded will also discuss the importance of client needs and how this particular can be done. There the focus will be to make clear how and why the CSIR and the government should include the end-user in the development phases.

4.2.3 Other important drivers to focus on

The matrix furthermore makes clear that the focus of the CSIR should be on the next main drivers. The market drivers explain that the focus should be on making a FC-system able to ‘grow’ when demand becomes greater over time. It would be too costly to install complete new systems and therefore the systems to be installed should be able to expand whenever necessary. This also has to do with the product property 'modularity'. This property makes it possible to extend the systems when necessary. The next most important market driver is the applicability in niche applications. This is from the CSIR's point of perspective important, and not from the rural electrification point of perspective. From economic point of perspective the CSIR should be able to use the developed techniques also in other markets. Some other niche markets than the rural market could i.e. be battery replacement.

The main business driver from CSIR's point of perspective is as stated above to comply with client needs. The next main driver is the development of IP (intellectual property). IP forms the heart of the CSIR's knowledge. All these drivers form the focus points in developing the FCs further.

From product and service point of perspective the main drivers are to be able to use FCs that can handle load change. The next most important driver is that the system should be easy in maintenance. If this is very complicated local people cannot perform maintenance by their selves and (national) companies should do all the service which eventually is more costly for the people who use the system. An option could be to educate local people in maintaining systems and provide training to set up small local service companies that do local maintenance. As stated before is the modularity of the systems an important product driver so that the system can expand whenever necessary. Furthermore is the use of liquid fuels important because this makes the transport easier, more efficient, and safer.

4.3 Technology Roadmap to electrify rural areas of SA

The next pages present the Technology Roadmap for rural electrification in SA using the concept of FCs. The TR also consists of the five layers already discussed in the trends and drivers in paragraph 4.1: Society, Economy, Environment, Technology, and Policy. Each will be discussed and all will have different drivers for the future. For each driver certain goals will be set in time. Because the future about the developments in FCs is very hard to predict, and guessing is not considered to be valuable, it is chosen to use three timeslots to cover the future up to the year 2030. The first slot is from 2008 until 2013; 5 years; the second one from 2014 up to 2020; 6 years; and the third one from 2021 until 2030; 9 years. Some goals can be set over multiple timeframes and therefore cover multiple timeslots at ones. The last column of the TR will discuss 'issues' considered with the goals set in the timeframes or clarify the statements of the timeframes shortly. Appendix 8 explains the roadmap in greater detail.

Technology Roadmap for Fuel Cells focused on rural electrification in SA

		2008 – 2013	2014 – 2020	2021 – 2030	Issues
Society	CSIR mandate to meet national needs	Continuous process			SA should be placed on the map considering FCs. CSIR has obligation towards government to innovate and find technical developments useful for SA Energy security for SA
	Knowledge transfer	Development of knowledge	Transfer of knowledge	Implementation of knowledge	Knowledge transfer in the CSIR and knowledge transfer to people in rural areas considering maintaining FCs
	South Africa's growing economy	Continuous process (hopefully)			From society point this enables the use of more electricity because more money is available. More people can afford to have electricity and buy electrical appliances.
	Client needs	**Continuous process of involving R&D and client needs** **Most input from client for FC product development**		**Test phase** **Exposure to client with feedback**	**Already from the beginning the client should be involved in specifying what the product (FC) is supposed to do.**
	Accessibility of fuel + pricing	Make recommendations to government to set up local rural energy centres and start pricing of the fuel to be used	Introduction of local energy centres by government in rural areas	Large amount of energy centres so that local rural people have access to spare parts and fuel	Fuel should be easily accessible in rural areas otherwise they will use the traditional fuels instead
	Increase skills locals		Programmes should be developed aiming to instruct locals how to maintain FCs. locals should be *taught* how to maintain there own PEMFC systems	Local people, educated earlier, start their (independent) company or become employees of corporations in maintenance of FCs as a profession or business opportunity	Skills at different levels: the level of local people maintaining the FC and the level of the employees at CSIR Monitoring is to be done by companies installing FCs (not CSIR)
	Increase number of skilled FC researchers at CSIR level	@2008-2010: search for specialist in direct alcohol FCs and PEMFC with reformers experiment in DAAFC	By 2014-2015 expand FC team with ± 5 researchers	Start new projects in FCs as follow-up	Part of National Capacity Building process Drive towards skills in modern technologies

		2008 – 2013	2014 – 2020	2021 – 2030	Issues
[Society]	Personal Value Points at CSIR	Continuous process of incentives that drives people to function optimally and become pro-active			These are internal business drivers CSIR uses as incentives to get more out of people.
[Society]	HR development	Continuous process of learning about a technology. Store knowledge in a knowledge database and keep this up to date. Furthermore, CSIR creates environment for getting degrees, experience, and student work			Experienced people need to be brought in and current people need to be retained
Economy	Costs / price (development, operating, and system costs)	Development costs for CSIR research Reduce cost targets	Development costs for manufacturing companies @ 2015 Price of FC system 20% less than 2008	Economies of scale in production to reduce cost of manufacturing @2030 Price of FC system >50% less than @2008	community FCs cheaper than 1 per household initial costs FCs high fuel expensive materials of FC costly
Economy	Beneficiation Platinum (benefits from use of Pt)	Continuous process			SA has world's largest Platinum resources, but it should not abuse its position because that only will stimulate other countries to search for alternatives.
			Beneficiation companies should support in development	Actual sales of Pt-based catalyst	
Economy	South Africa's growing economy	Continuous process (hopefully)			Government should support the developments in FCs
Economy	Price increase conventional fuels	Continuous process: decreasing availability oil and strive for CO and CO2 reduction using carbon taxation			The high oil or coal price can make FCs a competitor Price conventional fuels might become about the same as price of fuel for FC (about same MJ/Rand)
Economy	Intellectual Property (IP) development	Continuous process of obtaining patents and improving the FC			competitiveness try to get most out of FCs
Economy	Niche applications	PEM hydrogen FC: Telecom towers, backup power	Small to medium sized electrification up to 1kW systems like Battery replacement, mining, game farms		Mining, telecom, game farms, mini-grids, battery replacement, backup power

		2008 – 2013	2014 – 2020	2021 – 2030	Issues
Environment	Environmental improvement			@2020: introduction PEMFC with reformer @2025: Decline in percentage of traditional fuelled households in rural areas with 40% compared to 2007	FCs produce less greenhouse gasses as exhaust than conventional electricity generation. Especially in combination with LPG or solar heating, FCs are environmentally friendlier than using traditional or conventional fuels.
	Replacement 1x use batteries			Decrease in non-rechargeable batteries	Nowadays lots of batteries are used which in the future might be replaced by using FCs
	Indoor air pollution reduction			Reduction indoor air pollution by candles by 40%	Cleaner air in the house thanks to use of FCs instead of candles
	Awareness	Exposure of technology to school children	@2018 Make rural people aware about health benefits (e.g. cleaner air) and comfort Keep people posted about benefits for health and environment		Need to inform public of advantages of FCs so that they get familiar with technology and use
				Practical exposure in rural areas	
Technology	Use of PEMFC with reformer	(Final) development research in PEMFCs in combination with reformers	Field Test of PEMFC with reformer Transfer to mass production	Implementation phase @2020 PEMFCs with reformers are introduced in rural areas and locals should be monitored while performing maintenance 20% market penetration @2030	PEM with reformer can use liquid fuel (e.g. alcohol) to produce H2 through reforming Output voltage @ 600mV per cell
	Catalyst + electrode research PEMFC	Reducing amount of Pt in PEM Improve efficiency Research in (better) poisoning resistant catalysts			Try to use the Pt-reserves of SA but also to invest in alternatives to keep up with rest of world looking for alternatives.

		2008 – 2013	2014 – 2020	2021 – 2030	Issues
[Technology]	Fuel research PEMFC	PEM with H2 purity research; Goal CO: >10ppm			PEMFC are very sensitive to contamination with CO PEMFC should be fuelled with reformer to get H2 Fuel should be made from renewables, otherwise not very environmentally friendly
	Membrane research PEM	Optimization of conductivity using Nafion Cost reduction up to 10x		Develop new kind of membrane with better specifications: cheaper + better performance	Membrane to conduct H+ (now Nafion) Experiment with different kind of materials and reduce thickness so that less material is needed
	Use of AFC as Direct Alcohol Alkaline FC	Early fundamental development to make DAAFC possible and competitive		@ 2030 Direct Alcohol AFC (DAAFC) will be introduced in remote areas in SA and the maintenance should be monitored	AFC has higher output V @ 800mV per cell than PEM @600mV per cell
				Field testing	
				Transfer to (mass) production companies	
	Catalyst + electrode research DAAFC		From 2014 experiment to replace Pt with cheaper material in DAAFC		AFC uses less Pt because some can be replaced by Tin Try to use the Pt-reserves of SA but also to invest in alternatives to keep up with rest of world looking for alternatives.
		Reducing amount of Pt in DAAFC			
	Fuel research DAAFC	Use Direct Alcohol in AFC: start with methanol and ethanol	@2020 DAAFC should be able to run on other Alcohol fuels and improve fuel efficiency		FCs should become more fuel efficient. Amount of W/m3 should go up. E.g. efficiency should improve. DAAFCs can use alcohols directly as fuel; ((m)ethanol and glycol)
			Start of purity research; try develop DAAFC less sensitive to poisoning		Fuel should be made from renewables (e.g. bio-ethanol) in order to be environmental friendly

		2008 – 2013	2014 – 2020	2021 – 2030	Issues
[Technology]	Membrane research DAAFC	Research in finding stable and good conducting membrane to conduct OH^- Research in getting the power density same as PEMFC	Improving the material properties used for the membrane Improving of power density in order to become better than PEM Cost reduction up to 10x		DAAFC uses membrane to conduct OH-; There is no standard material yet; no monopoly like Nafion; CSIR could try to become market leader by developing a standard Experiment with different kind of materials for best efficiency (cost & performance)
	Capacity of FC and Electricity capacity expansion potential	Develop modularity option to be able to connect 2 or more systems	Improving modularity option		It is cheaper to have small decentralized networks + maintenance. A typical grid is supposed to supply basic electricity to use: - TV (B&W or colour) - radio - lighting (>3 bulbs) - fridge Cooking and heating should be done using other sources of energy: e.g. LPG Modularity needs: synchronization option between 2 or more systems
	Simplicity maintenance		Product design company should make the FCs using plug-in/out and modular interior design in order to make maintenance easy in local settings use a modular style in designing production in order to expand system whenever necessary	Feedback users for improvement Implementation	Energy centres in rural areas with spare parts, LPG, Fuel for When the centre will be too far away, people will not go there and use rather traditional fuels. Furthermore local people should be educated to maintain the FC system and repair it whenever necessary. To make maintenance easier eventually the whole system should be build using plug-in/out Easy maintenance requires the use of standard tools using the standard system for bolts, and screws, etc

		2008 – 2013	2014 – 2020	2021 – 2030	Issues
[Technology]	Efficiency	@2007: PEMFC with reformer: 50%	@2020: PEMFC with reformer: 50%+ co-generation of heat for indoor heating in winter	@2030: PEMFC with reformer: 50%+co-generation of heat for indoor heating in winter and use of waste heat for water heating	The cost per kWh using a FC is still a lot higher than kWh produced by coal. The concept of DAAFC is in research and no efficiencies are known yet. Expected is that the efficiency will become higher than PEMC because of higher fuel efficiency
		DAAFC: unknown yet, in research	DAAFC: goal to get greater efficiency than PEMFC with reformer		
	220-240V AC output and Peak power handling	Converter development (cost reduction + stability)	@2020 introduction of PEMFCs in rural areas output voltage should be according to grid standards: 220-240VAC, 50Hz	@2030 introduction of DAAFC in rural areas according to grid standards: 220-240VAC, 50Hz	Almost all electrical equipment uses 240V AC, 50Hz. To be able to use normal equipment (and keep initial cost of buying appliances low) this output is demanded. AFC and PEM can handle fluctuation in power demand. That is why these are favoured. Circuit has to have 2 steps to get from 50VDC to 240VAC; 1 is DC to AC and other is from 50V to 320V
		Over capacity design to handle peak power optimally			
Policy	Climate change	No standards but strict guidelines for air pollution in SA Kyoto protocol requirements to strive for	Follow-up of Kyoto protocol after 2012		Kyoto protocol is to be signed by SA plus its follow-up programme. SA agreed in principle on the non-binding successor of the Kyoto protocol in the 'Washington Declaration' on Feb 17th, 2007. National Environment Management Act 2004 including Air Quality
			Reduction of (greenhouse) gasses in whole life cycle of FC		
	Pollutants		Reduce indoor pollution		National Health Policy and Air Quality Act
	Safety		Reduce accidents by using FCs instead of candles in the house		Reduce number of houses burning down
	Re-use and recycling		Start national programme for recycling FCs	From the year 2022 zero waste production by disposing old FC	Polokwane (Pietersburg) declaration to produce "zero-waste" in 2022

4.4 SWOT analysis of the CSIR FC R&D programme

After the workshop a SWOT analysis was formulated as indicated in the T-plan using the information gained from the pre-interviews and the issues discussed in the workshop The Strength, Weaknesses, Opportunities and Threats show the current situation of the FC focus group of the CISR. The strengths and weaknesses are formulated from intern perspective while the opportunities and threats are formulated from an external perspective.

T-Plan: ***SWOT analysis***

#	Opportunities	#	Threats
	Electrify rural using FCs & stimulate economy		Employees leaving (country)
	AFC breakthrough using ethanol		FCs not accepted in community
	Patents for CSIR		Competitors breakthrough
	Oil price up → search for alternatives		Improvements internal combustion
	Energy packs (multiple sources of energy)		Search for other than Pt based FC
	Learning factor from earlier projects		People in rural areas too poor to pay any bills
	SA's growing economy		Resilience to social behavioral changes

#	Strengths	#	Weaknesses
	Research based		Bad at retaining employees
	PEM knowledge		No coordinated action plan; only lose divisions
	CSIR knowledge about rural area		Long way before FCs to be marketed to mass
	SA's rich Pt resources		Too much view from engineering perspective
	Energy carrier uses existing appliances, etc.		Technology too complicated for remote areas

Figure: 4.3 SWOT analysis

The weaknesses provided in figure 4.3 show that the skilled people working at CSIR change jobs often through which knowledge flows away. It was suggested in the interviews in appendix 9 that incentives should be used to retain employees. Furthermore it was recommended that divisions should work together more often to use in-house knowledge better. Using TRs could be helpful in this because TRs demand the interaction of experts from different fields. The TR in paragraph 4.2 shows that the actual introduction of FCs is still quite far in the future. PEMFCs are marketed in the year 2020 and DAAFCs only in 2030.

Currently, it is mentioned that people working at the CSIR are mostly researching without looking from a market (customer) point of view. Because of this engineering perspective the abilities of the end user are often forgotten and the technology tends to become too complicated. So, the FC focus group at the CSIR is very research based. This motivates developments and increases the knowledge in FCs. Currently the focus is on PEMFCs but the DAAFC is becoming a focus point as well. One of the reasons for interest in FCs is because SA has a lot of Platinum that it would like to use for the FC industry worldwide. To retain the use of Pt in FCs in the future in order to stimulate the economy it is CSIR's thrive to do breakthrough research and obtain patents.

One of the threats to knowledge management on FCs is that lots of knowledge flows out of the CSIR because people change jobs to work. The trend among young educated people is to leave SA after they have finished their honours programme (programme between bachelor and master programme) hoping to find a job in a safer and more stable country.

A serious threat considering developments in FCs is that FCs might not be accepted in a community. In order to make sure that this is overcome the main driver that came out of the TR is to include client needs already from the beginning. Furthermore a threat is that people living in these rural places cannot afford to pay the electricity bills. The interviews before the workshop suggested to financially help these areas in order for them to set up companies so that they can make money to pay their bills. Furthermore it was stressed that the free monthly electricity, 50kWh, should reach the people and areas that actually need it. Now everybody can apply for this amount with certain load restrictions. It might be good to revise this idea and provide it only to people who really need it and by these savings a little more could be provided to these people who need it.

Another threat is that competitors do a breakthrough in research through which the CSIR is forced to change its programme in order to keep up with (global) developments. Also improvements in the internal combustion engine can play a significant role. One of the biggest competitors of the FC is the diesel generator that currently is significantly cheaper. Improvements in these might increase the gap to be bridged by FCs. On the other hand the CSIR might achieve breakthrough research in developments in AFCs through which the gap might become closed and FCs eventual become a real competitor.

As becomes clear from this research the use of FCs in rural settings might stimulate the economy in those areas as well. Electricity can be used in shops so that they can stay open longer because of lighting. Also when electricity is available they can have computers, refrigerators, etc. This way the economy of SA gets stimulated because more people can spend money.

For the CSIR the developments in FCs are advantageous because they can use this technology also in other niche applications to replace e.g. batteries. Furthermore the CSIR has experience from earlier projects in which some rural areas around the Cape areas were electrified using solar home systems. They can learn from the good and bad things in these projects.

