ENERGY, ENTROPY, SUNNY SKIES AND SOUTH AFRICA

INAUGURAL ADDRESS: PROF THOMAS HARMS AUG 2006

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ABOUT THE AUTHOR

Thomas Harms was born in Oldenburg, Germany in 1954. Assisted by relatives who had emigrated to what was then known as South West Africa after World War II, he spent a year at the Deutsche Höhere Privat Schule (DHPS) Windhoek in 1970. This led to a decision to remain in South Africa, where he obtained Matriculation Exemption at the former German mission school, the Deutsche Schule Hermannsburg, in Natal, followed by the German equivalent ('Abitur') at the DHPS in 1974.

After initially embarking on legal studies, Thomas obtained a BSc (Eng) in Mechanical Engineering at the University of Cape Town (UCT) in 1981. After a number of years in consulting engineering practice in Cape Town with Watson, Edwards, Van der Spuy and Laubscher, he was eventually responsible for large mechanical services projects for hospitals and office buildings.

Following in the footsteps of Professor Rhino Stegen (UCT) thirty years earlier, however, he went to England where he completed an MSc (Eng) in Thermodynamics and Related Studies at the University of Birmingham in 1986.

Preferring to spend time with his mother, sister and brother, who had followed him to South Africa, he enrolled for doctoral research with Professor Theo von Backström of the Mechanical Engineering Department and Professor Prieur du Plessis of the Applied Mathematics Department at the University of Stellenbosch. Upon graduating with a PhD (Eng) in Computational Fluid Dynamics (CFD) in 1995 and a brief lecturing stint at UCT, he was appointed as senior lecturer in the Thermodynamics Division of the Mechanical Engineering Department of the University of Stellenbosch in 1996.

Since then he has promoted CFD and renewable thermal energy studies in the Department through numerous undergraduate and postgraduate student projects, leading to associated engineering science research opportunities for students in Antarctica. He motivated the prioritisation of funding for the development of energy systems, solar rooftop and computational fluid dynamics laboratories. In this context he recently co-authored the winning bid for the hub of the extensively state-funded National Postgraduate Programme in Renewable and Sustainable Energy Studies (Van Niekerk and Harms, 2006).

He motivated the introduction of new final-year undergraduate modules such as Thermal Energy Systems and Numerical Fluid Dynamics, and acts as internal and external examiner for a number of South African tertiary institutions. He has served on the organising committees of several local national and international conferences and regularly reviews articles for national and international accredited research journals. As a former member of the national council of the South African Institution of Mechanical Engineering, he is currently the editor of its R & D Journal.

After a tour as head of the Thermodynamics Division, he is presently head of the Thermofluids Division of the Department of Mechanical Engineering.

Energy, Entropy, Sunny Skies and South Africa

Inaugural lecture delivered on 15 August 2006

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Editor: Mattie van der Merwe
Language editing: Professor Edwin Hees
Design: Heloïse Davis
Printed version: Stellenbosch University Printers
Revised layout electronic version: Andrew Gill

ISBN: 0-7972-1128-4

ENERGY, ENTROPY, SUNNY SKIES AND SOUTH AFRICA

INTRODUCTION

Those of us who were around in the 1970s in South Africa might recognise in the title of this paper the General Motors advertising slogan “Braaivleis, Rugby, Sunny Skies and Chevrolet”. Like any good phrase of this nature the intention is to convey a brief, catchy and easy to remember message, which exploits existing associations, while at the same time creating new ones. The intention here is the same: it is to link the established positive associations of ample sunny skies and South Africa to energy. Entropy is not merely included here to maintain the rhythm of a successful slogan, but to highlight this thermodynamic property, which is all too often under-utilised in the optimisation of particularly thermal energy systems.

ENERGY

Many of us are familiar with the names of the 19th-century physicists who founded the scientific discipline of thermodynamics.[1] Some of them are Sadi Carnot (1796-1832), Emile Clapeyron (1799-1864), William Rankine (1820-1872), Rudolf Clausius (1822-1888) and Lord Kelvin[2] (1824-1907), followed by Max Planck (1858-1947) and Albert Einstein (1879-1955). Motivated initially by engineering needs at the dawn of the industrial age, thermodynamics has developed into a fundamental field of physical science of deep and wide significance today.

The first law of thermodynamics holds that *energy in the universe is neither created nor destroyed*. Classical philosophy attached space time uniqueness to ‘laws’, thus recognising them to be quite distinct from ‘objects’, which do not share these attributes (Bocheńsky, 1972). We know today that, when objects approach the speed of light, different or extended rules apply. For example, the mass conservation law is shown to be a subset of the first law. However, for most engineering purposes, the first law and continuity are crucial and distinct tools.

They are made usable by the concept of a control volume, which separates a region from the surroundings by means of a real or imaginary boundary. The energy in this volume can then be accounted for, and from the first law it follows that if some energy is removed from this volume (e.g. by mass transfer) over the defined boundary, the energy left behind in the volume will be reduced by an equal amount.[3]

An example is the naturally occurring hydro carbon resource we find on Earth. Being flora-based coal, oil and gas reserves, they represent stored solar energy. The exothermic reaction[4] of hydrocarbons with oxygen derived from the atmosphere, which is employed predominantly at present, produces water, carbon dioxide and heat, from which work can be derived, i.e. energy represents a capacity to do work. Thus fossil fuels have been a key component in our economies since the 19th century.

The typical ‘peak oil’ view holds that oil reserves[5] are being depleted at four times the rate of new discoveries (Campbell, 2002). Most scenario planners foresee significant changes in oil-consumption patterns during the first half of this century (IEA, 2006). This will be motivated by supply and demand pricing, energy supply diversification strategies, new technological developments and environmental concerns from converting significant amounts of atmospheric oxygen to carbon dioxide (Kammen, 2006).

At this point it is useful to introduce the analogy of a bank account. Perhaps even more so than our understanding of the first law of thermodynamics, we all know that if a withdrawal is made, the balance of what is left in the account will diminish by the same amount.

ENTROPY

All the researchers mentioned above contributed to the development and understanding of the second law of

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[1] Thermodynamics: Greek for heat and moving forces.

[2] William Thompson.

[3] This energy left behind can be in a variety of forms.

[4] The process in hydrogen fuel cells, for example, is an alternative.

[5] Known, quantified and economically exploitable oil finds.

thermodynamics. As one of the many corollaries of the original statements by e.g. Clausius, Kelvin or Planck, the second law holds that *a thermal engine producing work must exchange heat with at least two reservoirs*.

Consider a high-temperature gas trapped in a cylinder exerting a force on a piston such that it moves and produces work. To obtain net work output from the cyclic engine the gas must reject some of its energy (heat) to a low-temperature reservoir so that the piston can be returned to its starting position with less work than during the working stroke. This is, by the way, precisely what happens in the external combustion engine named after Reverend Robert Stirling (1790-1878).

Each time we use energy, therefore, a part of it has to be degraded, e.g. through heat transfer to a lower temperature or exhaust to a lower pressure. Note that the first law is not violated here. But the second law teaches us that energy can become unavailable to us.[6] For a thermal power station, for example, this process is constrained by the state of the environment. South African examples of low-temperature energy sinks would be the waters in Table Bay used by Eskom's Koeberg nuclear power station in Cape Town or the surrounding air used by one of the largest dry-cooled (car-radiator type) power stations in the world, Matimba, in Ellisras (Kröger, 2004). These processes reject about 2/3 of their primary thermal energy to the environment.