4.6 Reflection on TR process at CSIR

The future of R&D developments is less predictable than putting a certain tangible product in the market. The R&D developments in FCs are dependent on developments in the whole world. To set certain targets for the next 20 years is therefore rather difficult and will include many uncertainties. To put an (incremental) product in the market on the other hand is easier and more tangible than the introduction of a new technology as is the case with the introduction of FCs in rural places of SA without electricity grid. So, it seems easier to use the tool of TR for introduction of existing (incremental) products than new more (radical) technologies and products. However, with some modifications to the existing tool of TRM an attempt can be done to set targets for future developments; even when it considers a company in R&D settings.

It should be taken into account that even the introduction of grid power in these rural areas can be seen as radical innovation because in those places local people still use traditional fuels instead of electricity. So, whether grid electricity or electricity generated by FCs is introduced does not make any difference for them as long as the output is according to grid specifications. It stays a radical innovation for them because it is a significant change to go from traditional fuels to electricity. That is why these local people should be learned how to use this ‘new’ kind of technology: electricity.

The process of TRM at the CSIR is by the author considered to be an alternative to the fast-start technology developed by the University of Cambridge. To save lots of time from the participants it is considered to shorten the number of contact hours between the participants in the workshop up to one half day workshop. However, it should be noted that it might be wise to use a second half day workshop next time to verify all data generated in the first workshop and to discuss where the TR is heading. This way the specialists involved can confirm the path to set for the future and discuss it once more in a multiple disciplinary environment. All communication between different disciplines should be encouraged at all times. Each discipline has its own expertise and experience from earlier projects that might be helpful in solving particular problems in new projects. This also became clear from the pre-interview that this is not always the case. In order to learn from each other the multidisciplinary (multi-focus group at CSIR) should be utilized. It should not be forgotten that one of the main purposes of the TR is to get more communication between different disciplines so that more knowledge and viewpoints can be used. Therefore the second workshop is recommended to do in future TRM. Furthermore the author suggests that a first rough version of the TR is developed and presented at the beginning of the second workshop. This rough version can be developed from the discussions in the first workshop on the trends and drivers, and additionally from what is discussed in literature. The main focus of the second workshop will be on evaluating which trends and drivers to focus on and to set targets for these in the future. If the TR is about a new technology it is recommended not go into great detail when it concerns something for the far future (>10 years) because technology developments may often change over time.

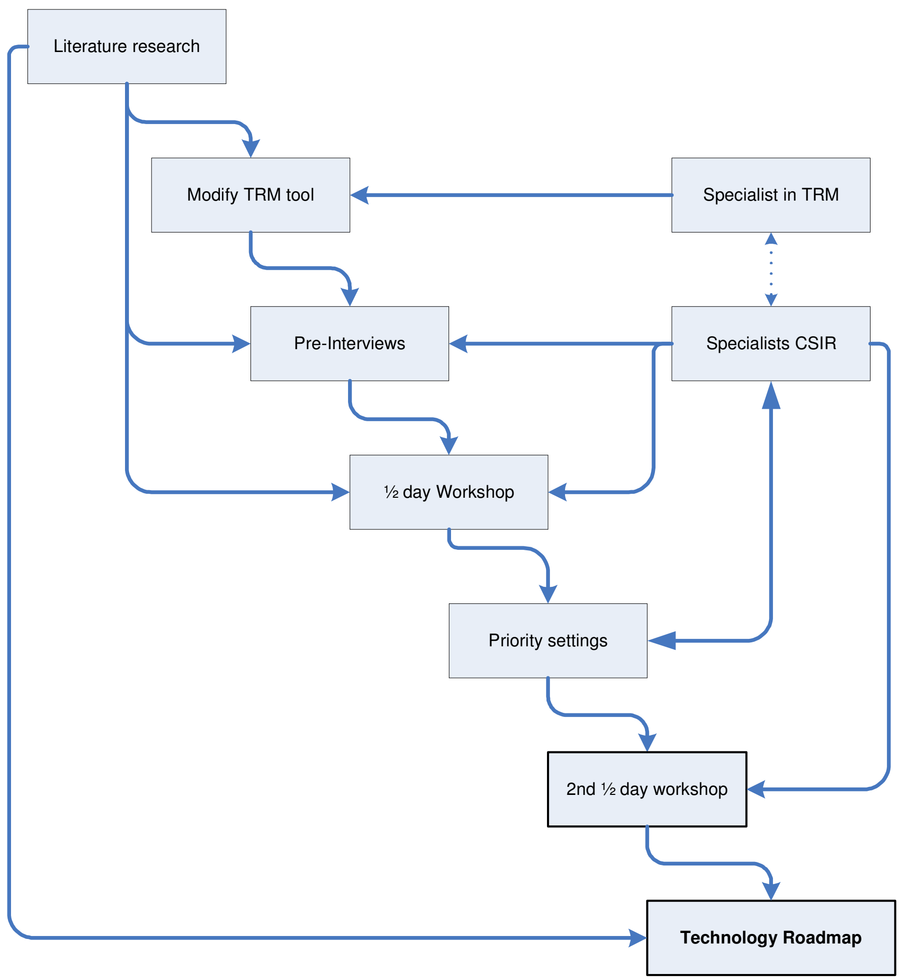


Figure 4.4: Proposed TRM model in R&D settings

5. Conclusions and recommendations

5.1 Conclusions

5.1.1 Electrifying remote South Africa without grid connection using stationary fuel cells

The first research question for this explorative research was to find out what the main considerations were for implementing Fuel Cells (FCs) in remote areas of South Africa (SA) and how the technology roadmap (TR) for such implementation would be.

The main considerations for implementing FCs can be split into five themes: society, economy, environment, technology, and policy. These themes discuss the main reasons for introduction of FCs in these areas. All these trends and drivers will first focus on the general 'picture' in SA, then the TR specific focus points for the CSIR are discussed.

Society:

General Trends and drivers

- After the apartheid ended in 1994 government did a concession which resulted in the 'electricity for all programme' that requires that all households in SA should have access to electricity for at least lighting by the year 2014.
- SA's population is growing and the number of households is increasing even more due to the trend that households become smaller.
- People feel inferior when they are not given the opportunity to connect to the national power grid or a grid with similar properties. Electricity makes it for people possible to use modern devices:
  - Lighting
  - Cell phones
  - Refrigerators
  - TV
  - Radio
  - Computer
- Safety increases:
  - Less people die from carbon mono-/dioxide poisoning or burning houses
  - On the streets by introducing streetlights

Focus points at CSIR; the TR outcome

- Client needs should be taken into account from the beginning of developing new technologies; there should be a balanced mix of technology push and market pull
- Knowledge transfer and the increase of skilled in people developing FCs should be focused on. The FC focus group needs to expand with about five researchers in order to increase the amount of intellectual property
- People should know how to use the FCs in order for them to use the system
- Maintenance should be organized locally so that they can go to a kind of familiar person. So, local people should be taught
- Create awareness at local people of benefits FCs have already before the system is introduced.

Economy:

General Trends and drivers

- SA has a great amount of minerals including Platinum that could be used on electrodes in FCs
- Introducing FCs in rural settings will stimulate economy in those regions and will contribute to local people being able to pay their (electricity) bills:
    - Small local businesses can use electricity for:
        - A computer for all kind of purposes (billing, ordering, etc.)
        - Possibility to stay open after dark (especially important for shops)
        - Use of security devices
        - Refrigerating through which fresh supplies hold longer
    - Education can be given after dark in schools thanks to lighting

Focus points for CSIR; the TR outcome

- The FCs should contain Platinum to stimulate export of this mineral
- Keep cost price low, including spare parts
- The FC should operate on 'cheap' fuels that can be supplied easily (e.g. alcohol)
- IP development in order to sell technology if it is a success
- Find niche markets to increase number of sales and applications the FC is utilised in

Environment:

General Trends and drivers

- The environmental burden by the increase of population growth in SA
- FCs can be cleaner in use than e.g. diesel generators
- SA signed the follow-up program of the Kyoto protocol in the Washington declaration in 2007
- SA set policy to produce 'zero waste' by 2022 in the Polokwane declaration.

Focus points for CSIR; the TR outcome

- Create awareness of health problems that might be caused by use of traditional fuels and teach school children in alternative energy sources including FCs so that they will use the technology when it becomes available
- Decrease of non-rechargeable batteries when the FC is introduced

Technology:

General Trends and drivers

- Two kinds of FCs could be applied in rural settings for small scale electricity generation: DAAFC and the PEMFC because these can handle continuous demand fluctuations
- SA mainly depended on coal for electricity generation
- SA's capacity for electricity generation is close to its limits there FCs could form a good alternative
- FCs only provide electricity when fuels are added in contrary to e.g. a battery
- Some FCs, e.g. PEMFCs, could work as backup energy systems in case of power failure (happens quite often because electricity supply is to its limits)
- SA would like to be placed on the 'map' considering research in FCs. Because they have lots of Platinum they would like to try to do breakthrough research on FCs that use Pt while other countries are more focused on alternative and cheaper materials. It is of great importance for SA's economy to sell lots of Pt globally
- FCs not for heating or cooking (direct hydrogen or LPG)

Focus points for CSIR; the TR outcome

- PEMFC:
    - Should be marketed by the year 2020, field testing from the year 2014
    - Needs hydrogen as fuel

        - Direct hydrogen gas
        - Hydrogen from reformer by using liquid alcohol that can be transported easily. Reforming process should be optimised
    - Keep Pt in system but reduce amount needed to decrease costs
    - Develop more poisoning resistant catalyst and make the system work on less pure hydrogen
    - Improve fuel efficiency
- DAAFC:
    - Should be marketed by the year 2030, field testing from the year 2025
    - Less developed technology: breakthrough research needed to make it competitive to PEMFCs
    - Power density and efficiency should be improved
    - Higher output voltage per cell expected than PEMFCs
    - Needs alcohol as a direct fuel, research in multiple alcohols needed
    - Purity of alcohol needs to become less without augmenting the poisoning of the system
    - The membrane of the FC needs research in stability and optimal conducting of hydroxy-ions.
- FC systems should be made modular so that capacity can be expanded when necessary
- Maintenance should be decentralised and taught to local people
- Output voltage should be according to grid specifications: 220V-240V AC, 50-60Hz

Policy:

General Trends and drivers

- 'Electricity for all programme' to connect all households by the year 2014
- 'Polokwane declaration' to produce zero-waste by the year 2022
- 'Washington declaration' to take part in the follow-up programme of the Kyoto protocol
- 'National Air Quality Act' since 2004 to set requirements for emissions into the air

Focus points for CSIR; the TR outcome

- Comply with the mandate of CSIR to improve life of SA people
- Comply with national laws, programmes, and declarations

Al these focus points are considered to be taken into account while developing FCs. The general trends mainly focus on South Africa's national aspects and the others on the CSIR-specific aspects. From national point of perspective the focus during this research has been on setting targets for implementation of FCs for small scale electricity generation while the CSIR's perspective has been on technology developments in FCs: PEMFCs and DAAFCs.

Considering the electrification of rural places not yet connected to the national power grid it can be concluded that they would like to be connected to it or get electricity that has similar properties. They feel left behind if no electricity is supplied at all. When electricity is supplied, the poverty tariff, 50kWh for free each month, can help people in paying their basic electricity need: lighting. However, this poverty tariff is often considered not to be enough because people just do not make enough money or have no job at all to pay the rest of their bill(s). Often when electricity is supplied the poverty tariff is not supplied to the people who actually need it due to bad local government regulations. Also when electricity is available people cannot afford to buy appliances to connect to it. Therefore electricity is still considered to be a luxury.

Considering the technology aspects in FCs it can be concluded that the CSIR should focus on developing a FC that can be applied both in rural and niche applications. This is to spread risks and increase the return on investments in research by selling the developed technology in FCs. The FC-use in rural settings will be stimulated and eventually the systems will be bought by government while the niche application FC-use will be driven by private companies. Two FCs comply with the use in both types of market because they can handle fluctuations in demand: DAAFC and the PEMFC. Research needs to be done to improve efficiency and materials to be used to make the FC a true competitor to e.g. the use of a diesel or small gas turbine generator. By 2020 the PEMFC should be ready to be marketed in the areas that still supplied with temporary electrification e.g. done by diesel generators.

5.1.2 Technology Roadmapping in R&D settings

The second research question was to find out what the benefits and constraints are of utilising the TR in an R&D institution, which considers developing a new technology in remote market settings. Furthermore, it is evaluated what aspects are useful and what not.

It is concluded that the concept of Technology Roadmapping (TRM) could be utilised in an R&D institution. However, modifications to the standard approach of TRM, the T-plan developed by the University of Cambridge to fast-start technology roadmapping, were considered necessary in order to be useful for the R&D settings at the CSIR. First, the number of contact hours between specialists involved in developing a technology roadmap (TR) was decided to be reduced with 75% up to only one half day workshop instead of four. To still get all the necessary information to set up the final TR it was chosen to pre-interview all specialists. The results formed the input for discussion during the workshop. Furthermore, results from the literature research and knowledge and experience from every specialist formed input during the discussions on setting the path to develop FCs for rural electrification in South Africa (SA). People were gathered from different disciplines as also is done in the standard approach of TRM. After the workshop people were asked to prioritize the outcome of all trends and drivers and to provide their opinion on the correlation between two drivers. Finally, the results were gathered in a TR.

Standard TR was considered to take too much time from all specialists involved. Also, standard TR was considered not applicable in the case of the CSIR. Standard TR is performed in incremental products but not in developing new kinds of technology. These development settings are coherent with R&D settings and differ from product development in that future capabilities of a certain technology are very hard to predict or to set. TRM nevertheless has been performed before in technology settings but then it was utilised for setting e.g. environmental targets country wide or to set a plan for introducing an existing technology into the market. However, this research is done for a technology that is still in development and some parts are even only in its infancy. This has made it even harder to predict and set a path for the future.

The benefits furthermore can be found in the properties of TRM itself. TRM stimulates the communication between departments or focus groups because the specialists all have their own expertise and during the workshop they can exchange information. This way more knowledge can be exchanged that might be useful and people can learn from earlier projects in a different department having similar settings and former pitfalls can then be avoided.

The modified TRM approach also has some constraints. First, because the number of contact hours between the specialists is decreased the communication between them is decreased as well. This might negatively influence the interaction process. The recommendations in chapter 5.2 will tell more about this.

Also, it should be taken into account that this research concerned developing a TR on fuel cells still in its infancy (DAAFC). It is not clear how this technology will further evolve. Only targets and rather vague expectations could be set, in contrary to the development of a simple product with a well known technology. In case of the new technology visualizations is impossible. Only few time slots could be set to work to with a rather wide spread of 5 years. During new product development it is easier to visualize where to head to using standard TRM tools. While developing the TR for the CSIR this was not possible and therefore it was chosen to use three timeslots to set future targets. In these timeslots the targets were described instead of visualized.

So, overall it can be concluded that TRM is a tool that can be utilised in R&D settings when some modifications are done like pre-interviewing and utilizing less workshops. This will save costly time from all specialists involved. The multidisciplinary environment in which TR are developed stimulate communications through which possible future pitfalls can be avoided. Communications between both the end-customer and the CSIR and within the CSIR are the main focus points of TRM in the future.

5.2 Recommendations

5.2.1 Electrifying remote South Africa without grid connection using stationary fuel cells

The TR developed in this research is a first-cut version. This means that the contents should be verified and update frequently. This can be done by redoing the whole process but another option could be to split the process up in small pieces. The pieces could e.g. be the five drivers from this research. When the pieces are handled separately, more specific targets can be set to comply with the whole targets of the general TR. In those driver specific workshops specialists from that field could join and set specific paths and goals for the future developments. Then, when specific targets are set, these should be executed according to plan or, when it is somehow not possible to execute (yet), the TR will need to be updated.

Furthermore, it is recommended to consider all five trends and drivers in developing FCs, and it should not be forgotten to include the requirements of the end-users: the local people who are not yet connected to the national power grid. They eventually will need to use the system and if they for some reason are not satisfied with it, they will not use it. Although the CSIR is not directly delivering products to the end-user they still should be taken into account in every phase of development.

From society point of perspective it is recommended that as many households as possible are connected to electricity because then they do not feel left behind. The poverty tariff can help people making their electricity bill decrease but it is recommended that the free electricity gets to the people who actually need it and really cannot afford electricity. Reduction in CO and CO_2 caused by decrease in use of traditional fuels should be the environmental divers. FCs could help in reducing these emissions. From technology point of perspective it is recommended that the output of the FC system is according to grid specifications. Furthermore, policies are the recommended drivers in reaching certain goals like the 'electricity for all' programme.

From the CSIR's point of perspective it the focus is recommended to be on IP development and to hire some more experts to boost the research programme. For rural electrification the transport issue of the fuel is to be researched in more depth. Or now it is recommended to invest more in research on the DAAFC because this FC uses easy to transport alcohol as a direct fuel. If the DAAFC can get the same or even better properties as the PEMFC then the introduction of FCs in rural areas could actually become a fact. PEMFCs can be used as well but they will need a reformer to make hydrogen first. When more researchers are improving the DAAFC developments will go faster; not only because the capacity is e.g. tripled, but those three people together can produce more than separately. Considering economy of SA it is recommended to keep using Pt in the FCs but the amount needed should decrease significantly otherwise the FC will still be too expensive and alternatives are researched for even harder. From both economic and environmental perspective the efficiency is recommended to be improved so that less fuel is needed. Also the developments in fuel purity need to be focused on because costs of fuel can go down when hydrogen or alcohol does not need to be very pure to prevent the FC to be poisoned.

5.2.2 Technology Roadmapping in R&D settings

From the TRM approach done in this research it is recommended to modify the currently used tool with an extra half day workshop after the prioritization. The first workshop's result should be the main input for this day and furthermore the input from specialists. At least the same specialists as in first workshop should participate but it is recommended that some more specialists are invited that have certain needed expertise in a certain field to share their knowledge to set the future R&D developments in the right direction.

Also, it is necessary that people come to the workshop prepared so that they actively participate in discussions and provide their experience and thoughts on future developments otherwise wrong paths might be set or not be complete. The second half day workshop might also have a positive influence on this because people might have thought about it and they might come with a better proposal or are then able to provide more detail because they have thought about it after the first workshop.

Most important is not to forget that the TR should be updated frequently and specialists from different fields should provide their knowledge and points of view on future developments. Knowledge sharing and communication between focus groups form the key to success.

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Appendices

Appendix 1: Map of South Africa

Appendix 2: Conversion factors, Prefixes, and Calorific values

Conversion factors:

From \ To	J	kWh	toe	Btu
1 J	1	0.278×10^{-6}	0.2388×10^{-6}	0.948×10^{-3}
1 kWh	3.6×10^{6}	1	0.86×10^{-6}	3.412×10^{3}
1 toe	42×10^{9}	11630	1	39.68×10^{6}
1 Btu	1.055×10^{3}	0.293×10^{-3}	0.252×10^{-9}	1

Source: DME (2006)

Note: toe = ton oil equivalent

Prefixes:

Prefix	Symbol	Power
Kilo	k	10^{3}
Mega	M	10^{6}
Giga	G	10^{9}
Tera	T	10^{12}
Peta	P	10^{15}
Exa	E	10^{18}

Source: DME (2006)

Calorific values:

Fuel	Calorific Value	Units	Density
Electricity	3,6	MJ/kWh	
Natural Gas	41,0	MJ/m^3	
LPG (Liquefied Petroleum Gas)	26,7	MJ/l	0,541
Petrol	34,2	MJ/l	0,723
Avgas	33,9	MJ/l	0,730
Illuminating Paraffin	37,0	MJ/l	0,788
Power Paraffin	37,5	MJ/l	0,813
Jet Fuel	34,3	MJ/l	0,793
Diesel	38,1	MJ/l	0,839
HFO (Heavy Furnace Oil)	41,6	MJ/l	0,984
Coal (Eskom - average 1994)	20,1	MJ/kg	
Coal (General purpose)	24,3	MJ/kg	
Coal (Coking)	30,1	MJ/kg	
Coke	27,9	MJ/kg	
Coke oven gas	17,3	MJ/m^3	
Blast furnace gas	3,1	MJ/m^3	
Refinery gas (estimate)	20,0	MJ/m^3	
Bagasse (wet)	7,0	MJ/kg	
Bagasse fibre (dry)	14,0	MJ/kg	
Biomass (wood dry typical)	17,0	MJ/kg	
Coal gas (Sasol)	18,0	MJ/m^3	
Coal gas (Sasol - methane rich)	38,0	MJ/m^3	

Source: DME (2006)

Appendix 3: Projections of electricity capacity by plant type in GW

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Existing coal	33.5	33.5	33.5	33.5	33.5	33.5	33.5	33.5	33.5	33.5	32.9	32.9
Nuclear PWR	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Bagasse	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Diesel gas turbines	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Hydro	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Interruptible supply	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Pumped storage	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Imported electricity	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Mothballed coal	-	-	-	-	0.4	0.8	1.5	2.8	3.6	3.6	3.6	3.6
New coal	-	-	-	-	-	-	-	-	-	-	-	-
New OCGT diesel	-	-	-	-	-	0.2	0.6	1.4	2.1	2.3	2.3	2.3
New CCGT	-	-	-	-	-	-	-	-	-	0.6	2.0	2.0
New FBC	-	-	-	-	-	-	-	-	-	-	-	-
New pumped storage	-	-	-	-	-	-	-	-	-	-	-	0.7

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Existing coal	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.2	30.3	30.3	30.3	30.3
Nuclear PWR	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Bagasse	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Diesel gas turbines	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Hydro	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Interruptible supply	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Pumped storage	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Imported electricity	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Mothballed coal	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
New coal	-	-	0.1	0.9	1.7	2.5	3.3	4.2	6.1	9.2	10.2	11.2	12.2
New OCGT diesel	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
New CCGT	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
New FBC	0.8	1.6	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
New pumped storage	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7

Source: Winkler et al. (2006)

Appendix 4: Households by dwelling and type of fuel for cooking, heating, and lighting

Energy for Cooking:

	N (1 000)										
	Energy for cooking										
Type of dwelling	Electricity from mains	Electricity from generator	Gas	Paraffin	Wood	Coal	Animal dung	Solar energy	Other	None	Total
Total	**8 222**	**12**	**291**	**2 086**	**2 011**	**271**	**38**	**2**	**4**	**18**	**12 972**
Dwelling/house/brick structure on a separate stand or yard or on farm	5 415	11	184	753	1 011	186	11	*	*	*	7 581
Traditional dwelling/ hut/ structure made of traditional materials	238	*	12	265	808	26	23	-	-	*	1 377
Flat/apartment in a block of flats	608	*	*	20	14	-	-	*	-	*	645
Town/cluster/semi-detached house (simplex/duplex/triplex)	265	-	*	*	*	-	-	-	-	-	278
Unit in retirement village	11	-	-	*	*	-	-	-	-	-	15
Dwelling/house/flat/room in backyard	468	-	*	62	49	*	*	*	-	*	592
Informal dwelling/shack in backyard	392	-	20	285	25	20	*	-	*	*	745
Informal dwelling/shack not in backyard	360	-	53	617	66	35	*	-	*	*	1 135
Room/flatlet	242	-	*	42	26	*	-	-	*	*	317
Caravan/tent	14	-	*	*	*	-	-	-	-	-	18
Other	202	-	*	24	*	*	-	-	-	*	245
Unspecified	*	-	-	*	*	-	-	-	-	-	24

* For all values of 10 000 or lower the sample size is too small for reliable estimates.
Due to rounding numbers do not necessarily add up to totals.
Totals include the 'unspecified' category of energy for cooking variable.

Source: StatSA (2006)

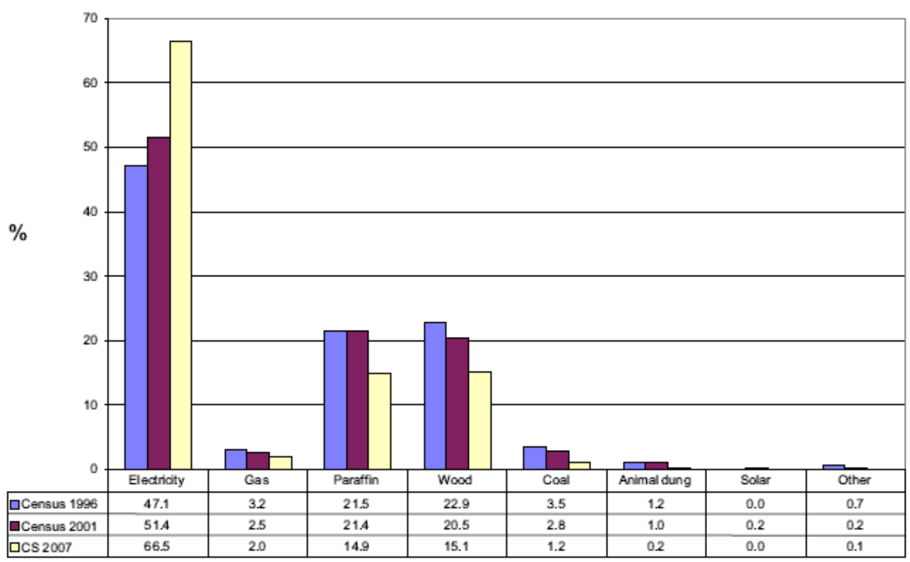


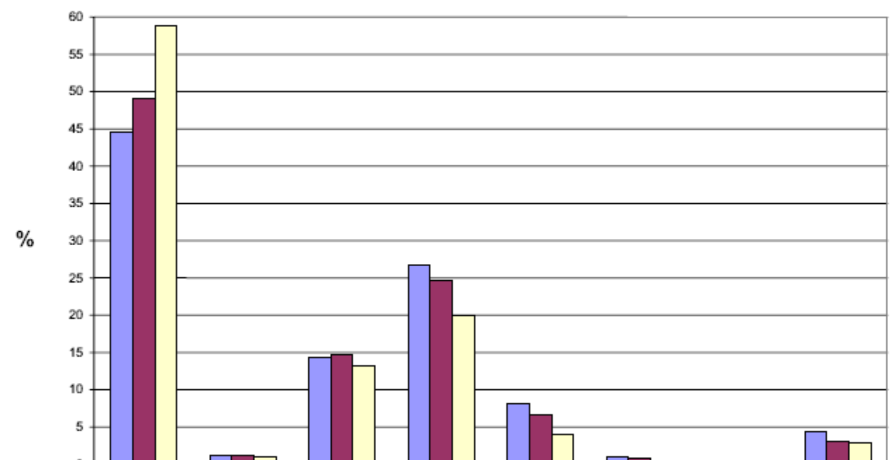
Figure a4.1: Percentage distribution of energy used for cooking (CS, 2007)

Energy for Heating:

Type of dwelling	N (1 000)										
	Energy for heating										
	Electricity from mains	Electricity from generator	Gas	Paraffin	Wood	Coal	Animal dung	Solar energy	Other	None	Total
Total	**6 470**	**7**	**119**	**1 772**	**2 631**	**599**	**50**	**11**	**52**	**1 227**	**12 972**
Dwelling/house/brick structure on a separate stand or yard or on farm	4 234	*	83	797	1 334	336	17	*	20	735	7 581
Traditional dwelling/hut/structure made of traditional materials	139	*	*	156	943	45	24	*	*	63	1 377
Flat/apartment in a block of flats	569	-	*	23	20	*	-	*	*	22	645
Town/ cluster/semi-detached house (simplex/duplex/triplex)	190	-	*	22	11	*	-	*	-	52	278
Unit in retirement village	*	-	-	*	*	-	-	-	-	*	15
Dwelling/house/flat/room in backyard	414	*	*	61	57	*	*	*	*	39	592
Informal dwelling/shack in backyard	282	-	*	235	52	52	*	*	12	98	745
Informal dwelling/shack not in backyard	209	-	14	427	168	148	*	*	*	155	1 135
Room/flatlet	205	-	*	27	32	*	-	*	*	43	317
Caravan/tent	13	-	-	*	*	*	*	-	-	*	18
Other	199	-	*	19	*	*	-	*	-	14	245
Unspecified	*	-	-	*	*	*	-	-	-	*	24

* For all values of 10 000 or lower the sample size is too small for reliable estimates.
Due to rounding numbers do not necessarily add up to totals.
Totals include the 'unspecified' category of energy for heating variable.

Source: StatSA (2006)



	Electricity	Gas	Paraffin	Wood	Coal	Animal dung	Solar	Other
Census 1996	44.5	1.2	14.3	26.7	8.1	0.9	0.0	4.3
Census 2001	49.0	1.1	14.6	24.6	6.6	0.7	0.2	3.1
CS 2007	58.8	1.0	13.1	20.0	3.9	0.2	0.1	2.9

Figure a4.2: Percentage distribution of energy used for heating (CS, 2007)

Energy for Lighting:

Type of dwelling	N (1 000)								
	Energy for lighting								
	Electricity from mains	Electricity from generator	Gas	Paraffin	Candles	Solar energy	Other	None	Total
Total	**10 520**	**9**	**10**	**449**	**1 925**	**30**	**5**	**2**	**12 972**
Dwelling/house/brick structure on a separate stand or yard or on farm	6 877	*	*	108	555	19	*	*	7 581
Traditional dwelling/hut/structure made of traditional materials	653	*	*	95	618	*	-	*	1 377
Flat/apartment in a block of flats	619	-	-	*	23	*	-	-	645
Town/cluster/semi-detached house (simplex/duplex/triplex)	273	-	-	*	*	-	*	*	278
Unit in retirement village	11	-	-	*	*	-	-	-	15
Dwelling/house/flat/room in backyard	519	*	-	*	63	*	-	-	592
Informal dwelling/shack in backyard	523	-	-	40	179	*	*	-	745
Informal dwelling/shack not in backyard	531	*	*	181	418	-	-	*	1 135
Room/flatlet	267	*	-	*	40	-	-	-	317
Caravan/tent	15	-	*	*	*	-	-	-	18
Other	221	-	-	*	17	*	-	-	245
Unspecified	11	-	-	-	*	-	-	-	24

* For all values of 10 000 or lower the sample size is too small for reliable estimates.
Due to rounding numbers do not necessarily add up to totals.
Totals include the 'unspecified' category of energy for lighting variable.

Source: StatSA (2006)

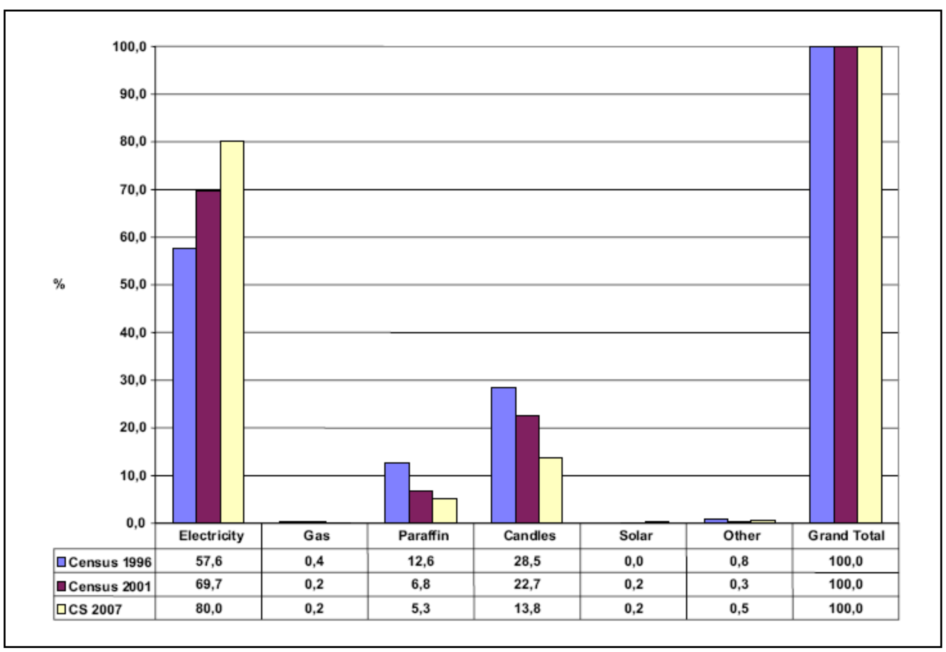


Figure a4.3: Percentage distribution of energy used for lighting (CS, 2007)

Appendix 5: Losses and transport of electricity

South Africa's electricity generation facilities are mainly coal-fired; this is not a very clean process because of the emission of greenhouse gasses as discussed earlier. The main coal reserves are found in the northern-central region of South Africa. Therefore, most of the electricity demand is supplied over long distances, which is inefficient and rather costly. This inefficiency is partly overcome by transferring the electricity in direct current (DC) instead of alternating current (AC) which has lower los of electricity in transport over long distances. Figure a5.1 provides information about how much energy is lost in GWh per annum. The amount lost per annum is rather high compared to the actual use as becomes clear in figure 5.6. During the rest of the research it should become clear why this amount of loss s so high. Most likely this is caused by the great distances from the production to the end-user.

High voltage [V] is used for transmission to reduce the energy lost in the resistance of the wires. For a given quantity of power transmitted, higher voltages reduces the transmission power loss. Power [P] in a circuit is proportional to the current [I] (P=V*I), but the power lost as heat in cables is proportional to the square of the current. However, power is also proportional to voltage as the formula is:

$$P_{loss} = RI^2 = R(\frac{P}{V})^2 = \frac{RP^2}{V^2}$$

This means that for a given power level, higher voltage can be traded off for lower current: thus, the higher the voltage, the lower the power loss in DC. Power loss can also be reduced by reducing resistance (R), commonly achieved by increasing the diameter of the conductor; but larger conductors are heavier and more expensive.