Our 19th century researchers established the property entropy $ds = (dq/T)_{rev}$ as a means to quantify the degradation of energy. Thus a further corollary of the second law states that for any process to occur at all, an overall increase of entropy must take place. The efficient use of energy therefore not only entails seeing where energy use can be minimised (e.g. Potgieter, 2004), but also whether different processes can be employed which would reduce the reduction of availability (exergy) or reduce entropy generation (see figure 1). This is often also referred to as exergy or second law analysis. In fact the typically Western economy has long been characterised by its enormous rate of entropy generation of questionable sustainability (Rifkin, 1982).

Returning to our analogy of the bank account, it can be stated that it is impossible to make a withdrawal from our account without some of the funds becoming unavailable to us. These are the charges the bank levies at every transaction which we make. Luckily for us, banks appear to be more efficient than the thermal power stations just mentioned!

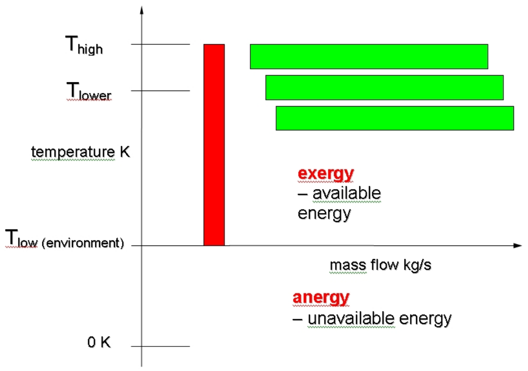

Figure 1: Looking for second-law efficiencies

For the sake of completeness it is worthwhile to mention the other two, more technical, conclusions given the status of law in thermodynamics. From thought experiments around the two first laws 19th century physicists were able to postulate a state of matter at a temperature which could no longer supply the energy for a heat engine, since no heat rejection to a lower temperature was possible, i.e. no further degradation of energy can take place. Thus the third law of thermodynamics states that *the entropy of solid substances is zero at absolute 0 K or -273,15 ºC.* – The bank balance is zero.

Finally, Sir Isaac Newton (1642-1727) had already stated that the heat transfer rate is directly proportional to the temperature difference that drives it. Nevertheless, as an afterthought, Sir Ralph Fowler (1889-1944) found it necessary to formulate the matter of temperature measurement through a corollary statement, really, which he named the zeroth (most fundamental) law of thermodynamics. It states that *if two bodies are in thermal equilibrium with a third, they are in thermal equilibrium with each other.* – To conclude our analogy then, correct accounting procedures are presupposed.

SUNNY SKIES

South Africa is a country characterised by its generous sunny climate. For example, the solar radiation levels experienced in the Northern

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[6] Available energy is also referred to as exergy and unavailable energy as anergy.

Cape of up to 2900 kWh/m^2 per year[7] are among the highest in the world (Stinnes, 1997). While the associated lack of rain severely impacts on water resources planning, and the health risk of solar radiation-induced skin cancer requires an educated response, the country remains a major tourist destination because of its natural beauty.

Add to this an enormously long coastline (2800 km), wide open, often arid spaces and a significant first world industrialised agricultural sector, there has never been any doubt about the vast potential this country holds for renewable energy, such as solar energy, bio fuels, wave or wind energy, for example, and some hydro power.

All renewable energy is derived from the sun. Present predicted lifetime for the sun is 6000 million years (*The Times*, 1998). Life might be untenable in our solar system long before that as a result of the onset of stellar decay. Other threats such as meteor strikes or loss of the protective magnetic field due to the cooling and hence solidifying of the inner liquid core of the Earth might be threatening 'much sooner'. It is to be expected that life, in whatever form then, will have started expanding beyond our solar system long before that. However, the point which can be made is that an investment in the development of renewable energy technology has, for all practical purposes, excellent long-term prospects.

Renewable energy is not free; it must be sustainably harvested. This requires equipment, from a low level to an extremely high level of technological complexity in small- and large-scale applications. This severely impacts on the economic competitiveness of renewable energy vis-à-vis conventional energy resources. This is aggravated by the fact that many sources of renewable energy are intermittent and of low energy density. Thus generally energy storage technology must be factored into the costs as well.

At this point in time the view is widely held that renewable energy is not generally feasible, particularly at bulk power-generation level. Sustainably planned hydro-power plants are the exeption. This is in part explained by the lack of prioritisation of research funding which would otherwise ensure that the rate of new development accelerates the technology to reach the head-on competitive cost zone of conventional non-renewable energy resources.

This is not to deny that millions of dollars of public and corporate funding has been poured into renewable energy research and development worldwide for decades. The astounding economic growth rates of India and China, and the concomitant hunger for resources, have put the peak oil scenario squarely into focus. And a US$70 per barrel oil price, albeit in the short term, is an excellent phenomenon which gives a welcome boost to initiatives aimed at developing a more sustainable energy turnover, both at the production as well as the utilisation sides.

While I was studying for an MSc in Thermodynamics and Related Studies at the University of Birmingham in England in 1986, it was possible for me to attend a course in solar energy presented by Leslie Jesch. His advice to that young man then was to drop everything and enter into research in direct solar photovoltaic conversion. Dr Jesch was recently honoured by the International Solar Energy Society on the occasion of his 80th birthday (Patterson, 2006). He no doubt contributed to my conviction that projects in interesting renewable energy technology ought to be supported whenever the opportunity arose.

Holding this conviction, I was neither alone in South Africa nor at the University of Stellenbosch, where many colleagues have supported research of this nature in the past.

In 1996 Niell Coetzee completed a final-year project (Coetzee, 1996) under my supervision for the design of a solar power station for South Africa. This ambitious undergraduate project was inspired by Remar (1995).[8] It led to a dialogue with Mike Prarie of Sandia National Laboratories in Livermore, California, manifested in a sizable parcel of hardcopy material[9] kindly made available and duly returned at the end of the project as requested. The recommendation then was that a central receiver-type power station as depicted in figure 2 and figure 3 should be the preferred choice for South Africa. Coetzee (1996) proposed Upington as a suitable site.

In 2001 Roos (2001) submitted a PhD proposal to use this concept to power – at least for part of the day – redundant Turbomeca Artouste helicopter gas turbine engines converted to stationary 400 kW generator packages (see figure 4 for 1/100th scale model

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[7] If this were converted to electricity at 10 %, three Osram Compact Fluorescent Lightbulbs consuming 11 W could continuously provide 180 W of lighting.

[8] Remar also proposed the projects of Hufkie (1996), Joubert (1996) and Lilly (1996).

[9] The digital age was in its infancy then.

configuration). Some financial support from the CSIR[10] was obtained. This work is ongoing and was supported by Joubert (2003).

Figure 2: Central receiver solar power plant, Barstow, California[11]

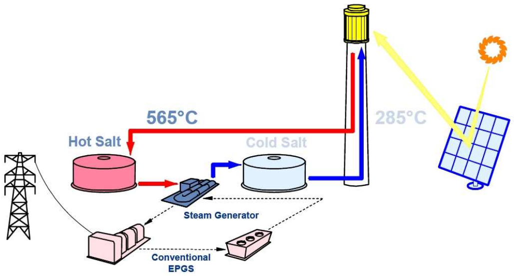

Figure 3: Schematic - central receiver solar plant[12]

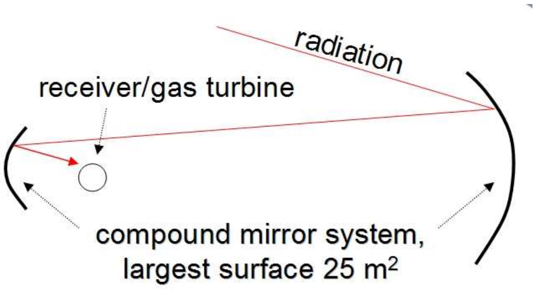

Figure 4: Small-scale central receiver plant

At the beginning of 1997 it was possible to offer a new final-year mechanical engineering elective entitled Thermal Energy Systems 414, which entailed a substantial renewable energy component[13]. This course was made a compulsory feature of the undergraduate curriculum in 2004.