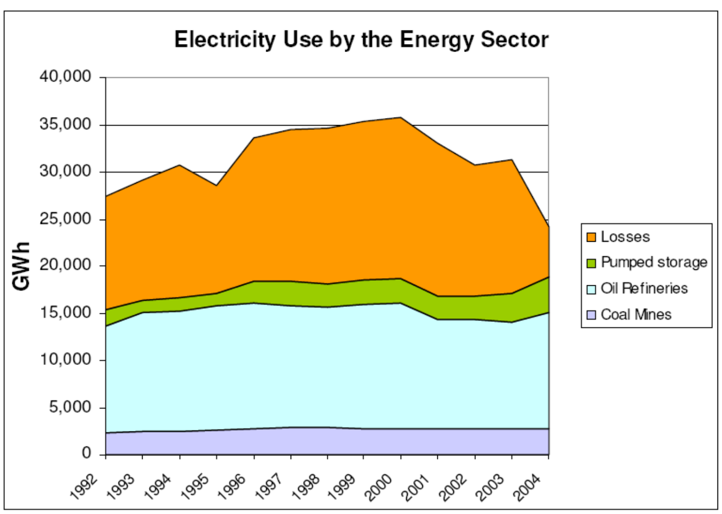


Figure a5.1: electricity use by energy sector and use

High voltages (e.g. 533kV as in South Africa, table a5.1) cannot be easily used in motors, so transmission-level voltage must be transformed to lower voltage to be compatible with end-use equipment. A transformer to reduce the voltage only works with alternating current but is an efficient way to change voltages. The biggest advantage of HVDC is its ability to transmit large amounts of power over very long distances at much lower capital costs and with much lower losses than AC. Its losses are quoted as about 3% per 1000 km. This has given rise to proposals to generate between 10-25% of Europe's electricity in Concentrating Solar Power Stations located in North African deserts, and feeding it to Europe via HVDC lines, see Trans-Mediterranean Renewable Energy Cooperation, www.trecers.net (2007).

In a number of applications the advantages of HVDC makes it the preferred option over AC transmission:

- Endpoint-to-endpoint long-haul bulk power transmission without intermediate 'taps', for example, in remote areas.
- Increasing the capacity of an existing power grid in situations where additional wires are difficult or expensive to install.
- Connecting remote generating plant to the distribution grid, for example Nelson River Bipole, Canada.
- Stabilizing a predominantly AC power-grid, without increasing maximum prospective short circuit current.
- Reducing Corona discharge (due to higher voltage peaks) for HVAC transmission lines of similar power
- Reducing line cost since HVDC transmission requires fewer conductors (i.e. 2 conductors; one is positive another is negative)
- Long undersea cables have a high capacitance. While this has minimal effect for DC transmission, the current required to charge and discharge the capacitance of the cable causes additional I^2R power losses when the cable is carrying AC. In addition, AC power is lost to dielectric losses.
- HVDC can carry more power per conductor, because for a given power rating the constant voltage in a DC line is lower than the peak voltage in an AC line. This voltage determines the insulation thickness and conductor spacing. This allows existing transmission line corridors to be used to carry more power into an area of high power consumption, which can lower costs.

The longest HVDC link in the world is currently the Inga-Shaba 1700 km 600 MW link connecting the Inga Dam to the Shaba copper mine, in the Democratic Republic of Congo (Siemens AG Power Transmission, 2007).

	2007	2006
Power lines		
Transmission power lines (km[1])	27 770	27 406
765 kV	1 153	1 153
533 kV DC (monopolar)	1 035	1 035
400 kV	15 799	15 691
275 kV	7 409	7 245
220 kV	1 336	1 336
132 kV	1 038	946
Distribution power lines (km)	44 044	43 330
165 – 132 kV	22 797	22 142
88 – 33 kV	21 247	21 188
Reticulation power lines (km)		
22 kV and lower	288 040	282 361
Total all power lines (km)	359 854	353 097
Cables (km)	8 622	8 031
165 – 132 kV	164	156
22 kV and lower	8 458	7 875
Total transformer capacity (MVA)	208 814	205 662
Transmission (MVA)[2]	118 630	118 445
Distribution and reticulation (MVA)	90 184	87 217
Total transformers (number)	314 507	305 776
Transmission (number)	377	374
Distribution and reticulation (number)	314 130	305 402

1. *Transmission line lengths as per Geographic Information System distances.*
2. *Transformers rated ≥30MVA and primary voltage ≥132kV.*

Table a5.1: Transmission and distribution equipment in service (Eskom Annual Report, 2007)

Table a5.1 shows all South African transmission lines in 2006 en 2007. Remarkable is the relative few kilometers of DC power lines. This means that lots of energy will get lost through distribution from the North East to the South West of the country (about 1800km). This is also visible in the graph that indicates the annual loss of electricity (figure a5.1, 1 page back). There will always remain electricity losses because of the geographical location of major power plants. These are located close to the largest coal mines in the northern part en eastern parts of South Africa. No evidence is found why so little DC lines are used. One reason could be that the power lines go from city to city through which AC lines will be cheaper because then less electricity will be lost in transforming from DC to AC.

Transformation from AC to DC and AC to AC into different voltages plays a second role in losses of energy. This is because transformers are needed and these produce heat. An ideal transformer would have no energy losses, and would therefore be 100% efficient. Despite the transformer being amongst the most efficient of electrical machines experimental models using superconducting windings achieved efficiencies of 99.85% (Riemersma et al., 1981). Energy is dissipated in the windings, core, and surrounding structures. Larger transformers are generally more efficient, and those rated for electricity distribution usually perform better than 95%. Transformer losses are attributable to several causes and may be differentiated between those originating in the windings, sometimes termed copper loss (Ohmic losses), and those arising from the magnetic circuit, sometimes termed iron loss. The losses vary with load current and the winding resistance dominates the load losses.

Appendix 6: Fuel Cells

General overview

Stambouli and Traversa (2002) describe an FC as an energy conversion device that generates electricity and heat by electrochemically combining a gaseous fuel (e.g. hydrogen) and an oxidant gas (e.g. oxygen from the air) through electrodes and across an ion conducting electrolyte. During this process, water is formed at the exhaust (figure a6.1). The FC does not run down or require any recharging; unlike a battery it will produce electricity as long as fuel is supplied. The characteristic of a FC is its ability to convert chemical energy directly to electrical energy giving much higher conversion efficiencies than conventional thermo–mechanical systems, so extracting more electricity from the same amount of fuel. It operates without combustion, so they are almost pollution free and have quieter operation since there are no moving parts. The next reactions are the basic features in the proton exchange fuel cell, the most commonly applied FC:

Anode: $2H_2 \rightarrow 4H^+ + 4e^-$
Cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$
Overall: $2H_2 + O_2 \rightarrow 2H_2O$ + energy

The Proton Exchange Membrane Fuel Cell (PEMFC) operates at a temperature of around 80°C. At this relative low temperature the electrochemical reactions would normally occur very slowly so it is catalyzed by a thin layer of platinum on each electrode.

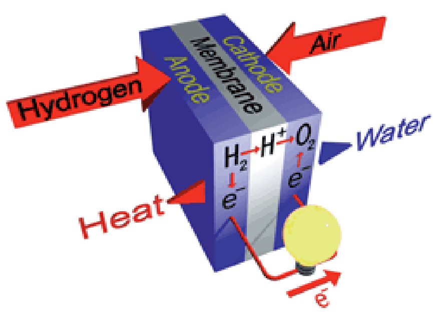


Figure a6.1: PEMFC schematically (www.fuelcelltoday.com, 2007)

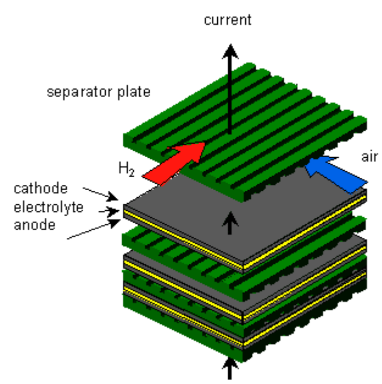


Figure a6.2: Fuel Cell stack (www.ecn.nl, 2007)

Multiple fuel cells in series form a fuel cell stack (figure a6.2) and the number of cells in the stack determines the output voltage in direct current (DC). Eventually the DC-current needs to be converted to alternative current (AC) in order to be useful for domestic usage. FCs are common in spaceflight transportation and make sense for use as portable power or home power generation (Stambouli and Traversa, 2002).

Besides PEMFC there are alternative fuel cells available with its own distinct properties, see table a6.1. The rest of this chapter will shortly define the properties of the different kind of fuel cells. At the end of the chapter a short conclusion will be drawn about which fuel cell would suit best in remote areas.

The first developments of the fuel cells go far back in time. The history of the fuel cell can be traced back to the nineteenth century to the work of the British judge and scientist, Sir William Robert Grove.

His experiments in 1839 on electrolysis where electricity was used to split water into hydrogen and oxygen, led to the first mention of a device that would later be called the fuel cell (fuelcelltoday.com, 2007). From there on the experiments started and made what the FC is today. Research and development has led to several different types of FCs to become applicable in different settings. Table a6.1 shows the main six most far developed kind of FCs.

	AFC	PEMFC	DMFC	PAFC	MCFC	SOFC
Operating temperature [Celsius]	80	40-120	60-130	200	650	1000
Electrolyte	KOH	Polymer	Polymer	Phosphoric acid	Molten Carbonate	Solide oxide
Application	Space, (transport)	Transport,Distributed power	Portable power, CHP	Distributed Power, CHP **	Distributed Power, CHP **	Distributed Power, CHP **
Status	Commercial/ research	Commercial/ research	Commercial/ research	Commercial/ research	Commercial/ research	Commercial/ research
Efficiency	Cell: 60-70%; system: 62%	Cell: 50-70%; system: 30-50%	Cell: 20-30%; system: 10-20%	Cell: 55%; system: 40%; co-gen: 90%	Cell: 55%; system: 47%	Cell: 60-65%; system: 55-60%
** = Combined Heat & Power, also known as co-generation						
* = Fuels accepting mixtures of H2 and CO2 can be combined with a reformer to also use hydrocarbons						

Table a6.1: Different kind of Fuel Cells and their properties (www.ecn.nl, 2007)

AFC: Alkaline Fuel Cell

According to www.fctec.com (2007) this kind of fuel cell, the Alkaline Fuel Cell (AFC), is one of the most developed technologies and have been used since the mid-1960s by NASA in the Apollo and Space Shuttle programmes. Alkaline fuel cells use an electrolyte that is an aqueous (water-based) solution of potassium hydroxide (KOH) retained in a porous stabilized matrix. The concentration of KOH can be varied with the fuel cell operating temperature, which ranges from 65°C to 220°C. The charge carrier for an AFC is the hydroxyl ion (OH-) that migrates from the cathode to the anode where they react with hydrogen to produce water and electrons. Water formed at the anode migrates back to the cathode to regenerate hydroxyl ions. This set of reactions in the fuel cell produces electricity and by-product heat which could be used in co-generation.

Anode Reaction: $2\,H_2 + 4\,OH^- \Rightarrow 4\,H_2O + 4\,e^-$
Cathode Reaction: $O_2 + 2\,H_2O + 4\,e^- \Rightarrow 4\,OH^-$
Overall Net Reaction: $2\,H_2 + O_2 \Rightarrow 2\,H_2O$

One characteristic provided by fctec.com (2007) about AFCs is that they are very sensitive to CO_2 that may be present in the fuel or air. The CO_2 reacts with the electrolyte, poisoning it quickly, and severely degrading the fuel cell performance. Therefore, AFCs are limited to closed environments only, such as space and undersea vehicles, and must be run on pure hydrogen and oxygen. Furthermore, molecules such as CO, H_2O, and CH_4, which are harmless or even work as fuels to other fuel cells, are poisons to an AFC.

On the positive side, AFCs are proposed to be the cheapest FCs to manufacture. This is because the catalyst required at the electrodes can be different relatively inexpensive materials compared to the more expensive catalysts as Pt required for other types of fuel cells. Because CO, H_2O, and CH_4 degrade the FC's performance rapidly, it is argued that this kind of FC is not (yet) the best to use in remote areas for electricity generation.

DAAFC: Direct Alcohol Alkaline Fuel Cell

The development in FCs continues all over the world because energy and especially electricity are demanded more every day. On the other hand people are becoming more and better aware about the consequences of the massive amount of energy generation. Global warming is nowadays high on the agenda of every country and alternative energy sources that are more environmentally are preferred and the exhaust of GHG is regulated and targets to reduce them are set.

Delivering fuels to fuel the FC in remote areas is one of the main issues; it is important that the fuel is a liquid. This makes transportation to the rural areas easier and also the transport from the distribution center to the houses where the FC is, a lot easier. Gas contains less energy than liquid in the same volume.

The DAAFC might be a very good option to use in rural settings. This FC uses an alcohol like ethanol and perhaps in the future glycerin directly. Using methanol the next chemical reaction is created:

Anode Reaction: $CH_3OH + 6OH^- \Rightarrow CO_2 + 5\ H_2O + 6e-$
Cathode Reaction: $3/2O_2 + 3\ H_2O + 6e- \Rightarrow 6OH^-$
Overall Reaction: $CH_3OH + 3/2O_2 \Rightarrow 2\ H_2O + CO_2$

As becomes clear from this reaction the GHG carbon dioxide is released in the air. As long as the amount of carbon dioxide is less than would have been produced using other kinds of energy sources, it is environmentally more efficient to use the DAAFC. Another option could be to capture the generated carbon dioxide and store it in the ground in old mines or to process it further into a less harmless (chemical) product.

PEMFC: Proton Exchange Membrane Fuel Cell

Proton Exchange Membrane Fuel Cells (PEMFC) (or Polymer Electrolyte Fuel Cells) are believed to be one of the best type of FC as the vehicular power source to eventually replace the gasoline and diesel internal combustion engines (www.fctec.com, 2007). First used in the 1960s for the NASA Gemini programme, PEMFCs are currently being developed and demonstrated for systems ranging from 1W to 50kW.

PEM fuel cells use a solid polymer membrane as electrolyte. This polymer is permeable to protons when it is saturated with water, but it does not conduct any electrons. The reactions at the electrodes are as follows:

Anode Reactions:	$2\ H_2 \Rightarrow 4\ H+ + 4e-$
Cathode Reactions:	$O_2 + 4\ H+ + 4e- \Rightarrow 2\ H_2O$
Overall Cell Reactions:	$2\ H_2 + O_2 \Rightarrow 2\ H_2O$

When the PEMFC is compared to other types of FCs, PEMFCs generate more power for a given volume or weight of FC. This characteristic of high-power density makes them lightweight and compact. Furthermore is the operating temperature less than 100ºC, which allows rapid start-up compared to others. These qualities and the ability to rapidly change power output are some of the advantageous characteristics that make the PEMFC, for now, the best solution to use in remote applications. Other advantages are that the electrolyte is a solid material, compared to a liquid in other kind of FCs. The sealing of the anode and cathode is simpler with a solid electrolyte, and therefore, cheaper to manufacture. (www.fctec.com, 2007). A disadvantage of using the PEMFC in remote areas is the degradation through various reasons: temperature, on-off or load cycling, and strong loads but not all these are not the major issues. The major issue is the price of both the platinum as electrolyte and the material Nafion for the proton exchange membrane. A last negative concern about the PEMFC is the distribution of the fuel (hydrogen) to these areas. It is costlier to get a gaseous fuel to these areas than a liquid one. Also the amount of fuel measured in Joule per Liter and mode of transport are better when liquid fuel would be used.

DMFC: Direct Methanol Fuel Cell

DMFC is similar to the PEMFC in that the electrolyte is a polymer and the charge carrier is the hydrogen ion (H^+), the proton and therefore this could be seen as a subgroup of the PEMFC. However, the liquid methanol (CH_3OH) is oxidized in the presence of water at the anode generating carbon dioxide, hydrogen ions, and electrons that go through the external circuit as the electric output of the fuel cell. The hydrogen ions go through the electrolyte and react with oxygen from the air and the electrons from the external circuit to form water at the anode completing the circuit (www.fctec.com, 2007). The reactions in this kind of FC are as follows:

Anode Reaction: $CH_3OH + H_2O \Rightarrow CO_2 + 6H+ + 6e-$
Cathode Reaction: $3/2\ O_2 + 6\ H+ + 6e- \Rightarrow 3\ H_2O$
Overall Cell Reaction: $CH_3OH + 3/2\ O_2 \Rightarrow CO_2 + 2\ H_2O$

These cells have been tested in a temperature range from about 50ºC-120ºC. This low operating temperature and no requirement for a fuel reformer, to produce hydrogen as e.g. the PEMFC requires, make the DMFC a very good option for relatively small to mid-sized applications e.g. cellular phones and other portable consumer products, even up to the use in automotive. (www.fctec.com, 2007). So, also the use to generate electricity in remote areas is one of the possible future applications.

One of the disadvantages of the DMFC is that the low-temperature oxidation of methanol into hydrogen ions and carbon dioxide requires a more active catalyst, which typically means that a larger quantity of expensive platinum as catalyst is required than in a conventional PEMFC. This increases costs significantly, but is, however, expected to be more than outweighed by the convenience of using a liquid fuel and the ability to function without a reforming unit (www.fctec.com, 2007).

Another disadvantages that becomes clear from the reaction given above is the fact that this type of FC produces CO_2 which is one of the GHGs and therefore the reaction should include an after process to capture this gas and store it e.g. in the ground or bind it in another chemical.

A last concern is in the fact that methanol is toxic. Therefore, an alternative to the use of the toxic methanol is researched: ethanol, which is not toxic. Direct Ethanol Fuel Cell (DEFC) is researched to become the not poisonous alternative. However, the performance of the DEFC is currently about half that of the DMFC, but this gap is expected to narrow with further developments in the future (www.fctec.com, 2007). When the DEFC is developed up to the same energy properties as the DMFC this system could be a better safer, and healthier option for electricity generation in remote areas because ethanol is easier and safer to transport and supply than hydrogen.

PAFC: Phosphoric Acid Fuel Cell

Phosphoric Acid Fuel Cells (PAFC) were the first fuel cells to be commercialized. Developed in the mid-1960s and field-tested since the 1970s, they have improved significantly in stability, performance, and cost. Such characteristics have made the PAFC a good candidate for early stationary applications. The PAFC uses an electrolyte that is phosphoric acid (H_3PO_4) that can approach to 100% concentration. The ionic conductivity of phosphoric acid is low at low temperatures; therefore PAFCs are operated between 150ºC–220ºC. The charge carrier in this type of fuel cell is the hydrogen ion (H+, proton). (www.fctec.com, 2007). The reactions considering this fuel cell are the next:

Anode Reaction: $2\ H_2 \Rightarrow 4\ H+ + 4\ e-$
Cathode Reaction: $O_2\ (g) + 4\ H+ + 4\ e- \Rightarrow 2\ H_2O$
Overall Cell Reaction: $2\ H_2 + O_2 \Rightarrow 2\ H_2O$

The PAFC operates at greater than 40% efficiency in generating electricity. When operating in cogeneration applications, the overall efficiency is approximately 85%. Furthermore, at the operating temperature of PAFCs, the waste heat is capable of heating water or generating steam at atmospheric pressure. In addition, CO_2 does not affect the electrolyte or cell performance and can therefore be easily operated with reformed fossil fuel. Its simple construction, its low electrolyte volatility and its long-term stability are additional advantages (www.fctec.com, 2007). For the use in remote areas this cell is a candidate as well. Only disadvantage is about the liquid electrolyte instead of a solid one. Therefore, if the phosphoric acid somehow will leak out of the fuel cell, this will have a negative impact on the environment.

MCFC: Molten Carbonate Fuel Cell

MCFCs work quite differently from other fuel cells (www.fctec.com, 2007). These cells use an electrolyte composed of a molten mixture of carbonate salts. Two mixtures are currently used: lithium carbonate and potassium carbonate, or lithium carbonate and sodium carbonate. To melt the carbonate salts and achieve high ion mobility through the electrolyte, MCFCs operate at high temperatures (650ºC).

When heated to a temperature of around 650ºC, these salts melt and become conductive to carbonate ions (CO_3^{2-}), see also figure a6.4. These ions flow from the cathode to the anode where they combine with hydrogen to give water, carbon dioxide and electrons. These electrons are routed through an external circuit back to the cathode, generating electricity and by-product heat.

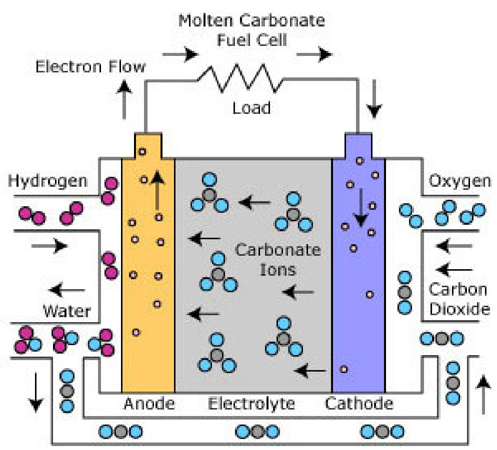


Figure a6.4: MCFC explained (www.fctc.com, 2007)

Typical reactions for this fuel cell are:

Anode Reactions: $CO_3^{2-} + H_2 \Rightarrow H_2O + 2e-$

Cathode Reactions: $CO_2 + ½ O_2 + 2e- \Rightarrow CO_3^{2-}$

Overall Cell Reaction: $H_2(g) + ½ O_2 + CO_2$ (cathode) => H_2O (g) + CO_2 (anode)

The higher operating temperature of MCFCs has both advantages and disadvantages compared to the lower temperature PAFC and PEFC. At the higher operating temperature, fuel reforming of natural gas can occur internally, eliminating the need for an external fuel processor. Additional advantages include the ability to use standard materials for construction, such as stainless steel sheet, and allow use of nickel-based catalysts on the electrodes. The by-product heat from an MCFC can be used to generate high-pressure steam that can be used in many industrial and commercial applications or water heating in remote areas when the system would be used for this purpose.

The high temperatures and the electrolyte chemistry also have disadvantages. The high temperature requires significant time to reach operating conditions and responds slowly to changing power demands. These characteristics make MCFCs more suitable for constant power applications like industries and not to provide energy to remote areas who demand most energy during the evening for cooking, heating, and lighting. The carbonate electrolyte can also cause electrode corrosion problems. Furthermore, since CO_2 is consumed at the anode and transferred to the cathode, introduction of CO_2 and its control in air stream becomes an issue for achieving optimum performance that is not present in any other fuel cell (www.fctec.com, 2007).

SOFC: Solid Oxide Fuel Cell

The Solid Oxide Fuel Cell (SOFC) is currently the highest-temperature fuel cell in development and can be operated over a wide temperature range from 600ºC–1000ºC allowing a number of fuels to be used (www.fctec.com, 2007). To operate at such high temperatures, the electrolyte is a thin, solid ceramic material (solid oxide) that is conductive to oxygen ions (O^{2-}). The SOFC has been in development since the late 1950s and has two configurations that are being investigate-planar (flat panel) and tubular.

As a solid electrolyte, it is impermeable to gas cross-over from one electrode to another when liquid electrolytes usually consist of the electrolyte contained in some porous supporting structure. The charge carrier in the SOFC is the oxygen ion (O^{2-}). At the cathode, the oxygen molecules from the air are split into oxygen ions with the addition of four electrons. The oxygen ions are conducted through the electrolyte and combine with hydrogen at the anode, releasing four electrons. The electrons travel an external circuit providing electric power and producing by-product heat.
Typical reactions at this process in the fuel cell are:

Anode Reaction: $2 H_2 + 2 O_2- \Rightarrow 2 H_2O + 4 e-$

Cathode Reaction: $O_2 + 4 e- \Rightarrow 2 O^{2-}$

Overall Cell Reaction: $2 H_2 + O_2 \Rightarrow 2 H_2O$

The operating efficiency in generating electricity is among the highest of the fuel cells at about 60%. Furthermore, the high operating temperature allows cogeneration applications to create high-pressure steam that can be used in many applications. Combining a high-temperature fuel cell with a turbine into a hybrid fuel cell further increases the overall efficiency of generating electricity with a potential of an efficiency of more than 70% (www.fctec.com, 2007).
SOFCs operate at extremely high temperatures (600ºC–1000ºC) resulting in a significant time required to reach operating temperature and responding slowly to changes in electricity demand. It is therefore considered to be a leading candidate for high-power applications including industrial and large-scale central-electricity generating-stations. So, this fuel cell is no candidate for small scale electricity generation in remote areas.

RFC: Regenerative Fuel Cell

Maybe it is not to be stated as a distinct group because almost any kind of fuel cell could become a regenerative fuel cell, but it should be clear that there are options for closed loop systems that could serve as the basis of a hydrogen economy operating on renewable energy. Fuel cells generating electricity, heat, and water from hydrogen and oxygen would be used throughout the economy, powering factories, vehicles, and houses. The hydrogen would be generated from the electrolysis of water, splitting it into its constituent components of hydrogen and oxygen, using renewable energy sources such as wind, solar, or geothermal (www.fctec.com, 2007).
Such a system would not require any specific type of fuel cell, but would need an infrastructure to deliver hydrogen, methanol, ethanol or whatever kind of fuel is to be used in the fuel cells. Little to no new technology is required to implement a renewable-based system. However, there does not exist any infrastructure for hydrogen delivery currently; methanol and ethanol could already be provided easier using the current supply system with only few adaptations. Also, the basic cost of electricity generated by fuel cell will be high, but will decrease as costs decrease for each of the components used when economies of scale occur: massive use of fuel cells, hydrogen storage, and delivery, renewable energy collection, etc.
Currently, there is a project led by NASA to develop an efficient and lightweight regenerative fuel cell system for use on board an airplane called the Helios that can fly at altitudes near 100,000 feet (www.grc.nasa.gov, 2003). The predecessor aircraft was powered by photovoltaic solar cells. The goal is to incorporate both photovoltaic solar cells and a regenerative fuel cell on board. The solar cells will power the aircraft during the day and generate a supply of hydrogen that would be stored for use by the fuel cell overnight. Such a system would then be capable of flights lasting many days (www.fctec.com, 2007). Regenerative fuel cells could be used in remote areas very well and might also solve distribution problems to these areas.

Appendix 7: Fuels for Fuel Cells

Introduction to fuels for FCs

The hydrogen economy first was discussed around the 1970s and was mostly based on producing hydrogen using nuclear power plants. Now that nuclear power is not that popular anymore in most countries of the world, this way of producing large amounts of hydrogen is not favoured anymore. In SA however, nuclear power still is used for electricity generation. The hydrogen FC is an environmentally friendly FC because only water is produced while operating it. Hydrogen is however a difficult fuel to produce and store. It is rather difficult and costly to liquefy from gas. The low energy content compared to natural gas when pressurized in tanks in not in favour of hydrogen either.

Still there is no way of making cheap hydrogen. Laws of energy demand an equal or larger amount of another form of energy to produce it. Nowadays hydrogen is often made from natural gas. This process is only 65% efficient when storage losses are considered; so it would be better to use natural gas directly instead of transforming it into hydrogen when it i.e. would be used for heating or cooking.

The SOFC (see appendix 6) even can use natural gas directly but this kind of FC is more for larger use. However, the SOFC cannot handle fluctuation in demand and is more used in larger systems. Producing hydrogen by electrolysis is generally even less efficient because the electricity is generated by a gas turbine which is no more than 57% efficient. If hydrogen would be made from the electricity produced by solar panels or fusion power plants, the situation would be somewhat different. Presently however the cost of making hydrogen from the electricity of solar panels is much higher than making it from natural gas. Also the life cycle analysis should be considered in this case. It is true that carbon dioxide, a by-product of the alcohol FC and reforming natural gas, is a greenhouse gas. It is not a local type of pollution however. There is no advantage in producing hydrogen from natural gas far away from city areas. The carbon dioxide quickly mixes throughout the globe. There are benefits in using renewable hydrocarbon fuels rather than hydrogen.

Production of Ethanol

Ethanol is presently viewed by many scientists as the perfect fuel for portable fuel cells. Methanol and ethanol presently can be made from either natural gas or biomass. This process is also about 65% efficient. Therefore hydrogen and alcohol cost about the same to produce and store. The DMFC however is slightly less efficient than a PEMFC operating on stored hydrogen gas. Many consider that the benefits of storing a liquid fuel more than offset this loss of efficiency. In the future it may also be possible to produce alcohol directly in solar panels or in fusion power plants. Because this is not yet the case, alternatives should be considered until then.

The production of ethanol or ethyl alcohol from starch/flour or sugar-based feedstock is among man's earliest ventures into value-added processing. While the basic steps remain the same, the process has been refined a lot in recent years, leading to a very efficient process. There are two production processes: wet milling and dry milling. The main difference between the two is in the initial treatment of the grain. As of January 2007, dry mill facilities account for 82% of ethanol production and wet mills 18% in the USA (RFA, 2007).

Appendix 8: Technology Roadmap expound

This appendix will elaborate on the content of the technology roadmap from chapter 4. The five layers will be discussed in more detail for the three timeslots provided for the future. Furthermore the issues considering the implementation will be discussed here in more detail.

Society

CSIR mandate to meet national needs

This is a continuous process that will take all three timeslots; therefore it is written as one block over three time layers. The mandate of the CSIR (website CSIR, December 2007) is the next: "The objects of the CSIR are, through directed and particularly multi-disciplinary research and technological innovation, to foster, in the national interest and in fields which in its opinion should receive preference, industrial and scientific development, either by itself or in co-operation with principals from the private or public sectors, and thereby to contribute to the improvement of the quality of life of the people of the Republic [of South Africa], and to perform any other functions that may be assigned to the CSIR by or under this Act." So, the CSIR has an obligation towards the people of SA and the government to innovate and to find new technical solutions that might help all people of SA, rich and poor.

By doing research in FCs, it is a goal to put SA on the global map considering research in these. Now, the CSIR is mostly trying to catch up with global developments but soon it is hoping to equal the prominent researchers, and perhaps in the future even outperform them. The outperforming will however become very difficult because CSIR (FCs group) has not enough capacity to become a main player in the leading developments in the world of FCs.

The research in FCs is also important for the energy security of SA. Because the population number is growing every year it is important that all can be served with electricity. Nowadays, thanks to the electrification programmes, 80% of the population (GHS, 2007) is already connected to the national power grid. The use of alternative energy sources is very welcome because SA is almost at its maximum generating capacity. Old power generating stations are already refurbished to generate extra MWs to fulfill demand and an extra nuclear power plant is being built in Koeberg. All of this is to secure that demand can be fulfilled.

Knowledge transfer

This goal consists of three different aspects of knowledge transfer in time. In the first timeslot from 2008-2013 the goal is to develop as much knowledge about FCs. This knowledge consists of deep technical knowledge of the FC itself and how to make it more efficient, reliable, and cheap, but also the knowledge about how to use the FC in practice. This includes thinking about how you are going to transfer the generated knowledge to the people who are actually going to work with the FC. Last but not least you need to think about which knowledge is relevant and which not for transfer.

The next phase, the years 2014-2020, consist of the actual transfer of knowledge to the people who are going to use the FC to generate electricity. More of this will be explained in the “increase skills locals”.

The last phase of this TR, the years 2021-2030, are the years in which the first FCs are actually implemented and the knowledge should be applied in practice.

South Africa’s growing economy

The economy of SA is growing each year. Because the economy is growing the demand for electricity grows even more. People can afford more and more and buy electrical appliances for more convenience. Hopefully for SA the economy will keep on growing. In the TR it is spread over three columns in time as a continuous process. As long as the economy keeps growing the demand for electricity is expected to grow. In addition to this is that more and more people can afford to live in formal dwellings instead of informal ones and that these dwellings more and more are electrified thanks to the electrification programmes. All of this increases the national demand for electricity.

Client needs

This goal is one of the most important aspects for the CSIR to focus on. CSIR is mostly focused on pushing ideas into the market without even thinking about the requirements from the market. With this new kind of technology it is one the one hand important to show what is technical possible to the potential user. But on the other hand it is important to include the wishes of these customers because they only use it when they are satisfied with the options for use. From the interviews it became clear that the customer requirements are only gathered occasionally. Client needs should be input for R&D to focus on. Therefore the first two phases of the TR consist of the interaction with the client to gather their requirements. Of course the client should also know what the possibilities are considering technological developments in the field of FCs. It has no use to explain that in full detail, but the applicability of that specific type and the benefits for the users should be made clear.

The last phase, from the year 2021-2030, will be a trial period to test the FCs in practice and improve them when necessary. During this phase the customer will provide its feedback in order to optimize where necessary.

Accessibility of fuel + pricing

Fuel for the FC should be easily accessible in order for local users to use the system of FCs. In rural settings people often do not possess a car so they need to get there fuel close by. If the distance is too great people incline to use fuel that can be obtained closer. Fuels like paraffin or wood are distributed in lots of places and are relatively cheap. The price of the fuel determines in a large extend whether or not FC will be used. People living in rural setting mostly do not make much money and therefore they cannot afford expensive fuel. They will use what is cheapest for them.

So, the fuel for FCs should be distributed over the whole area in the same way the traditional fuels are now and the price should be (more than) competitive. Especially in the beginning the price of the fuel should be low so that people actually are going to use the FC and get used to it. As will become clear from the rest of the report, it is recommended that the FC is not appropriate for heating or cooking because these require a large amount of energy. It is more energy efficient to burn e.g. LPG directly for cooking or heating. Therefore it is recommended to sell an alternative (sustainable) energy carrier next to the fuel for the FC; or the fuel for the FC should be able to be used for the non-FC applications as heating and cooking.

In order to make government aware that some kind of local energy centers are needed in these rural settings, this is scheduled for the first timeslot between 2008 and 2013. Between 2014 and 2020 these local energy centers should be build wherever necessary so that people do not need to go far to get fuel and the present energy centers should be supplied with the right amount of fuel to supply that area. From the introduction of the FC in rural settings the fuel should be provided. These energy centers furthermore should be supplied with spare parts so that the FCs can be maintained. More about the maintenance will follow in the 'increase skills locals'.

Increase skills locals

As becomes clear from the TR as a whole, the intention is to introduce PEMFCs in 2020 and the DAAFC in 2030. Locally people should be educated in maintaining the FCs because it is too costly to send a repair team every time from a bigger city. Also this is too costly in matter of time. For convenience and maximum use of the system by people living in rural settings they should not need to wait for some team to come by somewhere that week but just someone from around who can solve most of the problems.

It is recommended to educate some locals in repairing the FC systems. They first should be taught how to maintain the PEMFC and later, just before the introduction, the DAAFC. Eventually these people will be in control of an area as a profession. This can be regarded a local business and can be combined with the local energy centers that sell the fuel. These people/local companies can solve local problems and now and then people from the FC 'mother' company come by and monitor the local repair people and update them about the developments and give them instructions about the reparations.