Together with this new elective, a number of under- and postgraduate energy, solar and waste heat-related projects were supported. This combination exploits the overlap between applications in similar temperature ranges.

Potgieter (2004) looked at the waste heat potential in the plant of large South African French fries producer as a typical industrial example (see figure 5). A review of a Koeberg nuclear power station steam-production analysis by Harms and Beyers (2000) is also grouped under these activities.

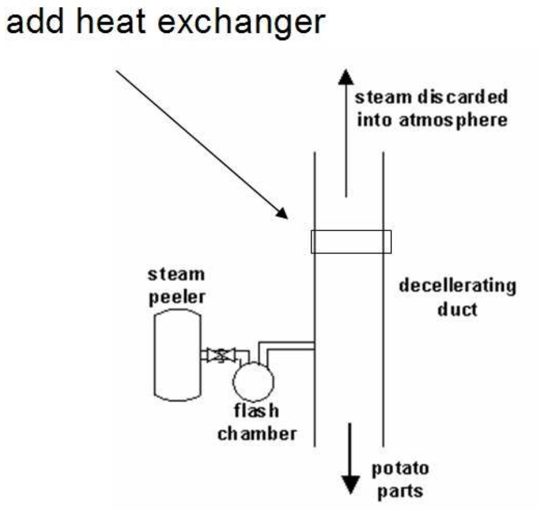

Figure 5: Typical waste heat recovery setup[14]

Interestingly, the relationship between solar and waste heat also extends to internal combustion (IC) engine exhaust gas waste heat recovery. This technology is well established on board large ocean-going vessels that utilise exhaust gases to generate steam and thus electrical power at the end of a Rankine cycle (Joubert, 1996). An IC engine[15] typically rejects 1/3 of its primary energy in the exhaust system, while a Rankine cycle typically rejects 2/3 of its primary energy in the condenser; hence the potential efficiency gain of an exhaust gas

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[10] Council for Scientific and Industrial Research.

[11] Picture http://www.energylan.sandia.gov/sunlab

[12] Picture http://www.bohlweki.co.za

[13] Professor Detlev Kröger suggested in 1996 that an elective entitled ‘Steam Machines’ be modernised to suit the needs of graduates heading for power industries.

[14] Diagram courtesy Johan Potgieter, 2004.

[15] IC engine remaining energy distribution: 1/3 power and 1/3 cooling system.

Rankine vapour power cycle is in the order of 11% (1/3 of 1/3) for IC-engine operations. Anticipating rising fossil fuel costs, the view was taken that the time might have come to accomplish some modest groundwork for such systems for large road utility vehicles and locomotives.

Examples of such projects are Joubert (1996), Koorts (1998), Lotun *et al.* (2001) and Wipplinger *et al.* (2006). This work is presently being continued by Snyman (2005) in collaboration with Johan Strauss of the Electrical and Electronic Engineering Department of this University. Our view was recently vindicated, when it became known that the automotive manufacturer BMW[16] expects to develop such systems to be commercially available within 10 years (Sapa-dpa, 2006).

An interest for solar and waste heat applications spawned a whole series of projects when Paul van Staden, former MEng graduate of the Department of Mechanical Engineering (Van Staden, 1990) gave a presentation at the Faculty in 1999. As the then mechanical engineer for the South African National Antarctic Programme (SANAP), he suggested that we examine opportunities for engineering research associated with the South African research base SANAE IV[17] shown in figure 6. In subsequent years a number of projects were undertaken relating to the sustainability and efficiency of base operations.[18] These led to engineering science becoming a recognised research activity for SANAP, now administered through the National Research Foundation (NRF). The wind energy feasibility study by Teetz *et al.* (2003) and the solar energy feasibility study by Olivier (2006) are highlighted here.

Figure 6: Antarctic research base SANAE IV[19]

The work of Teetz *et al.* (2003) is presently being continued by Stander (2006), and Professor Maarten Kamper and his team of the Electrical and Electronic Engineering Department were encouraged to submit a proposal of their own to SANAP/NRF in 2006.

A further project utilising low-quality heat (waste or solar heat) to accomplish refrigeration was initiated by Robert Dobson, senior lecturer in the Mechanical Engineering Department (e.g. Rabie, 2004). The basic idea dates back to the early 20th century and the name Charles Parsons (1854-1931) should not go unmentioned. The concept has many industrial applications where waste heat is available and cooling is required. Briefly, a high-pressure gas generated through heat addition is discharged through a nozzle. The emerging jet entrains, through momentum transfer, gas from the evaporator, thus generating a very low pressure over a fluid. This fluid in turn is able evaporate at very low temperatures and thus absorb heat, as shown in figure 7.

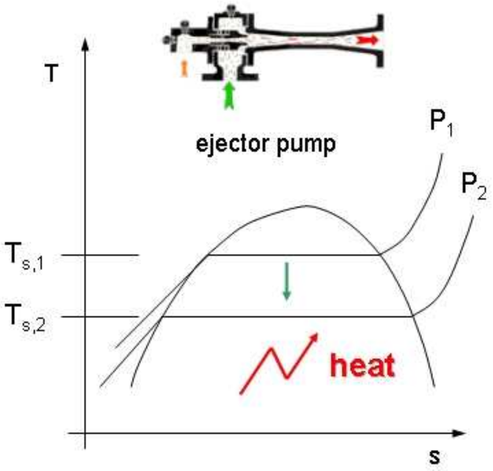

Figure 7: Refrigeration principle

Figure 8 shows the experimental demonstrator constructed by Katot Meyer (2005), who was the first student to successfully commission such a device in the Department.

The simplicity of the concept belies its ingenious execution. The evaporation temperature is robustly controlled over a range of degrees of wetness in the evaporator by its pressure. Two converging-diverging nozzles introduce further robustness by potentially decoupling the heat source from the heat sink through sonic choking in the nozzle throats, allowing discharge into elevated pressures.

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[16] Bayrische Motoren Werke, Munich, Germany.

[17] South African National Antarctic Expedition IV.

[18] Engines: Taylor *et al.*(2002), Energy: Cencelli (2002), Snow: Beyers (2004), Waste: Underwood (2003).

[19] Picture courtesy of Jürgen Olivier, 2005.

Figure 8: Heat-driven refrigeration test unit[20]

In 1999 a written motivation was prepared[21] and supported by University line management[22] for the construction of a R250 000, 400 m^2 solar energy roof-top laboratory, which was successfully completed on budget in 2001. Figure 9 shows a view of this facility. Some greenhouse work was undertaken by Combrink and Harms (2001), and a number of small initial parabolic trough projects supervised, e.g. Davids *et al.* (2001).

Figure 9: Solar roof-top laboratory[23]

This facility served as a model for Mangosuthu Technikon in Durban, which, under the leadership of lecturer Mike Brooks, obtained funding to construct a similar facility (Brooks and Harms, 2005a, b). This facilitated Brooks's (2005) subsequent work on a parabolic trough solar concentrating receiver, which is the largest such unit in the country at present and shown in figure 10.

In part also motivated by the aforementioned activities and interest, during the late 1990s the Department was approached by Stinnes (1997), consultant to the government of the Northern Cape province at the time, to undertake research on aspects of the solar chimney power station, an alternative bulk solar power-generation plant shown in figure 11, which Stinnes (1997) had concluded to be superior to the alternative configurations.