Increase amount of skilled FC researchers at CSIR level
This is part of the National Capacity Building process to put SA on the global map considering developments of FCs. As part of the mandate it is the duty of people working for the CSIR to improve the life of South African people. Their drive is to find new solutions, improve current technologies, and increase their own skills.
More specific there are set targets for the three timeslots of the TR. During the first timeslot and especially before the end of 2010 the target is to find an extra specialist in the field of direct alcohol FCs. This is to expand the amount of knowledge of the FC-focus group. The in-house knowledge in FCs is just enough to keep up with developments in PEMFCs worldwide but to extend this knowledge with DAAFC using anion exchange will become too much. Therefore the capacity of the team will have to expand in order to keep up with global developments.
The trend to expand keeps continuing in the second timeslot. By the year 2014-2015 the FC-team should be expanded with about 5 researchers in order to grow significantly and to be able to keep up with global developments in FC-techniques. It is meant that SA eventually is able to catch up and even might do breakthrough research in order to put SA on the 'map' considering developments in FCs.
The last timeslot shows that the researchers recruited earlier will stay at the CSIR and get follow-up projects in order to grow further. This timeslot is still far away and therefore it is not clear what exactly the need will be for 'skill increase'.

Personal Value Points (PVPs) at CSIR
PVPs at CSIR are mostly incentives to keep personnel satisfied and to let them strive for this point. The employee's performance will increase using this kind of incentive and that is all that matters. The employee might get an incentive as extra bonus, holiday, time for education. The PVPs are not split for the timeslot of the TR because this is a continuous process that drives people and it makes people motivated and act in a more pro-active way.

HR development
This is also a continuous process that takes place over three timeslots. Its goal is close to the 'Increase number of skilled FC researchers at CSIR level' for which Human Resources mostly is responsible. Important in this goal is that knowledge is to be stored in some kind of database which much be kept up to date. This database can make knowledge easier accessible to all members of the organization. The implicit knowledge is hardest to store because this is the knowledge people have 'in' them which is very hard to express. For as far as possible this expertise should be made explicit so that people know where to go to when they get stuck and need a specialist to look at the problem.
From HR point of perspective it is furthermore recommended that the CSIR creates a certain kind of environment in which degrees are important and employees can get lots of experience in a certain way. People can learn from experts in practice by working together with them. The collaboration with universities is a major point to strive for in order to get new student researchers and fresh opinions.

Economy

Cost/price
The development of FCs costs lots of money, as are the cost of production and of operating it. It might be cheaper to have one FC system that fulfills the needs of e.g. five households than a single FC per household. Especially if we focus on rural areas it might be wise to share costs with multiple households and come up with kind of local mini-grids. Than the costs can be spread and divided over i.e. five households. The complication in sharing arises in sharing the costs of fuel and the costs of maintenance.
For the TR the three timeslots can be filled with targets. From 2008 until 2013 the costs for research are expected to stay fully for the CSIR. During this time it is the goal to reduce the costs of the FCs. A reduction of price can be expected in using less expensive materials in the FC, or mass production of expensive parts. By mass production the constant costs can be spread over more products through which the costs per product decrease. This is also known as 'economies of scale'.

From 2014 until 2020 the development costs are expected to be for the manufacturing companies. CSIR will sell its technology to a manufacturing company so that the FC can be actually produced. This manufacturing company will work close together with the CSIR to reduce further. The objective is to reduce the price of a system with about 20% compared to the year 2008.
Between 2021 and 2030 the economies of scale are supposed to decrease the price of a system much further. It is expected that the price can decrease up to more than 50% compared to the price of a system in 2008.

Beneficiation of Platinum
South Africa has one of the largest resources in Platinum (Pt). Therefore SA has a unique position to sell to the rest of the world. SA hopes that it can export lots of Pt for the FC industry. The FC industry on the other hand is trying to become less depended on countries as SA and is researching alternatives than Pt. By using less expensive materials the price of the FC might come down significantly and at the same time the dependency on SA might decrease enormously.
The companies that actually are going to sell the Pt (the beneficiation companies) should be approached in the second timeslot for splitting the costs in the FC research. The beneficiation companies otherwise are earning lots of money in the last phase of (mass) production without contributing to the research phase.

South Africa's growing economy
After the period of apartheid the South African economy keeps growing. International companies settle in SA and provide work, mostly in the cities. Most of the companies do their production in SA because this is cheaper than in their own country. Examples of these companies are BMW and VW. Furthermore is the unique position of SA regarding the reserves in Pt positive for its economy. Hopefully for SA the economy keeps growing in all classes of society. Especially the very poor should be able to become financially more capable. If these people also can spend money on luxury products this might boost the economy significantly.

Price increase conventional fuels
The price of the conventional fuels as coals and oil keep going up because of scarcity. Especially the price of oil has gone up enormously the past years. The price of a barrel now (January 2008) is about \$85.- on average while it had cost about \$30.- per barrel in the year 2000; last year (2007) a barrel had cost \$64.20 on average and the price peaked up to about \$100.- (www.ioga.com, www.wtrg.com, Feb 2008) The rise of the price of crude oil also increased the price of petrol and other products made from it. Consumers rather not spend a lot of money on expensive fuels otherwise if they can they rather use conventional fuels as wood or paraffin because (they think) that is cheaper.
Also there is an artificial price increase on conventional fuels because of taxes on these that try to decrease the amount fuel used. This concerns fuels that produce lots of CO2 and CO while used like petrol and diesel for (small) engines. All these price increases cause that people are getting interested in alternative energy sources because at the end these might be cheaper for them than the use of conventional fuels. If the price of FCs will (ever) become cheaper or the amount of MJ per Rand will be about the same, then the use of conventional fuels might decrease and the use of FCs increase significantly.

Intellectual Property (IP) development
Also this is a continuous process in which CSIR strives to obtain as many patents as possible. By obtaining patents CSIR shows researchers around the world what they have been able to. Eventually the techniques can be sold or licensed to manufacturing companies and CSIR gets money for the use of the technique. The strive for patents contributes to the improvements in quality of the FC and the competitiveness of the FC compared to the FCs developed elsewhere.

Niche applications
CSIR is developing FCs for small scale applications. This research focuses on using small scale FCs (up to 1kW per household) for electrification of rural areas where no power grid is available. The

CSIR could develop FCs for other purposes. FCs could also be used in telecom towers or as back up power source for e.g. a small refrigerator in which medicines are stored. FCs, in theory, can be used to replace backup batteries. In the future FCs could be used also to power game farms or in mining. The electrification using FCs is expected mainly to be used for small devices as light bulbs or recharging of telephone batteries.

Environment

Environmental improvement

FCs produce less greenhouse gasses than the conventional energy sources. Although some of the FCs produce CO2 (e.g. AFC) this amount is still less than would have been produced in the conventional way. Other FCs only produce H2O, e.g. the PEMFC. Environmental improvements are even greater when FCs are used in combination with other relatively clean energy sources for cooking and heating (e.g. LPG); then less GHGs are produced compared to the use of traditional or conventional energy sources.

The environmental improvements will only become noticeable after the actual introduction of FCs. That is why the first two timeslots of the TR are left empty. The introduction of the first FC is expected to take place in 2020. In 2020 the PEMFC is expected to be introduced in rural settings. By this time the products should be marketable and fully ready. By this introduction the environmental improvements should become noticeable within the next five years. The aim is to reduce the number of people that use traditional fuels as wood and paraffin by 40% by the year 2025 compared to 2007.

As sub part of environmental improvements is the decrease in use of non-chargeable batteries. When people are not yet connected to the power grid they might use batteries to power small radios or flash lights. When people get electrification they will use this at first for lighting. Also they might buy rechargeable batteries instead of ‘single use’ batteries however these are quite expensive to purchase.

Another sub part of environmental improvement might be the reduction of indoor pollution caused by smoke of candles. The use of candles for lighting will decrease when houses are electrified; eventually all rooms in the house will have at least a single bulb. Fewer houses will burn down because of accidents with candles. The introduction of FCs does not reduce the amount of pollution caused by smoke of cooking. This is because cooking and heating is not done on electricity from the FC. When FCs are introduced together with alternative fuels for cooking and heating (e.g. LPG), then the indoor air pollution will even become less. Just by the introduction of FCs for lighting the reduction of use of candles is expected to decrease by 40% between 2021 and 2030. People still will use candles because of habit but gradually this is expected to decrease.

Awareness

Awareness is one of the most important issues dealt with in this TR. Without a proper understanding of the need for alternative fuels the introduction of new ones will never work. People should be made aware that FCs can be a solution for rural electrification without having to extend the national power grid to their houses. People should be made aware of the capabilities of FCs and they should be familiar with it before they actually will use it.

Therefore, it is recommended in the TR that already in the first timeslot from 2008-2013 children should be confronted with FCs at school. They should be taught what the FC is and what its capabilities are. This way FCs might get the attention from people who are going to use it in the future. From the year 2018 people living in rural areas should be made aware of FCs. Often in rural settings people live in communities that have a headman or very influential person. At the introduction of FCs in these areas it is important to convince this man of the importance otherwise people might resist in using the new technology. This phenomena is called “influence the influencers”.

From the beginning of the second timeslot it is recommended that the rural people are made aware of the health benefits (cleaner air) and the comforts of using a FC.

In the last timeslot it is of importance that people learn how to use the FC and learn them to appreciate the use of it. By making them aware of the advantages in practice people are convinced earlier than when they are tried to be convinced in theory.

Technology

Use of PEMFC with reformer

Proton Exchange Membrane Fuel Cells use hydrogen as a fuel. Because hydrogen is not an ideal fuel to use in remote areas when the PEMFC is t be used for electricity generation in these areas, hydrogen will have to be replaced by another fuel. Another fuel might be methanol or ethanol. These alcohols can be reformed and hydrogen can be formed using chemical reactions in the reformer. Then the hydrogen from these alcohols can be used as input fuel for the PEMFC. A typical PEMFC can deliver about 600mV per cell as output voltage. Multiple cells together form a fuel cell stack and the output power increases.

During the first timeslot the research in PEMFC in combination with reformers will have to be finalized. Afterwards the technology can be sold to the 'next' company in the value chain. These on there turn can further develop the FCs in more practical detail.

During the second phase the PEMFCs should be tested in the field. By the field tests it becomes clear what is to be changed in order for the FC to function in practice. At the end of this phase it is clear what the end consumer would like to have and the product can be mass produced.

During the last phase, the implementation phase, the product is introduced in rural areas. From 2020 PEMFCs are installed and local people are responsible for the maintenance and monitoring of the FCs in use. The goal is a market penetration of 20% by the year 2030 in rural areas.

A sub part of the use of PEMFCs with reformer is the research in catalyst and electrodes that are used in PEMFCs. Only by proper research the amount of Platinum (Pt) to be used in the FC can be reduced significantly. For SA it is important to keep using Pt in the FC because SA has a unique amount of Pt in its soil. By a steady or even growing demand for Pt the economy of SA is continuously stimulated and assured. Another point in the catalyst research is to research how they become better resistant to poisoning by CO2.

A second sub part in the use of PEMFCs with reformers is the research in fuels for this technique. Considering the fuel the purity is still a point of improvement. The PEMFC requires very pure hydrogen in order to work optimally and longest. As soon as the fuel gets poisoned by CO the fuel degrades the lifetime of the catalyst. The goal is to develop catalysts that can handle >10ppm of CO in it or to develop reforming techniques that produce very pure hydrogen.

Thirdly, the membrane needs to be further developed and optimized through which the conductivity increases. Now Nafion is used as membrane to transport protons. The costs of this product are very high and during the first two timeslots of the TR the aim is to reduce the price of the membrane with a factor ten. In the third timeslot it is expected to replace the Nafion with another material less expensive and with the same or even improved properties. Of Course this needs not to wait until the third timeslot but at this time no other similar alternative is known yet. The research in membrane can contain research in thickness, the amount of material needed, or the increase of lifetime; its durability.

Use of AFC as Direct Alkaline FC

This kind of FC is still in its infancy compared to the PEMFC. DAAFC uses an anion exchange membrane to transport hydroxy-ions instead of protons. The DAAFC is supposed to be marketed in 2030; so about ten years later than the PEMFC. The first field test can only be done in the second part of the last timeslot. Around 2025 the first field tests can expect to take place to further investigate what needs to be done to make the DAAFC work in practice. From the beginning of the 2020s the

technology of the DAAFCs can be sold/presented to manufacturing companies so that they can invest in optimizing before actual field testing can occur.
The first two phases of the TR up to the year 2020 will be dedicated to fundamental research in making the DAAFC technically possible and competitive to the PEMFC. The AFC has as advantage that the output voltage is about 800mV per cell, compared to 600mV per cell using the PEMFC and it is expected that the DAAFC will generate about the same amount of output voltage. This means that the stack of FCs can become smaller. Because the stack becomes smaller there will be less loss of energy in the form of heat. The total efficiency of a DAAFC stack might be greater than the stack built of PEMFCs.

The sub part in this group also concerns the research in electrode and catalyst just as in the PEMFC part of the TR. Because the developments in the DAAFC are in its infancy, the research phase of experimenting other materials to decrease the amount of Pt in the FC will start later than in the PEMFC research. However, from the beginning of research in DAAFC people (mainly outside SA) are searching for alternatives than the expensive Pt. South Africa tries to include the use of Pt because of its resources in this mineral. Alternatives considered by other companies are i.e. tin. SA however should try to minimize the amount of Pt needed in the FC.

Considering the research in fuel for the DAAFC the TR suggests that in the first time slot the research starts with using methanol and when that works fine the step to ethanol as fuel should be made because this is a non-poisonous fuel. The disadvantage is the double connection between the carbon molecules that need to be broken in the reforming process to form hydroxy-ions.
In the second and third timeslot of the TR the DAAFC research should focus on making the FC work on other kind of alcohols. E.g. the FC might work on glycerin, the byproduct of bio-ethanol. Also the efficiency of fuel use is expected to improve during developments. The purity of fuel is another issue to investigate. Preferable the fuel does not need to be very pure. This also makes the use in rural settings easier. When the fuel does not need to be very pure the catalysts can be used longer because the get poisoned slower. Now this is still a major issue.

The last sub part of using Direct Alcohol for AFC concerns the research in membranes. This part is similar to the developments still to be done for the PEMFC but the DAAFC differs in that this technology is in its infancy and that the membrane itself conducts hydroxy-ions. The research in membranes focuses in the first timeslot mostly on finding stable and good conducting materials for hydroxy-ions.
The second and third timeslot should focus on improving the power density of the DAAFC in order to become similar to the AFC; the goal is to develop a FC that has a higher output voltage than the PEMFC. Furthermore is a cost reduction based on cheaper materials desirable; this is in order to become better competitive to other manners of local energy generation like small generators. Last but not least, CSIR could contribute to setting a kind of standard in membrane use for anion exchange as is Nafion at this moment for proton exchange in the PEMFCs.

Capacity of FCs and the electrical capacity expansion potential
From the workshop it became clear that this option is important. In the future demand might become more and the systems placed in the near future should be able to handle demand without having to replace the whole system. One option suggested is to design the FCs in a modular style that if demand grows and extra system can be placed and coupled to the old one so that the capacity grows. The ability to connect multiple systems increases the ability to produce more electricity enormously, however the problem is that the systems should be synchronized before they can be connected. Without synchronization the systems might cause interference that might damage components. Another option than modular systems would be to place small decentralized systems that provide electricity to multiple households. Multiple households together need a smaller system because the design for overcapacity accumulated for single households is bigger than for a system that is designed for i.e. four households. Also has the mini-grid option advantage that initial costs can be split over

multiple families. The disadvantage is the way the operation costs are divided over the households. Electricity meters in every house might solve this easily as long as nobody cheats using them.
A typical household in rural SA would like electricity to power the lighting in the house. Every room in the house is expected to eventually be electrified. When electricity is in the house people furthermore would like to own a refrigerator, a radio, and if they can afford it, a small television (color or black white. Cooking and heating is left out of this because it is very inefficient to use a FC for this. It is recommended to use e.g. LPG.

Simplicity maintenance
From the beginning of the introduction of FCs in rural setting it is important that the maintenance is organized in a professional way. From 2020 the first systems are expected to be operational, by that time local energy centers should be formed so that people can get fuel and spare parts. Furthermore local people should be educated in maintaining the systems. Only for major problems people from the parent company should have to come to the rural areas. Local people should be educated because then the step is smaller to report a problem. When the FCs are in use and might fail the failure should be reported and collected. This forms a lot of feedback that can help the designers and manufacturers in optimizing the FC. This feedback also might suggestions for improvements without something to breakdown.
By designing the interiors of FCs in a ‘plug and play’ manner the maintenance can be organized easier. Components then can be swapped without needing a lot of advanced tools that might be costly. Considering the easy of maintenance it is recommended that standard tools should be able to do the required maintenance. Standard screws drivers, spanners, and wrenches should be used to mount the FC.

Efficiency
Currently the PEMFC has an efficiency of about 50% in combination with a reformer. This efficiency is not expected to become much higher because experts think this is the highest achievable. The system will always generate heat and reforming fuels always is done with a certain loss. For the second timeslot it is recommended to re-use the heat for indoor heating during winter time. This is called co-generation of heat. In the third timeslot it was even suggested to expand this co-generation with the re-use of heat for heating water.
The efficiency for the DAAFC is not known yet because this FC is still in its infancy. The efficiency is still significantly less than the PEMFC but it is expected that eventually the efficiency will become higher. This is expected because probably the DAAFC can generate a higher voltage per cell than the PEMFC as discussed in the technology part of this TR. The goal for the second and third timeslot of the TR is therefore to get a higher efficiency from the DAAFC than the PEMFC.

220-240V 50Hz AC output
During the discussion in the workshop it was discussed whether or not the output of the FC system should be able to generate electricity according grid specifications: 220-240Volt, 50-60Hz AC. One option discussed was to develop a kind of min-grid based on 12V DC. This is similar to earlier electrification programmes using solar panels and batteries to store electricity. All kind of equipment is available using 12V DC like small black and white TVs, bulbs, and (camping) fridges. From the discussion it became clear that people living in those rural settings would prefer the cheapest and most accessible solution. People living there do not have a lot of money to buy special devices that run on 12V DC. They prefer the ‘normal’ appliances that are produced in mass production and therefore are cheaper and easier to acquire and replace.
However, the FC systems provide normally around 50V DC (between 35V and 60V depending on the load) and not the desired 220-240V AC. The circuit to make the desired output feasible will exist of at least two separate steps. The first step will be to transform the 50V DC up to around 320-400V DC using a step up converter in one or two steps. The second/third step will be to transform the DC into AC. All conversions will cause a loss in the form of heat through which the efficiency decreases with about ten percent.

Furthermore it is to noted that during the workshop was chosen to use the PEMFC and the AFC (and so the still to be developed DAAFC) instead of the SOFC because the PEMFC and AFC can handle peak power better and can be used to electrify houses in small settings. SOFCs are commonly used to electrify places where the acquisition of electricity is stable and rather large. SOFC cannot handle fluctuations very well nor can they start up as quickly as PEMFCs can when demand suddenly increases.

Policy

Climate change

South Africa does not participate in the Kyoto-protocol. However the South African government is becoming aware of the need to change its current policy in order to save environment. SA strives to participate in the follow-up programme that will have to be formulated before the end of 2012. Now, SA has agreed to the non-binding 'Washington declaration' which they signed on February 17th 2007.
In 2004 a 'National Air Quality' act has been formulated with strict guidelines for emissions into the air. Before this time there was no act and therefore the new act at first works as a guideline which eventually will become legislation. This way the air pollution should diminish and very polluting companies need to change their facilities in order to comply with emission standards. The second and third timeslot of the TR still are expected to focus on the improvement of the air quality by reducing the GHG and amount of particles in the air.

Pollutants

Part of the National Health Policy of SA and part of the National Air Quality Act is the decrease in use of pollutants. By using FCs the indoor air quality might improve because fewer candles will be used. When in combination with the FCs i.e. LPG is used, the indoor (and outdoor as well) air quality will improve because this burns cleaner than e.g. wood.

Safety

From the beginning of the introduction of the FC in rural settings this will also improve the safety in the houses because lighting will than come from bulbs instead of candles. The chance of fire inside the house decreases significantly by this change. Fewer houses will burn down and less people will be burned. As part of a safety programme it could be recommended to ban the candle from being used for lighting as much as possible.

Re-use and recycling

FC systems will not have a never ending life. To harm environment minimal it is advised to think already in the development phase about the disposal of the FCs. As much as possible should be able to be re-used or used in another product. Awareness is needed to dispose the FC in a proper way after its lifetime instead of dumping it somewhere in nature or a landfill. National programmes could make people aware of this.
From the year 2022 SA would like to produce 'zero-waste' as declared in the Polokwane (Pietersburg) declaration. This means that all devices by then should be fully recyclable.

Appendix 9: Interviews with specialists

Interview/discussion Mark Rohwer

Function in TR: "Senior R&D fuel cells"

General part:
Next 10 years up to 2020 he does not expect rural electrification by the use of Fuel cells (FCs)
Competing technologies are now cheaper and easy to maintain. So for the next 15 years he is not convinced that FCs will take over in electrification.

Prime electrification:

- small diesel generation (5kW) can electrify few households and the costs for this device is only R3000 – R4000
    - If the price of diesel goes up significantly then the debate starts again. Only if diesel will be around the same price as competitors than a shift might occur.
    - By 2020 if the price of diesel is way up and the price of H2 way down than might be competitive.
    - So, <u>price</u> of fuel is most important
    - When price will be competitive, than comes social acceptance. Lots of people will continue using traditional fuels as coal, wood, and paraffin for cooking and heating (even when they have electricity). So, question is whether if FCs are available, will they be used?
    - Also, electrical appliances are expensive and people in rural areas who are not yet electrified are generally poor

Viable alternatives:

- solar energy for water heating (then you decrease the demand for electricity)
- Photovoltaic power + advanced batteries

Complicated factor in lots of renewables is the output in DC instead of AC. Almost everything connected to the grid uses 240V AC and probably that will stay the same until 2030.
FC systems now deliver about 50V DC; so, other/special appliances are needed. These will probably be expensive so that's not going to work in rural areas; should be cheap!!
Conversion DC to AC is very expensive for FC use
So, if it should be competitive you need normal power grid standards to keep it cheap for the end user.

Niche applications:

- When kWh costs are not the matter e.g. as a backup function
- Direct use e.g. battery replacement; FC is ideal for battery replacement!!
    - Hospitals (still expensive conversion to 240VAC)
    - Telecommunication towers (using 50V DC)

DC to DC conversion is more expensive than AC to AC conversion
DC network will not evolve in urban areas; in rural areas it might but probably not Mr. Rohwer states.
Only with separate, local generation it might work

Performance dimensions (customer view):

- Cost for the customer
  - Capital (initial) costs (Government could/would probably pay this
  - Operation costs (should be cheap)
- Convenience e.g. show how easy and pleasant it is to work with compared to paraffin
- Reliability this is not as important but it should work of course.
- Maintenance
  - Educate local people, train them in maintenance
  - Low maintenance is desirable

Performance dimensions (CSIR view):

- Competitiveness in costs (should be competitive to similar systems in costs)
- Competitive in other dimensions e.g.
  - Battery capacity is becoming too small; FC have larger capacity and might solve this problem
- Environmental usage in Life Cycle important for CSIR. If CSIR can market green products that is a plus point
- develop for applications
  - e.g. small use (should be very reliable)
  - backup (should be fast in start up)
  - market decides how to specify the FC
- robust systems

Technical features

2 factors play an important role:

- energy density of fuel
- power density of fuel cell

Fuel perspective:
Liquid + solid fuel (e.g. diesel, (m)ethanol, coal have high density)
Gaseous (e.g. H2) has lower energy density, so you need a big container + compression
The liquefying of H2 is not very efficient, takes about 30% of H2 to liquefy
So, moving towards <u>liquid</u> or <u>solid</u> fuels is an important step for if you would like to use FCs in rural areas.
Liquid or solid = advantage and convenience

Fuel cell perspective:
H2 FC can deliver more power (W/m3) than (m)ethanol FC (of the same size FC)
Radical development is needed in this FC, maybe before 2030.
Ethanol from renewable sources

- only advantages, but these should have same or better characteristics than competitive products. Use direct ethanol or glycol as fuel

Rural:

- Liquid FC otherwise transport issues
- Fluctuating demand:
  - SOFC and MCFC are not suitable in these settings
  - Lower temperature PEMFC are suitable

Membrane:

- determines the performance of the cell
- should not leak fuel but should transport H+ or OH-
- should be permeable to H2O

Catalyst:
- Methanol is relatively easy to oxidize; others are more difficult and in research now

PEM is
- versatile
- adaptable
- wide range of loads
- can handle fluctuation

Now also AFC in research
e.g. Ethanol in PEM has a membrane to conduct H+
Ethanol in AFC has a membrane to conduct OH-
→ oxidize ethanol easier in alkaline medium; so, there might come a shift of research focus of the CSIR to AFC instead of PEM within 5 years. Both should be researched.

AFC has higher power output
- cell voltage of AFC is about 800mV while the PEM has about 600mV per cell; this is because of easier oxidation
- So, for rural application AFC would be better

Electrodes:
- This is the point where fuel is split into chemicals and electrons
- It consists of an electric conductor (cheap) and a catalyst (expensive)
- OH- conducting alkaline systems have different catalysts then the PEM
- AFC replace some of the Platinum with Tin in catalyst so these are cheaper than PEM

CSIR is developing competences in the FC department

FC is multidisciplinary:
- electro-chemistry (level @ CSIR: good)
- material science (level @ CSIR: not strong; but can use neighbouring centre skills)
- Physics (level @ CSIR: not strong [except in nanotechnology])
- Surface science (level @ CSIR: not strong)
- Electrical engineering (level @ CSIR: hardly any skills; can use neighbouring centre skills)
- Coating technology (level @ CSIR: not strong)
- Chemistry (level @ CSIR: good)

CSIR:
- Software (level: separate department: good)
- Control (level: separate department: good)

Invest in what more?
- in most FC promising technology
- start research in less researched areas to become more competitive and hope for promising results
    - use literature
    - own initial research
- decision points in this are: (e.g. to go to AFC)
    - literature and international developments
    - own research and experience

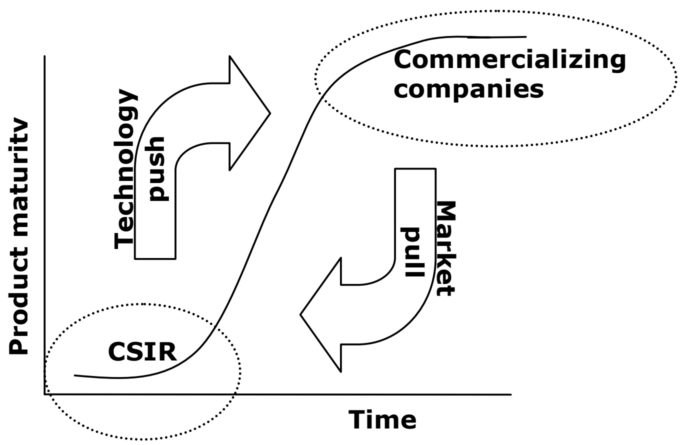
Interview/discussion Max Mapako and Alan Brent

Function in TR: "specialist in rural electrification"

Mr. Mapako is not a specialist in Fuel Cells (FCs) but he is in rural electrification and also he knows about solar PV systems which have been used for earlier projects in rural electrification.

Performance dimensions:

- maintenance
- costs
- new technology introduction needs acceptance by people who are going to use it.
- Mr. Mapako argues that a new technology should not be implemented Top-Down but Bottom-Up. So, the community perspective point of view is a very important dimension not to forget. Too often engineers are at work without thinking about the customer perspective and needs. They should also include maintenance, public acceptance, and discuss problems locally (so, at the place where it actually will be used in the future)



Mr. Mapako states that already at the beginning of the process the customer should be involved. Also CSIR should learn from earlier projects in the same kind of settings. E.g. CSIR should learn from PV system integration in rural areas in order not to make the same mistakes again.

CSIR is dealing with industrial companies mostly but still should look at customer requirements. They should look at:

- efficiency
- reliability
- price of product at the end. Try to keep costs low for manufacturing (materials)

External drivers:

- policy environment
- government tries to push innovate
- make government aware to get more funds for innovation in certain field
  - e.g. the policy to make more 'green' electricity and deliver this to the net. Make standards for reward in doing this. (e.g. done in Denmark)

Internal drivers (CSIR):

- costs
- capacity: Human Resource capacity is not very stable at the moment; knowledge management. To save/retain knowledge, all reports and publications are stored on servers with backup

functions.
People start working somewhere else to get more salary. So, people should be tried to stay at CSIR by:
  - incentives to stay, opportunity to grow in position and earn more money

The economy of SA is growing rapidly; skilled people are sought-after and the supply of these is small. Because skilled people from SA can make more money abroad they often choose the path of the earning more money abroad.
- <u>modular</u> systems can make the systems more dynamic if more demand comes or the load increases in future (more appliances); furthermore should LPG or solar water heating be used next to other systems to reduce the use of electricity.
- turnover of CSIR

FCs in remote areas drivers:
- low maintenance & should be serviced locally by local people & spare parts + fuel should be widely available in energy centres.
- Durability of the system
- Power capacity; should be able to power at least:
  - Radio
  - TV Black&White
  - Lights
    - All these last 3 to 4 hours on solar energy in the evening hours using Solar Home Systems (SHS); mostly people using the SHS find this too short Mr. Mapako states. They would like to be able determine their selves when it should be over. FCs might help in this.
    - Households would like to connect also
      - A fridge
      - Colour TV
      - More lights (3 is about standard)
      - Maybe a computer or other more advanced electronics
        - For cooking they prefer wood because this is cheap and at some places even for free.
- In rural areas Mr. Mapako states that energy centres will be needed: rural energy centres (ECs). In these centres LPG is sold and spare parts. If FCs are to become real in rural areas than these ECs need to have all parts available to repair a system and also have fuel. People are not very mobile in very rural areas so if the system is not working they will abandon it and start using the traditional lifestyle again.

Free electricity
- Mr. Mapako thinks that the targeting of the free electricity should become better organized. The free electricity should reach the people who actually need it. Now he argues that everybody can apply for the free 50kWh per month [only with load restriction]
- The amount of free electricity, 50kWh a month, is less than a household actually needs
- Would be better to start up companies and supply those with cheap/free electricity so that people can make money and after a while can start paying their (electricity) bill.
  - All kind of business arise when electricity becomes available:
    - Welders
    - Barbers
    - More advanced (fresh products) shops
    - Etc.
- The biggest problem Mr. Mapako addresses is that government (local authorities) at some places cannot implement the demand for electricity
  - The local people should get the poverty tariff but in reality they will have to pay the full amount because there local system is not ready to payout the people.

Interview/discussion Sibbele Hietkamp

Function in TR: "business owner"

CSIR is a parastatal research company and therefore it has to report to the SA government. The goals of the CSIR are to educate employees and to develop technologies for SA. Aim is to support government and private companies.

The Fuel Cell department started 3 years ago.
It became a National Programme in order to get South Africa (SA) on the map considering Fuel Cells (FCs). The Parliament accepted the National Hydrogen and Fuel Cell proposal and provided money for this research. The goal was (from government perspective) to research alternative energy sources for the future.
Furthermore, from economic perspective FCs can contribute because of the use of Platinum (Pt). SA has one of the biggest reserves of Pt in the world so the exploitation and export can contribute positive to the financial status of SA.
Also, some applications are unique for SA like the non-grid applications and opportunities for using FCs in mining industry (e.g. electric vehicles using FC technology). In mining now mostly diesel generators are used or electric with very long cables and batteries.
FCs furthermore are expected to be used in niche markets.

In the year 2030 government would like to have every household connected to the power grid. Mr. Hietkamp does not think that this will happen because some households are too rural and therefore it would be too costly to electrify these areas by connecting them to the normal power grid. FCs might solve this problem because FCs can be used in very rural areas to supply electricity in a certain way.
He does state that this might happen but the chance is rather small because FCs are very costly in purchase and use. Diesel generators nowadays are cheaper but less environmental friendly. Only when the price of oil will rise further and become competitive with the fuel of the FC then the FC will become a real competitor to the diesel generator. The big advantage of the diesel generator is that the output voltage is AC and 240V in comparison to the DC and lower voltage of the FC, e.g. 50V.

In the year 2030 mini-grids can be the outcome for the very rural villages. The maintenance and responsibility should be decentralized in order to prevent that the systems will be abused and a lack of trust might be taken away by the local responsibility.
Another advantage of mini-grids is the lower "peak power". The use of a mini-grid in comparison with small systems per household is that a mini-grid will be cheaper than household systems.
Furthermore he states that the FCs should be used in combination with other energy friendly systems like solar water heating. Especially in these rural areas this is important to do because fuel needs to be transported to this area which is rather expensive. Also LPG should be used instead of coals or paraffin in order to cook and/or heat more environmental friendly.

The biggest problem with hydrogen is transport. Gaseous Hydrogen takes a lot of space for relatively low power output compared to liquid fuels. Liquid fuels are easier in transport and have a higher density, so more power output per m3.
In systems <10kW Mr. Hietkamp thinks that PEM and AFC can replace batteries.
In systems >10kW Mr. Hietkamp thinks that SOFC might become an option but actually thinks that grid connection will be cheaper and better.

Alternative options to use FCs in:

- All kinds of small portable applications; the battery will be replaced by FCs

- Cars; in this market is lots of competition so the future in this is very insecure. It might be the driver for improvements in becoming cleaner. The internal combustion engine is becoming cleaner.
- Stationary applications like telecom towers or small local industries using limited amounts of energy. Examples he gave were also:
    - Agriculture
    - Gamefarms (should use LPG, solar energy, and diesel generators now to be replaced by FCs later)
    - Cold store places

Strategy:
Biggest driver is the government for energy security. Large and small systems should be developed.

Performance (customer):
- price is not that important at smaller applications
- price is indeed important at bigger applications if you talk about a certain number of kWh/month
    - there should be a comparable grid-price; not more than 2x as expensive because than people just would like to have to normal grid
- local maintenance
- reliable; it should work whenever there is demand

Performance (CSIR):
- no research in the FC as a whole product
- only research in quality parts like the catalyst, membrane, and water management
- CSIR is in FCs mainly in materials but he would like to do product side as well in future.
- Efficiency is the most important one here. The maximum W/m2 is the main performance driver.
- Human Resource is an important driver as well. People need to be educated and experienced people to be gathered to research. People can come from SA but also from abroad.

Market and Business drivers (external)
- cost reduction to become competitive to other technologies and to replace diesel generators and batteries
    - cost reduction in W/cm2
    - pgm contribution decrease
    - balance of plant; all electronics and pumps around system are expensive as well. Especially the bipolar plates are expensive.