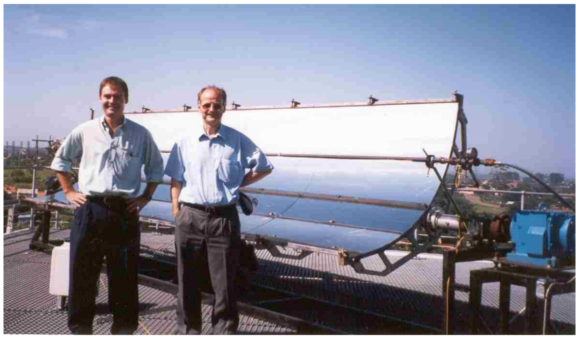

Figure 10: Largest parabolic trough in SA[24]

This was taken up with great enthusiasm by Professors Kröger, Von Backström and others, and a rich bounty of theses and publications appeared in the years that followed. A small contribution to this effort was made by the work of Beyers *et al.* (2001) and Harris (2004). An Australian initiative to construct a 1000 m high plant is presently being driven by Environ Mission Ltd[25] and supported by Schlaich, Bergerman and Partners,[26] the originators of the concept (Schlaich, 1995). Stinnes (1997) steadfastly pursues his dream as well, particularly in Southern Africa.[27]

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[20] Picture courtesy of Katot Meyer, 2006.

[21] Suggested by Professor Detlev Kröger.

[22] Professors Anton Basson, Head of Department, PW van der Walt, Dean of Engineering, and Walter Claassen, Vice-Rector (Research).

[23] Picture courtesy of Dimitra Westdyk, 2004.

[24] Author to the right of Mike Brooks. Picture courtesy of Mike Brooks, 2004.

[25] http://www.enviromission.com.au/

[26] http://www.sbp.de/en/fla/index.html

[27] http://www.greentower.net/

Figure 11: Solar chimney plant, Manzanares, Spain[28]

At about the same time, the South African public enterprise utility, Eskom, went into consultation with Sunlab, a consortium of the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories of the United States Department of Energy to allow its South African Bulk Renewable Energy Generation (SABRE-Gen)[29] division to make a recommendation on which generation technology to pursue. A most welcome result of a long process is that the first phase of an environmental impact assessment was recently launched[30] with regard to a 100 MW central receiver solar power plant. Three possible sites have been identified in the vicinity of Upington in the Northern Cape, all bordering on the Orange River! Thus, quite satisfactorily, the circle has been closed, although the construction of what would be one of the largest single concentrating solar power (CSP) plants in the world remains to be achieved.

An additional thought puts this in an interesting perspective: a back-of-the-envelope calculation shows that an area in the Northern Cape of 50 km by 50 km has a potential to supply about 100 000 MW solar electricity day and night, provided there are regular sunny skys of course.

With regard to the projects supported, the strategy has been to engage in all four concepts of solar power plant. The solar chimney represents a low-temperature (~80 ºC) option, incorporating storage and potentially reduced power production cost as a result of agriculture in the collector.

Parabolic trough technology can be considered as the most advanced and proven (see figure 12), and operates at the approximately 400 ºC plus range. For example, the nine solar energy generating systems (SEGS) parabolic trough plants in the Mojave desert in California have probably sold more than US$2 billion in electricity so far (extrapolating from Trieb, 2000).

Figure 12: Parabolic trough plant, Boron, California[31]

The dish Stirling option depicted in figure 13 represents a modular approach of a 25 kW unit, without storage and technologically less mature. Eskom has been testing such a unit at Midrand near the Ben Schoeman highway for some time now.

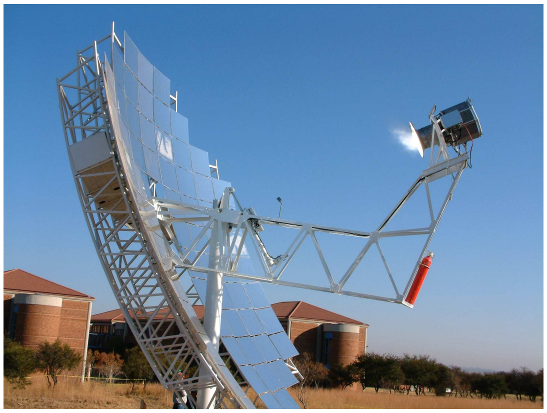

Figure 13: Eskom dish with Stirling generator[32]

The central receiver plant can reach temperatures near to the order of 1000 ºC, however. This maximises the availability of the energy as discussed above and thus also facilitates energy storage. In addition no pipe network in the field is required. The plant envisaged by Eskom is 10 times larger than the 10 MW Solar Two power tower pilot plant near Barstow, California, which completed

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[28] Picture courtesy of Wolfgang Schiel, 2002.

[29] http://www.sabregen.co.za

[30] Bohlweki Environmental (Pty) Ltd (2006) http://www.bohlweki.co.za

[31] http://www.energylan.sandia.gov/stdb.cfm

[32] Picture courtesy of Eskom, 2003

operations in April 1999 (see figure 2) and performed reasonably well (Pacheco, 2002).

The South African version will typically require a 210 m high tower and a field of 6000 times 130 m^2 heliostats and operates at 600 ºC.[33] Perhaps a hybrid of the central receiver concept with the more proven parabolic trough concept could eventually lower the visual impact of such a plant and reduce the performance risks. In fact, I personally would prefer an all and all low profile direct steam-generating parabolic trough plant.

Solar energy conversion efficiency would range from ~2% for the solar chimney type to +15% for the other concepts (Weinrebe, 1999).

Finally, photovoltaics are not far off the bulk plant market as well and could eventually be used to recharge a pumped storage scheme, for example.

SOUTH AFRICA

The 25000 MW Coal Plan

Energy has been very much in the news in recent months in South Africa. A price of oil in excess of US$70 per barrel certainly reflects a supply bottle neck (not without overtones of speculation), with its associated inflationary and hence monetary pressures for stifling higher interest rates. The powerful and welcome growth spurt of the South African economy toward the dream target of 6 % in recent times has put Eskom's commissioned power supply reserve capacity margin under pressure.

Transmission grid failures and the generator damage to the Unit 1 Koeberg nuclear power generator has brought rolling black-outs to some regions, in particular the Western Cape Province. An additional associated liquid petroleum gas shortage for cooking and heating has taken the shifted awareness of our energy needs beyond the financial impact of high oil prices have at the petrol pump. Temporary fuel shortages experienced near the end of 2005 as a result of the introduction of lead-free petrol added to this awareness. This is healthy because it helps us to appreciate just what a precious resource usable energy represents.

South Africa is blessed with its own sizable coal reserves. Eskom, one of the world's largest power utilities, continues to be able to offer an extremely internationally competitive average tariff of 17 c/kWh, which includes a regulated profit margin (Craemer, 2006). This is partially based on the result of utilising pulverised cheap low-grade coal and limited gaseous emission restrictions. South Africa's performance is particularly poor in that regard, contrasted by our excellence in dry cooling (Dutkiewicz and Gore, 1998; Von Blottnitz, 2006). While the availability of competitive electrical power from a parastatal with a virtual monopoly hitherto has been an economic advantage for South Africa, this has impeded the development of a significantly diversified energy industry. It has also in the past entrenched the view that renewable power alternatives are fundamentally uneconomic. This is unfortunate.

The outages described above have perhaps accelerated the decision that, in order to support an economic growth rate target of 6 %, a strong electrification programme with free basic electricity is necessary, and that it is therefore high time for capital expenditure, particularly in view of the considerable lag periods from three 3 to twelve 12 years, depending on technology, before planned capacity becomes available online.

Thus the recently announced R97 billion (Gcabashe, 2006) five-year capital expenditure programme by Eskom is to be welcomed. This is so from the sunny sky point of view particularly, for this programme will no doubt put a desirable pressure on electricity tariffs to increase.

A brief review of this programme based on the authoritative report by O'Connor (2006) is instructive. At the beginning of 2006 total installed capacity available was 38 188 MW.

This is made up of 32 446 MW coal-based power from 12 power stations, i.e. 85 %. This includes two 'de-mothballed' Camden units of 200 MW each. The 15% non-coal capacity of 5742 MW is made up of two times 920 MW Koeberg nuclear power units, 600 MW base load hydroelectric power, and two times 171 MW gas turbines, 1400 MW pumped storage[34], and 1600 MW from Cahora Bassa. Occasionally additional imports from Inga power station in the DRC and Kafue power station in Zambia occur.

Eskom's internet-based hourly demand indicator[35] lists a maximum demand record of 34 195 MW during July 2004. O'Connor (2006) concedes that reserve margins are not near a possible ideal of 25 %, although 10-20 % might be more realistic. In fact, e.g. should Cahora

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[33] http://www.bohlweki.co.za

[34] It is likely that pumped storage is actually mostly coal-based.

[35] http://www.eskom.co.za/zqf/process.asp

Bassa not be available, for example, and the pumped storage be exhausted, the margin comes down to 3 %. Nationally speaking, if the Koeberg station is not available, this would be about 6 %. This scenario is addressed by 2500 MW of interuptable power supply contracts with low-tariff bulk users, who in return negotiated to be disconnected in a capacity crunch.

Projecting on a diminishing average demand expansion rate of 4,2 %, which anticipates a diversifying energy industry, nevertheless an annual capacity expansion of 1500 MW is envisaged, although the Energy Intensive Users Group (EIUG, 2006) suggests that this should be closer to 2000 MW added capacity per year. Gcabashe (2006) agrees, if a 6 % economic growth target is to be achieved. The majority of this will come from coal. But some pumped storage, direct hydro, gas and nuclear power enter the picture as well, however.

Further de-mothballing (R13 billion)[36] of the Camden, Grootvlei and Komatie unit will add 3600 MW. It is interesting to note that Grootvlei was the first ever dry-cooled coal-powered plant built by Eskom. A further 300 MW will result from upgrading Arnot power station. The construction of a new 2 100-2 400 MW coal-based power station for about R20 billion has been approved (project Alpha). The first unit is expected to be online in 2010. Welcome flue-gas desulphurisation might be an option (Craemer 2006). Presently Eskom is contemplating a total of 25 000 MW of new coal capacity (de-mothballing, new construction, new technologies, feasibility studies). In this context Eskom does foresee the introduction of new, clean coal technologies.

Arnot	2100
Duvha	3600
Hendrina	2000
Kendal	4116
Kriel	3000
Lethabo	3708
Majuba	4110
Matimba	3990
Matla	3600
Tutuka	3654

Table 1: Nominal coal-fired capacity (MW)[37]

While construction of an additional 1050 MW open-cycle gas turbine (OCGT) in the Western Cape is well under way, the 1333 MW pumped storage project near Braamhoek has not yet been finally approved, although prequalification of consultants and contractors has begun. Feasibility studies on a further 6900 MW of various gas turbine plants are taking place, which includes a Kudu gas project.

The picture which emerges here is a dynamic large-scale reaction to ongoing industrialisation and electrification growth in South Africa. This is in keeping with a successful track record of electricity supply to this country (McRae, 2006). Recent power shortages have come as a shock to many and have lead to significant economic damage to in the Western Cape economy. That showed how reliant and complacent we had become after, say, thirty 30 years of high availability of ample electric power supply. The successful intensive demand side management efforts and the accomplished repair of the Koeberg generator involving the sourcing, importing, installing and commissioning of a 200 t generator rotor in minimum time is a considerable engineering feat. The fact that project Alpha refers to a water-saving dry-cooled station, a technology proven in this country at world-dominating scale, particularly with the support of the work continuing under Professor Detlev Kröger of Stellenbosch University's Mechanical Engineering Department, is certainly something to be proud of.

The Western Cape

The fact that, at least nominally on a national scale, there is a manageable power-supply does not mean this is the case regionally. This discrepancy is brought about by the result of the vast expanses of South Africa being covered by an under-redundant, coarse-grid power grid, which is not easily remedied unless through major capital expenditure.

The power grid is not capable of supplying the Western Cape electricity needs. The region has outgrown the redundancy of the contribution of Koeberg nuclear plant.

A typical winter Cape load would have to be catered for by Koeberg's two 920 MW generators supported by the Palmiet pumped storage scheme of two 200 MW units, the three 57 MW Arcadia Boeing 707 aero engines

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[36] Still less than half the cost of new plant.

[37] Exceeds actual total by 5000 MW; O'Connor (2006)

kerosene gas turbines,[38] opposite Canal Walk shopping complex, and the city council's four times 48 MW Steenbrass pumped storage scheme and by the transmission lines from our northern coal-belt power stations. Typically, a shortage of about 300 MW results if one of Koeberg's unit is not available. This has, however, successfully been reduced by Eskom's recent intensive demand-side management efforts. The Western Cape 'power alert' indicator regularly broadcast on TV during peak times[39] made a significant contribution in this regard, revealing an inspiringly responsible social base.

The Atlantis five times 146 MW OCGTs and the Mossel Bay four times 146 MW OCGTs due on line by mid-2007 will essentially return one Koeberg generator to redundancy, however, but at a price. The generating costs are put at up to R 2,60/kWh if run at 1% load factor (Craemer, 2006).

Similarly, intensified efforts to complete the outstanding upgrade of the power lines to the Cape grid from Hydra substation in De Aar are now scheduled to be completed by mid-2007 as well.

While these actions will significantly increase the short-term capacity in the Western Cape, the situation remains uneasy.

The Western Cape power-supply reliability will still rests depend on the well being of Koeberg nuclear generating capacity before, e.g. for example, more expensive gas power plans can be realised. Koeberg power station was commissioned in 1984 and has been functioning as an expensive-to-run base load station ever since (more than 1100 employees and 350 full-time contractors normally – Eskom, 2006a). While a further life expectancy of 40 years is not unheard of (Eskom, 2006b), longer duration maintenance and inspection[40] shut-downs must be expected. With continually growing demand, significant additional power-generating capacity construction needs to be initialised now. In terms of the lead time of a new nuclear plant of 12 years (O'Connor, 2006), a medium-term reliable power supply of a growing Cape Town seems far from assured. Additional gas turbine plants (e.g. at Saldanha and Coega) need to be constructed. An additional 765-kV (600 MW) transmission line from the north could also be in place by 2012 (Craemer, 2006).

The recent decision by Stellenbosch University to invest in additional emergency diesel-power generation capacity, therefore, seems appropriate under the circumstances.

The Cost of Bulk Solar Power

In most cases grid-based electricity is sold by Eskom to municipalities, for example, who in turn resell it to the public at a premium to fund development. A number of autonomous regional electricity distributors (RED) are, however, to be introduced and RED1 in the Western Cape is due to become functional in 2006. In Stellenbosch, depending on consumption, we are charged approximately 42 c/kWh of electric energy used. We recall the average supply tariff of 17 c/kWh mentioned above (Craemer 2006). This was also put in perspective by the R 2,60/kWh it would cost to occasionally run an OCGT to meet peak demand. An existing base-load coal power station is probably still able to deliver at below 20 c/kWh (ignoring externalities and life cycle costs). But if it is run at low load factors on peaking duty only, this figure will be significantly higher. Being able to negotiate 2 c/kWh[41] for Cahora Bassa power helps the average. Koeberg before the generator failure is rated at 30 c/kWh, which is also the same ball park for peak pumped storage (27 c/kWh). This probably assumes recharging with a good base-load station.