Market and Business drivers (internal)
- added value PGMs
- HR development
- Competitiveness; 2 companies in FCs and X number of research companies

Trend:
- small applications for battery replacement
- diesel generator replacement
- internal combustion replacement in cars

Strategic objectives:
- technology development useful for actual use in SA
- IP (Intellectual Property) developments

Alternative energy:

Solar power as complement to FCs; pump water powered by solar energy to make a stock/storage.

SA can produce lots of H2 by using coal

“Green” H2 is still far away according Mr. Hietkamp and not very presumable.

- biomaterials will not be used to gain H2;
  - not enough water in SA to grow lots of crops
  - not enough wind for gaining energy from this
- Solar energy might be used
- Nuclear energy thermo process to convert chemicals into H2 (not completely green process)

Gaps:

- knowledge in FCs; This is connected with the certain amount of money available
- General knowledge ‘normal’ people about FCs is very little
  - Create awareness
    - Schools
    - Government to public
    - To government to gain more money for research
- Incentives in alternative energy are important for development; price should be around the cheap grid-price, so very cheap

Interview/discussion Steve Szweczuk

Function in TR: “specialist in rural infrastructure implementation”

Mr. Szweczuk is not part of the Fuel Cell (FC) department but he is a specialist in rural infrastructure implementation. He studied mechanical engineering. On the sideline he is keeping track of developments in FCs because of personal interest.
At this moment Mr. Szweczuk does not expect FCs to become very attractive for actual use in rural areas because they are too expensive if compared to other methods of electrification.

In 2030 he does not expect FCs to become the standard for rural electrification (off-grid). He believes in a different competing technology: small gas turbines. Even the rest heat from this can be used efficiently.
All together he does not believe in 1 sort of device for making electricity like FCs do, he argues; He believes in “energy packs” in which multiple sources of energy can be and also includes the reuse of waste heat.

Considering the FCs Mr. Szweczuk thinks that for now SA might have a good position on the world market because SA has lots of Pt. Mr. Szweczuk expects that other countries try to become less depended on Pt from SA by investing and researching in alternatives. So, he expects the dependency of the world on the Pt resources not to last very long.

The new developments in alternative hydrogen making he is interested in. He mentioned the Microbial FC to be an option. This FC uses waste water and organic matter as a fuel. Typically for this FC is that it does not require O2. The efficiency of this FC is low

Performance dimensions:

- community FC can be used when electricity is to be generated in high density settlements
  - community FC will be cheaper than single household FCs

  - decentralized networks including decentralized maintenance

- Typical households need electricity for: TV B&W/color, radio, freezer, lighting. The energy needed for space heating and cooking should come from extra energy sources and not the local power grid because heating + cooking require lots of energy.

- Customer perspective, most important dimensions:
  - Reliability; customers expect their supply to be firm at 240V 50Hz
  - Costs; this is always important from customer perspective. To keep the costs down a larger system will be needed to supply multiple households; he calls this distributed energy systems

- internal perspective:
  - Mandate: CSIR as a parastatal company has the responsibility to improve the life of the SA people by researching opportunities in this.
  - For energy there is no coordinated action plan; different divisions are developing. Nowadays they are becoming more proactive in energy solutions

- alternative product strategies that could satisfy market and business demand:
  - sustainable: solar, wind, and ocean wave energy, (satisfies M+B)
  - non-sustainable: Natural Gas (LPG), coal, paraffin, wood, traditional biomass, (satisfies Market only, CSIR wants more sustainable manner)

- to become cleaner: Small Gas Turbines (SGT) might work; now they use fossil fuels which are expensive and not environmentally friendly. They could also use solar thermal energy to become cleaner.
- The exhaust gas of the SGT is very hot and can be used for regeneration of electricity or water heating.

- Mr. Szweczuk expects that FCs might become more reality in the far future but for now he believes more in the SGT.

- For off-grid electrification he refers to the HomerGIS: a off-grid electrification planning tool. HomerGIS = Hybrid Optimization Model for Electric Renewables, Geographical Information System

- From economic perspective Mr. Szweczuk states that the income of the people in the rural areas not yet connected to the power grid are too low to pay electricity bills. They need to have a power plant to start up their region so that they can make money and are able to pay their electricity bill.

- Rural energy and economic development is about the provision of energy and economic development

- Quality of supply of electricity should be the same as urban areas. To predict where FCs might be needed the human settlement trend patterns should be made first in order to predict demand of electricity and to develop the best cost forecast.

Appendix 10: Prioritisations

Name: Mark Rohwer

Market perspective / Business (CSIR) perspective

VVV= Strong correlation
VV = Medium correlation
V = Weak correlation
- = No correlation
1=highest priority driver

(Priority of product driver 1-6)	Product / Service	CSIR mandate to meet national needs	Beneficiation Pt	Niche applications	Price increase conventional fuels	Electricity capacity expansion potential	SA's growing economy	Awareness	HR development	IP development	Knowledge transfer	Client needs	Personal value Points (PVP)	CSIR Mandate
6	Capacity 1-20kW	V	V	VV	-	VVV	-	-	-	V	-	VVV	-	
3	Response to load change	-	-	VV	-	VV	-	-	-	V	-	VVV	-	
1	Simplicity maintenance	V	-	VV	V	VV	-	V	-	V	-	VVV	-	
5	Modular systems	V	-	VVV	-	VVV	VV	V	-	V	-	VVV	-	
2	Liquid fuels	V	V	VVV	VV(V)	V	V	V	-	-	-	VVV	-	
4	Efficiency	VV	-	VVV	-	VV	VV	V	-	VV	V	VVV	-	
	(Priority of Market driver 1-7)	7	2	3	1	4	6	5						
	(Priority of Business driver 1-6)								6	1	4	2	5	3

Name: Sibbele Hietkamp

Market perspective / Business (CSIR) perspective

VVV= Strong correlation
VV = Medium correlation
V = Weak correlation
- = No correlation
1=highest priority driver

(Priority of product driver 1-6)	Product / Service	CSIR mandate to meet national needs	Beneficiation Pt	Niche applications	Price increase conventional fuels	Electricity capacity expansion potential	SA's growing economy	Awareness	HR development	IP development	Knowledge transfer	Client needs	Personal value Points (PVP)	CSIR Mandate
1	Capacity 1-20kW	VV	VV	VV	V	V	VV	VV	V	VV	V	VVV	V	
3	Response to load change	V	-	V	-	-	-	V	V	VV	V	VVV	V	
5	Simplicity maintenance	V	-	V	-	V	-	V	V	V	V	VVV	-	
6	Modular systems	-	-	V	-	-	-	V	V	V	V	V	-	
4	Liquid fuels	-	V	V -	-	-	-	V	V	V	V	V	-	
2	Efficiency	V	V	-	V	V	V	-	-	VV	V	V	-	
	(Priority of Market driver 1-7)	3	1	7	4	2	5	6						
	(Priority of Business driver 1-6)								3	2	6	1	5	4

Name: Alan Brent

Market perspective / Business (CSIR) perspective

VVV= Strong correlation
VV = Medium correlation
V = Weak correlation
- = No correlation
1=highest priority driver

(Priority of product driver 1-6)	Product / Service	CSIR mandate to meet national needs	Beneficiation Pt	Niche applications	Price increase conventional fuels	Electricity capacity expansion potential	SA's growing economy	Awareness	HR development	IP development	Knowledge transfer	Client needs	Personal value Points (PVP)	[CSIR Mandate]
4	Capacity 1-20kW	-	V	VV	V	VVV	VV	VV	-	V	V	VV	-	-
1	Response to load change	VV	-	VVV	VV	VVV	VVV	VV	V	VV	-	VVV	V	V
2	Simplicity maintenance	V	-	VV	-	VV	V	VV	VV	V	VV	VVV	-	-
3	Modular systems	V	-	VVV	VV	VVV	VV	VV	V	VV	V	VVV	V	V
6	Liquid fuels	VV	V	VV	VVV	VV	VVV	VV	-	V	V	VV	V	V
5	Efficiency	VV	V	V	VV	VV	VV	V	-	V	V	V	V	V
	(Priority of Market driver 1-7)	6	7	4	2	1	3	5						
	(Priority of Business driver 1-6)								6	2	1	3	5	4

Name: Overall

Market perspective / Business (CSIR) perspective

= Very Strong correlation
= Strong correlation
= Medium correlation
= Weak correlation
– = No correlation
1 = Highest priority driver

(Priority of product driver 1-6)	Product / Service	CSIR mandate to meet national needs	Beneficiation Pt	Niche applications	Price increase conventional fuels	Electricity capacity expansion potential	SA's growing economy	Awareness	HR development	IP development	Knowledge transfer	Client needs	Personal value Points (PVP)	CSIR Mandate	Total
2	Capacity 1-20kW	61	93	46	42	111	66	42	24*	81	24	147	12*	40	789
1	Response to load change	44	-	116	72*	158	90*	44	22	124	4*	204	20	30	928
3	Simplicity maintenance	26	-	102	42*	130	25*	52	18	61	62*	186	-	30	734
5	Modular systems	10	-	79	48*	96	48	32	8	57	25*	84	8*	20	515
6	Liquid fuels	9	52	86	88	34	25	27	12*	20	9*	101	2*	23	488
4	Efficiency	39	37	53	44	82	47	15	-	96	26	83	4*	45	571
	Total:	189	182	482	336	611	301	212	84	439	150	805	46	188	
	(Priority of Market driver 1-7)	6	7	2	3	1	4	5							
	(Priority of Business driver 1-6)								5	2	4	1	6	3	

*=input gained by 1 person only

Appendix 11: Social impact of electrification

Socio-economic development

Electrification changes lifestyle. Generally, access to electricity is seen as an important step to socio-economic development. Energy is in itself a basic survival need. Fuels that are commonly used by poor communities for cooking and heating (fuel wood and paraffin) may be adequate to meet immediate basic energy needs, provided that these fuels are affordable and available. On the long run these fuels might be bad for health because the exhaust might be bad for the environment which on its turn influences the health of people. Where there is extreme energy poverty, it is argued that the effects can be malnutrition, exposure to disease, and even death (NER, 2004).
The most commonly discussed socio-economic benefits of electrification in summary are:

- Job creation through energy intensive manufacturing, new employment opportunities
- Small business development, e.g., shops, welding shops, hair salons
- Change of life style, e.g., access to refrigeration, extended working hours, access to communications
- Improved security, especially after dark through lighting
- Improved education levels, use of electronics as computers, overhead projector
- Rural development which eventually can increase South Africa's GDP
- Improved quality o f life
- Access to modern technology
- Reduced local air pollution levels, if electricity is used instead of traditional fuels.
- Major health benefits through fewer paraffin burns and poisoning, as well as vaccine refrigeration, water pasteurization and a decrease in fatal diseases.

The possible future privatization of electricity supply will have a serious effect on further electrification. A private electricity company will not electrify any household unless it can make money out of it. Only if they would receive government subsidies, electrification of rural areas becomes attractable to them.

Non-grid as inferior

For remote communities far from the main power grid there are already some options for non-grid electricity but these are rather scarce. These systems include mostly photovoltaic panels. The 'energy outlook for South Africa: 2002' (DME; Energy research institute, University of Cape Town, 2002) indicates that local people unfortunately view the PV panels as inferior to grid electricity, and believe that accepting PV power systems to be installed, would mean for them that their connection to the 'real' grid will be delayed. They regard the PV systems not only as practically inferior, because less power is provided and only 12V DC, but also as socially inferior. This is because of not being connected to the grid implies to them that they are not as good as the people connected to the grid (DME, 2002). In respect to the user perception it can be stated that the user perception is different than the supplier would like it to be. Mom (unpublished, 2007) argues to translate 'properties' into 'functions' in order to get the two parties both satisfied. He argues that in order to be able to design an artefact's properties, a designer has to translate the future function in its design. This is in accordance with the opinion of Mr. Mapako as can be viewed in appendix 9. Conversely, Mom (unpublished, 2007) states that a user will translate the properties into functions while using the artefact. To get the optimum result Mom (unpublished, 2007) argues that the user should be considered as active participant in the design process. He calls this 'co-construction'. He argues that it is necessary for users to participate in this process because designers tend to go in the way they think is the right one without really looking at the market, the end-users of fuel cell systems in this case.

Electrical devices and use

Some information on electrical appliance ownership and use was obtained in a post-electrification study in Loskop (KwaZulu-Natal), conducted as part of the Role of Electricity in the Integrated Provision of Energy to Rural Areas (REIPERA) project (Hansmann et al., 1996). A small quantitative survey was undertaken in an area where households had been electrified for two years or more. It is interesting to compare the percentage of households that use appliances frequently with the percentage that own the devices. A significant percentage of households that own an electric stove or hotplate do not use these frequently for cooking purposes. The difference is even more striking in the case of electric heaters (Hansmann et al., 1996).

Research in urban areas of SA has confirmed that households who own appliances do not necessarily mean that they use them (Mehlwana, 1999). In fact, anthropological studies have indicated that some of the factors that contribute to the purchasing of appliances are not related to use at all. According to White (2000), utilitarian considerations such as usefulness, cost, and the availability of space are the only factors that influence decisions to buy, use or keep appliances. Coupled to this are considerations of symbolic value. Examples of such considerations are the wish to conceal poverty, and to 'embody' a particular lifestyle: The fashioning of the 'public' spaces within the home is one of the primary mechanisms used to keep off the suspicion that one is struggling. In an attempt to create an image of style and well-being for outsiders, any electric appliances that can add to that image are prominently displayed. In some cases, devices have symbolic value only, as broken devices are kept on prominent display in many homes (White, 2000). Electricity is a marker of modernity and progress; electrical devices serve to distance people from the way of life of paraffin, the fuel associated with poverty (White, 2000). One of the main problems in SA is that many people living in rural settings cannot afford electricity as has become clear in chapter one.

Multiple fuel use

Multiple fuel use (the use of more than one fuel for household purposes) is a key feature of energy use among lower-income households in South Africa, including electrified households. The National Domestic Energy Use Database (NDEUD) indicates that about 68% of all households (electrified and non-electrified) use combinations of two or more fuels, with many households (about 30%) using three fuels (Afrane-Okese, 1999). Some energy studies in low-income urban areas have found that the majority of electrified households use electricity in combination with other fuels as paraffin and wood. This is confirmed by Eskom (1996) which has found that the use of electricity in combination with other fuels is particularly prevalent among lower-income groups and among newly electrified households. Regarding the reasons for combining electricity with other fuels, White (2000) points out that most lower-income households in urban areas with access to electricity, and particularly the recently electrified ones, perceive electricity as being too expensive for meeting all their energy needs, although electricity is cheaper than paraffin as will be showcased later in this chapter. Cost is not the only reason for multiple fuel use: The choices involved are driven not by economics only but also by factors as tradition, and culture, in other words, people's personal histories of using fuel (White, 2000). If the prices of electricity and paraffin are compared the next results will become clear:

The price of illuminating paraffin in the province Gauteng, used for lighting, heating, and cooking is 675 Rand cent per litre (www.info.gov.za, 5 Sept. 2007). Electricity costs are hard to calculate because Eskom uses different ratings per area and purpose, plus that the larger part of the costs is charged by the municipality. The average costs are about 50 cents/kWh for households. Appendix 2 shows the calorific values of all kinds of fuels which are necessary to compare different fuels (DME, 2006). Electricity has a calorific value of 3.6MJ/kWh and illuminating paraffin 37MJ/l. If both are converted to cents per MJ the next prices are generated:

Paraffin: *18.243 cents/MJ*
Electricity: *13.889 cents/MJ*

This calculation shows that electricity is cheaper than paraffin, which contradicts the belief of local people in rural areas about which energy source would be cheaper to use. So, in theory electricity is cheaper but in practice people first need to get to know how to use electricity efficiently as they now know to use paraffin efficiently. Also, it should not forgotten that electrical appliances are relatively expensive compared to e.g. a simple paraffin stove.

One of the most interesting phenomena in post-electrification energy use among low-income households is the persistence of paraffin as a fuel, particularly for purposes other than lighting. A general trend towards using paraffin for time consuming cooking processes has been found in areas such as Loskop and Tambo (Thom, 2000). Cooking processes such as simmering were seen as expensive by households in Loskop, and paraffin was preferred because it was regarded as cheaper than electricity (Hansmann et al., 1996). Paraffin stoves were also seen as easy to regulate in order to simmer food (Annecke, 1996). Households therefore tended to prepare the main meal (in the evenings) on paraffin stoves. By comparison, the speed of cooking food was regarded as one of the main advantages of cooking with electricity; it was thus sometimes used exclusively for dishes that require quick, intense heat inputs such as frying (Hansmann et al., 1996). Coupled to this were some forms of behaviour that probably added to the experience that electricity is expensive for cooking purposes. E.g. some people tended to use electric hot plates on the highest setting all the time, without reducing the heat once the food is boiling. One of the reasons given for this was that they thought it was more expensive to use all the settings on the hot plate (Annecke, 1996). The main uses of electric hot plates were: boiling water and making porridge for breakfast in the mornings, making tea and preparing fast cooking vegetables (such as cabbage), soups, and occasionally fried meat in the evenings. Paraffin, on the other hand, was used specifically to prepare slow-cooking foods such as maize and beans (Thom, 2000).