An initial estimate for Eskom's CSP plant is R2,2 billion (Venter, 2001). Assuming 5 % inflation over five years, and a pre-tax return of investment of 5 %, and the plant supplying evenings and mornings for 4 hours each yields a charge of 48 c/kWh, discounting running cost. A recent New Mexico study (ENMRD, 2005) selected parabolic trough type technology as most advanced and came up with an average figure of 10 c US$/kWh, taken as 70 c/kWh. This did not generally include dry-cooling, storage or carbon credits but allowed for some tax concessions. Quachning (2003) gives a figure of 10-15 c €/kWh, taken as 80-120 c/kWh, the lower figure incorporating large-scale production effects.

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[38] These plants are now normally reserved as Koeberg auxiliaries. Special Nuclear Regulatory Authority permission was given for peak-time use.

[39] http://www.poweralert.co.za/index_actual.php?location=online

[40] Nuclear Regulatory Authority.

[41] Negotiated to be about double when no surplus generating capacity is available in SA.

Let us assume then a figure of 84 c/kWh as a base for a first off, bulk solar generating cost, not yet subject to economies of scale, which incorporates storage, dry cooling and makes use of income from carbon abatement. We then have a situation where a first off bulk thermal solar energy power plant could compete as a peak load plant in South Africa. It is therefore concluded that a CSP unit as proposed by Eskom would be viable but is clearly seen as a very low priority (Craemer, 2006).

The Need for Change

Eskom represents a healthy hard-core capitalist venture under pressure to supply electricity as cheaply as possible for the benefit of industrial development. Eskom has a commendable track record of supplying reliable electrical power, despite recent setbacks. We all want the electricity to come out of the socket at any time, especially industry. However, more than 90 % of our electrical power is coal-based, with its associated emission issues and non-renewable nature. While ample coal is available, bottle necks in coal provision can be expected in 20 years. Coal demand for base-load electricity generation will in effect double from 100 million tonnes to 175 million tonnes by 2025. At that time the cost per tonne of coal should have equally doubled from about R 50 to R 100/tonne as the easily accessible reserves become diminished (Venter, 2006).

In addition to supply considerations, the effect of carbon dioxide emissions that cause dramatic, detrimental changes in global weather patterns despite the optimisation of hydro-carbon combustion processes still needs to play itself out. The Kyoto Protocol and the Clean Development Mechanism (CDM) have the potential to affect international trade as more severe restrictions come into effect in the future.

The greenhouse effect is nevertheless associated with global warming occurring at an accelerated rate. In turn noticeable severe and detrimental changes in weather patterns occur. The recent eastern USA hurricane season might suffice as an example. The long dry Western Cape summers 1999/2000 and 2000/2001 might be a harbinger of climate changes to be experienced locally.

South Africa needs to diversify its energy and fuel supply to more environmentally friendly alternatives.

The vast surface expanses of the South African landscape give rise to the need for localised power production from small power station size (100 MW) to micro-power systems. There is excellent potential in this market niche for a large variety of renewable and sustainable power technology.

Lastly but most importantly, South Africa is a mixed economy with extensive socio-economic upliftment requirements, which demand a search for new economic opportunities, particularly in rural areas. The production of bio-fuel material comes to mind as a quick example. This is coupled to energy life style factors, such as low cost energy, effective sustainable housing and cooking technology for example.

There is a great need for economic opportunity in South Africa which provides employment at lower skills levels. There is evidence in the literature (Wesgro, 2000; Austin *et al*., 2003) that a renewable and sustainable energy industry, despite its high technology facet, is particularly suited to provide such opportunities.

The Pebble Bed Modular Reactor

The pebble bed modular reactor (PBMR) programme comes highly recommended in the light of what has been said above. It could eventually lead to a welcome diversification of South Africa’s energy supply. It is an appropriate technology for a country, and perhaps a continent, with great surface expanses which are covered at great cost by a national grid. And it will have an export market, assuming also that anti-nuclear sentiments will rather weaken than strengthen in the years to come. Environmental considerations always require compromises, and the world does need emissions free nuclear power now. However, the question can be raised as to how quickly the PBMR can become significant to the South African electricity supply. The estimate is not in under ten years, considering inevitable technical and licensing delays. Also six of such 165 MW units, ready for commercial operating licences, would be required to replace the capacity of one unit of Koeberg nuclear power station.

A further point needs to be made in this regard. Approximately R14,5 billion in capital has been committed to achieve the goal of a licensable commercially deployable PBMR system (Cokayne, 2005) with electrical output around 165 MW. As is the nature of such projects, their costs are likely to escalate (Naidoo, 2006). In the meantime Eskom has given notice that it intends to reduce its shareholding in the project from 40 % to 5 %, in other words, to become a user rather than an owner of the technology (Cokayne, 2006).

The costs to decommission a nuclear power station and to rehabilitate the environment to its original state are so astronomical (e.g. PE, 2006), that I will state the premise that a nuclear station once built is forever. This also puts into question a figure of 30 c/kWh production cost for nuclear power-based electricity production usually reported (Craemer, 2006).

Something is wrong here. Time and again we are told renewable and sustainable energy technology has not yet reached economic maturity. The energy storage issue has not been solved. The energy intensity is too low despite the well known fact that just 1 % of the surface of the Sahara desert covered with solar thermal power plants would satisfy the present entire global electricity demand (Quaschning, 2003). Our weather prediction is not good enough yet so that renewable power generators wind turbines can bid on the 24 h peak power market. We do not know yet how we can liquefy the hydrogen for the new energy age in order to supplement the existing liquid fuel infrastructure, although liquid petroleum gas use for automotive use is on the increase. Ask a university engineering researcher how far he or she thinks just R 1 billion of research funding would go to get answers to some of these questions!

The Photovoltaic Breakthrough

In the light of the advice received from Dr Jesch, the recent revolutionary advance in photovoltaic technology announced by Professor Vivian Alberts and his collaborators of the Department of Physics at the University of Johannesburg (UJ) ought to be mentioned. This serves as an example of a breakthrough, which can increasingly be expected as high energy costs and environmental concerns accelerate research in sustainable energy technology.

During the last 20 years commercially viable efficiency breakthroughs were not really achieved for photovoltaic cells. The cheaper, amorphous spray on type cells operated in the 5 % solar to electricity efficiency region and the more expensive crystalline cells in the 15-20 % efficiency band. This could be lifted to 30-50 % in laboratories, but not commercially viably. What did, however, happen in this period is that the production cost of such cells fell nearly exponentially.

It appears that what has been achieved here is to find a low production cost, spray-on type substrate, which nevertheless performs at 16% plus conversion efficency. The German Company IFE Project- und Beteiligungsmanagement GmbH&CoKG has obtained a licence from Photovoltaic Technology Intellectual Property (PTIP) (Pty) Ltd, the UJ spin-off company of Professor Alberts, to enter into production with an investment of € 72 million, which equates to an output of 30 MW total panel capacity by mid 2007. World market shares of 10 % by 2010 and 20 % by 2012 are predicted (FMET, 2006).

A third partner in this agreement, the South African Central Energy Fund (Pty) Ltd. (CEF) will ensure that a further production facility will be set up in South Africa.

After 12 years of investigations, a way has been found by means of which the increasingly rare and expensive silicon could be replaced by copper, indium, gallium, sulphide and selenium (CIGS) type collector structures, at production costs of 25 % of previous high-purity silicon based cells of similar efficiency (Botha, 2006).

Gosling (2006) reports that Alberts predicts that the cost of solar power will drop below that of fossil fuel based power within 10 years.

The Sensible Things to Do

The White Paper on Energy Policy [1998], the National Research and Development Strategy and the White Paper on Renewable Energy [2003] have nobly committed the government for a while now to a renewable energy path (typically +1 % renewable contribution to the national energy mix per year in the current century). Perhaps the commercial response of Europe to the UJ breakthrough, high growth rate induced strained Eskom resources, an oil price persisting above US$ 70 and mounting evidence of man made global climate change contributed to a highly commendable government decision to dramatically energise its policies. The Energy Efficiency Strategy [2005], National Renewable Energy Research Strategy and the Energy R&D Strategy further attest to that.

Phumzile Mlambo-Ngcuka, Minister of Minerals and Energy, announced the intent to promote renewable energy electricity generation and other forms of renewable energy with assistance of the World Bank and the Prototype Carbon Funds starting early 2007, after the release of a further policy document before the end of 2006. This would describe a target of 10 000 GWh of renewable energy consumed by 2013, to be achieved via renewable power generation, use of bio diesel, solar water heating, solar photovoltaics and solar passive house design (Loxton, 2006).

Mputumi Damane, the chief executive officer of CEF commits the organisation to diversifying the technology basket in South Africa: “South Africa has one of the best solar regimes in the world, yet this clean form of energy is highly under-used.” (Botha, 2006)

Ongoing education as to the impact of fossil fuel dependence and the need to diversify our energy supply is required. More funding prioritised for renewable energy research and skills development has become crucial.

In the light of what has been said above in the context of PBMR investment, a matching amount of capital expenditure would not only lead to world-leading developments in a renewable and sustainable energy supply industry in South Africa but would certainly place this country at the forefront of another, i.e. complementing the PBMR program, 21st century technological development, where in terms of natural and human resources of this country it ought to find itself!

“The South African National Energy Research Institute (SANERI), a subsidiary of CEF, is a joint initiative of the Departments of Science & Technology and Minerals and Energy. SANERI was established to regenerate the knowledge base for the South African energy sector. The two departments collaborated in putting together a draft energy R&D strategy as an initial agenda for SANERI. The draft energy R&D strategy identifies renewable energy sources as of the main research and development (R&D) themes for South Africa. Funding for human capital development was also identified as one of the challenges that have resulted in the thinning knowledge base in the energy sector in South Africa. The Post-graduate Programme in Renewable and Sustainable Energy Studies was initiated as one of targeted government funded programmes to generate high quality Masters and Doctoral graduates specifically trained to meet the needs of an expanding and sustainable energy industry in South Africa.”[42]

For the University of Stellenbosch winning at this point in time the hub for this through a multi-disciplinary bid led by Prof Wikus van Niekerk (Van Niekerk and Harms, 2006) is a breath-taking opportunity.

This is an opportunity to help steer the South African energy industry in a direction, where it one day will become fully compatible with the dramatically beautiful natural surroundings that South Africans and its tourist visitors have always cherished. This would thus be in keeping with our best values and traditions.

CONCLUSION

There is widespread understanding of the first law of thermodynamics. The effectiveness of the supply structures, however, often let us forget, how enormous our appetite for energy and how vast the rate by which we deplete our fossil fuel bank account are. We just do it, macho and gang ho, to understandably meet our socio-economic needs by developing our economy. We are converting the oxygen in the precious atmosphere of our beautiful space ship Earth to carbon dioxide at an enormous rate. That makes economic sense in our life time. True enough, climate change always happens somewhere else. Germany has started lifting its North Sea coastal fortifications by 1 m.

The second law consequences are devastating when we consider the manner in which we convert our future fossil fuel gold to useful work. Our thermal coal plants and internal combustion engine just puff out 2/3 of the available thermal energy we are able to derive from hydrocarbon combustion into the atmosphere. This has brought a lot of welfare to many economies, but is it sustainable and will subsequent generations have to foot the bill?

Thankfully national and internationally fossil fuel supply bottle necks prioritise investment in skill which are charged to harvest and utilise incoming solar energy rather than stored solar energy in sustainable ways compatible with the healthy of our fragile atmosphere.

World renowned South African engineering skills are in demand and I believe can play a leading role, wisely incentivised and supported by our government, to leap frog this country onto the 6000 million year high road.

Untold new opportunities for engineers, in practice and research, to be sure!

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[42] Draft ‘Terms of Reference’ for the Programme, 2006

NOMENCLATURE

q	heat	J/kg	
s	entropy	J/kgK	
T	temperature	K	[Kelvin]
	energy, work	J	[Joule]
	power	J/s = W	[Watt]

energy	kWh	
power	MW	[Mega Watt]
time	h, s	
voltage	V	[Volt]

REFERENCES

Austin G, Spalding-Fecher R and Worthington R (2003) *Employment potential of renewable energy in South Africa*, joint project report: Agama Energy, sustainable energy & climate partnership, Earthlife Africa

Beyers JHM, Harms TM and Kröger DG (2001) A finite volume analysis of turbulent convective heat transfer for accelerating radial flows, *International Journal for Numerical Heat Transfer*, A, 40, 117-138

Beyers M (2004) *Numerical modelling of snow flow characteristics surrounding the South African Antarctic Base,* PhD (Eng) Thesis, Department of Mechanical Engineering, University of Stellenbosch

Bocheński JM (1972) *Wege zum philosophischem Denken – Einführung in die Grundbegriffe*, Verlag Herder KG Freiburg im Breisgau

Bohlweki Environmental (Pty) Ltd (2006) *Environmental scoping study for the proposed establishment of a concentrating solar power (CSP) plant and related infrastructure in the Northern Cape Province – Draft Report*, http://www.bohlweki.co.za

Botha Z (2006) New technology to help cut manufacturing cost of alternative energy source, *Engineering News*, 19, May 26 – June 1

Brooks M (2005) *Performance of a parabolic trough solar collector,* MScEng thesis, Department of Mechanical Engineering, University of Stellenbosch

Brooks MJ and Harms TM (2005a) Development of STARlab: The Solar Thermal Applications Research laboratory, *Proceedings of the ISES Solar World Congress,* Orlando, Florida, 6-12 August

Brooks MJ and Harms TM (2005b) Design, construction and testing of a parabolic trough solar collector for a developing country application, *Proceedings of the ISES Solar World Congress,* Orlando, Florida, 6-12 August

Campbell CJ (2002) *Peak oil: an outlook on crude oil depletion*, http://greatchange.org/ov-campbell,outlook.html , February

Cencelli N (2002) *Energy utilisation of the SANAE IV base in Antarctica*, BEng final-year thesis, Department of Mechanical Engineering, University of Stellenbosch

Coetzee N (1996) *Solar power plant*, BEng final-year thesis, Department of Mechanical Engineering, University of Stellenbosch

Cokayne R (2005) PBMR contracts usher in new phase, *Cape Times Business Report*, 5, Wednesday, 7 December

Cokayne R (2006) Eskom closer to phasing out stake in pebble bed reactor, *Cape Times Business Report*, 16, 6 March

Combrink NJJ and Harms TM (2001) The use of solar energy for a small recirculating hydroponic system, *Acta Horticulturae*, 554, 285-288

Craemer M (2006) Project Alpha, project Hotel – latest code-named new-builds to emerge into the construction phase, *Engineering News*, 26 (18) May 19 – 25

Davids RC, Harms TM and Lamprecht AJ (2001) Parabolic trough research, Abstract Only, *Proceedings of the Thermal Energy Fluids Conference*, Western Cape Forum for Mechanical Engineering, University of Stellenbosch, 13-14 September

Dutkiewicz RK and Gore BJ (1998) Emission comparison for Eskom and some international utilities, *Journal of Energy in Southern Africa*, 9(3),79-83, August

EIUG (2006) South Africa's electricity supply/demand balance – 2006 to 2021, *Energize*, Power Journal of the SA Institute of Electrical Engineers, June, 13-15

ENMRD (2005) *New Mexico Solar Feasibility Study*, Energy, Minerals and Natural Resources Department, New Mexico, http://www.emnrd.state.nm.us/emnrd/ecmd/ConcentratingSolarPower/ConcentratingSolarPower.htm

Eskom (2006a) Investing in the Cape region, advertisement feature, *Cape Argus*, 26 April

Eskom (2006b) Koeberg – the facts and figures, advertisment feature, *Cape Argus*, 26 April

FMET (2006) *The licence for the energy of tomorrow*, Federal Ministry of Economics and Technology, Germany, http://www.german-renewable-energy.com

Gcabashe TS (2006) *Chief executive report*, Eskom annual report 2006, http://www.eskom.co.za

Gosling M (2006) Government should subsidise solar power energy, says inventor, *The Cape Times*, 5 May

Harms TM and Beyers JHM (2000) *Independent review of the secondary heat balance: thermohydraulic and error calculation methodology* (for the Koeberg nuclear reactors), prepared for Eskom, December

Harris R (2004) *Analysis of the flow field above a solar chimney power station*, MScEng thesis, Department of Mechanical Engineering, University of Stellenbosch

Hufkie SS (1996) *Computer simulation of the transient behaviour of a heat exchanger*, BEng final-year thesis, Department of Mechanical Engineering, University of Stellenbosch

International Energy Agency (2006) *Energy technology perspectives – scenarios & strategies to 2050*, http://www.iea.org/w/bookshop

Joubert A (2003) *Design and testing of a two-dimensional solar self-tracking heliostat*, BEng final-year thesis, Department of Mechanical Engineering, University of Stellenbosch

Joubert RdeV (1996) *Waste heat recovery system for marine propulsion plants*, BEng final-year thesis, Department of Mechanical Engineering, University of Stellenbosch

Kammen DM (2006) Personal communication, Director – Renewable and Appropriate Energy Laboratory, University of California

Koorts TT (1998) *Design and testing of an engine exhaust gas waste heat steam generator system*, BEng final-year thesis, Department of Mechanical Engineering, University of Stellenbosch

Kröger DG (2004) *Air-cooled heat exhangers and cooling towers*, (2 volumes) PennWell Corporation, Tulsa, OK, USA

Lilly WH (1996) *The thermal performance of phase change material*, BEng final-year thesis, Department of Mechanical Engineering, University of Stellenbosch

Lotun D, Harms TM and Taylor AB (2001) Vehicle exhaust heat recovery revisited, Abstract Only, *Proceedings of the Thermal Energy Fluids Conference*, Western Cape Forum for Mechanical Engineering, University of Stellenbosch, 13-14 September

Loxton L (2006) State recommits itself to renewable energy, *Cape Times Business Report*, September 16

McRae I (2006) *The test of leadership*, EE Publishers (Pty) Limited, South Africa

Meyer K (2005) *A new solar refrigeration cycle*, a MScEng research proposal, ongoing

Naidoo S (2006) Proposed pebble-bed reactor 'not feasible', *Sunday Times*, 7, 26 March

O'Connor P (2006) Eskom's generation capacity expansion plans, *ESI – The Power Journal of Africa*, 1, 40-43

Olivier J (2006) *Technical and economic evaluation of the utilisation of solar energy at SANAE IV base in Antarctica* – MScEng Thesis, Department of Mechanical Engineering, University of Stellenbosch

Pacheco JE (2002) *Final test evaluation results from the Solar Two project*, Solar Thermal Technology, Sandia National Laboratories, SAND2002-0120

Patterson A (2006) Leslie Jesch turns 80, *ISES Membership Newsletter, No. 4, pp. 8-9*

PE (2006) Clean-up for Sizewell A will take 100 years, *Professional Engineering*, 19(10), 4

Potgieter J (2004) *Energy utilisation analysis for the purpose of thermo-economic optimisation of a Western Cape food production plant*, MScEng Thesis, Department of Mechanical Engineering, University of Stellenbosch

Quaschning V (2003) Technological Fundamentals – Solar Thermal Power Plants, *Renewable Energy World*, 6(6), 109-113

Rabie CJ (2004) *Vapour jet refrigeration system*, vacation work report, Department of Mechanical Engineering, University of Stellenbosch

Remar J (1995) Personal communication, senior lecturer, Department of Mechanical Engineering, University of Stellenbosch

Rifkin J (1982) *Entropie – Ein neues Weltbild*, Hoffman und Kampe Verlag, Hamburg (*Entropy: a new world view*, Viking Press, 1980)

Roos T (2001) *Design of a low cost solar collector system for integration with a recuperated gas turbine engine for distributed power generation*, PhD research proposal, Department of Mechanical Engineering, University of Stellenbosch, ongoing

Sapa-dpa (2006) New auxiliary turbosteamer to reduce fuel consumption by 15%, Platinum Collection, *Supplement to the Cape Argus,. 15, February 10*

Schlaich J (1995) *The solar chimney – electricity from the sun*, Edition Axel Menges, Stuttgart

Snyman H (2005) A feasibility study for onboard electricity generation system powered by a Stirling engine utilising waste heat exhausted by heavy duty trucks, MSc proposal

Stander J (2006) *Investigation of a small scale wind turbine system for the South African Antarctic research station SANAE IV* – MScEng thesis proposal, Department of Mechanical Engineering, University of Stellenbosch, ongoing

Stinnes WW (1997) *Solar power for an arid country*, Pre-Feasibility Study on a 200 MW Solar Power-Station in the Northern Cape Province of South Africa – May

Taylor AB, Gunaselvam J, Bester W and Stone* A (2002) *Investigation into reducing the impact of diesel engines on the Antarctic environment with associated maintenance benefits*, final report presented to SANAP, Department of Mechanical Engineering, University of Stellenbosch – *Centre for Automotive Engineering (CAE)

Teetz H, Harms TM and Von Backström TW (2003) Assessment of the wind power potential at SANAE IV base, Antarctica: a technical and economic feasibility study, *Renewable Energy*, 28, 2037-2061

The Times (1998) Sun set to flame out in 6bn years, as reprinted in *The Cape Times*, 26th January

Trieb F (2000) Competitive solar thermal power stations until 2010 – the challenge of market introduction, *Renewable Energy*, 19, 163-171

Underwood A (2003) A study of the waste management at the SANAE IV base in Antarctica, BEng final-year thesis, Department of Mechanical Engineering, University of Stellenbosch

Van Niekerk W and Harms TM (2006) *Postgraduate Programme in Renewable and Sustainable Energy (P^2RSE)*, Proposal prepared for the Department of Science and Technology

Van Staden P (1990) Supersonic, four shock, ramp type intake design, with boundary layer bleed, MEng thesis, Department of Mechanical Engineering, University of Stellenbosch

Venter I (2001) Hot price for big N Cape sun chimney, *Engineering News*, 13, July 27 – August 2

Venter I (2006) For how much longer can South Africa depend on coal for its power needs, *Craemer Media*, 21 April, https://www.researchchannel.co.za

Von Blottnitz H (2006) A comparison of air emissions of thermal power plants in South Africa and 15 European countries, *Journal of Energy in Southern Africa*, 17(1), 72-81, February

Weinrebe G (1999) personal communication, Institute of Energy Economics and the Rational Use of Energy, University of Stuttgart, Germany

Wesgro (2000) *Renewable energy industy in the Western Cape of South Africa*, Wesgro background report, Wesgro, www.wesgro.org.za , April

Wipplinger KPM, Harms TM and Taylor AB (2006) Stainless steel finned tube heat exchanger design for waste heat recovery, *Journal of Energy in Southern Africa*, accepted for publication