Incorporating stakeholder preferences in the selection of technologies for using invasive alien plants as a bio-energy feedstock: applying the analytical hierarchy process

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Abstract

Invasive alien plants (IAPs) impose significant social costs on the population of the Agulhas Plain region in South Africa due to their adverse impacts on ecosystem goods and services (decreased water supply and increased fire risk) . While the cost of clearing IAPs is considerable, this paper assesses opportunities to reduce some of the social and environmental burdens (e.g. disruptions of ecosystems which have negative impacts on livelihoods) by using IAP biomass to produce bio-energy. However, such an initiative could increase financial dependency on these plants and is thus considered to be a major risk factor which could create adverse incentives to illegally grow these plants. A participatory decision-making process with active stakeholder participation is a key element in managing such an initiative. We used a multi-stakeholder engagement process and the analytical hierarchy process to define and weigh suitable criteria for the assessment of different "IAP biomass to bio-energy" technology scenarios on the Agulhas Plain. Feasible scenarios were constructed by means of an expert panel which were then ranked according to stakeholder preference. The six criteria were: minimising impacts on natural resources; job creation; certainty of benefits to local people in the study area; development of skills for life; technology performance and cost efficiency. This ranking was largely determined by the preference for resource efficiency in terms of minimising impacts on natural ecosystems and the localisation of benefits. The smaller, modular technologies were consequently preferred since these realise direct local benefits while developing local skills and capacity in their manufacture, sales and maintenance. The rankings as obtained in this study are context-bound, which implies that the findings only have limited application to areas with similar biophysical and socio-economic characteristics. However, the method itself is fully generalisable, and the same prioritisation process can be followed in any study area to ensure that a participatory decision making process fulfils local energy needs and contributes to sustainable development.

Keywords

invasive alien plants; bio-energy; analytical hierarchy process; stakeholder preference; multi-criteria decision analysis

1 Introduction

The growth in human populations has been accompanied by unprecedented encroachment on terrestrial ecosystems, and the expansion of global trade has led to the widespread distribution of large numbers of species beyond their native ranges- this increasingly threatens the integrity of ecosystems and the services they deliver (Perrings et al., 2010, Pimentel, 2002, Pimentel et al., 2001, De Lange and Van Wilgen, 2010). In South Africa, invasive alien plants (IAPs) in South Africa have increased sufficiently in terms of magnitude and distribution (Marais et al., 2004, Marais and Wannenburgh, 2008, Mgidia et al., 2007, Kotzé et al., 2010, Van Wilgen et al., 2008) to degrade biodiversity and ecosystem resilience by changing the configuration of ecosystems and ecosystem-derived goods and services (De Lange and Van Wilgen, 2010, Pimentel et al., 2005, Moran et al., 2005). This creates serious economic losses and management challenges, since biodiversity has a direct value to society through the provision of life-sustaining ecosystem goods and services; as well as ecological resilience. IAPs have a significant negative impact on the reliability and security of these ecosystem services, which hampers economic growth and eventually (often unwittingly) degrades social welfare. Specifically, one of the most substantial impacts of IAPs in South

Africa is their impact on water availability, causing an estimated 6.7 % decrease in mean annual runoff (Versfeld et al., 1998; Le Maitre et al, 2000). Given the arid climate and delicate water balance in South Africa, these losses present a serious opportunity cost to the economy. For example, one study has estimated that the monetary cost of these losses is close to ZAR6 billion per annum (De Lange and Kleynhans, 2008).

South Africa has been heavily impacted by IAPs, with approximately 2.5 million condensed hectares currently invaded (Kotze, 2010), however this figure is heavily debated. Globally, the response to the threat of IAPs has varied, with several countries (including South Africa) developing strategies for dealing with the problem in an integrated fashion, which includes combinations of mechanical, chemical and biological control, and habitat management (McNeeley et al., 2001). These control measures create a substantial fiscal burden to the South African economy. The Working for Water programme was established by the Department of Water Affairs in 1998 in order to address this problem (Turpie et al., 2008, Buch and Dixon, 2008). The Working for Water programme is an expanded public works programme in which IAPs are cleared using labour-intensive techniques. Funding for the Programme originates from various sources including water user charges, government funding aimed at poverty relief. The programme is seen as a success-story in controlling IAPs in South Africa, while at the same time creating employment (Turpie et al., 2008, Hobbs, 2004, Buch and Dixon, 2008). Financial benefits from the utilisation of IAP biomass removed through the Programme has been limited to use of the wood for fire-wood, crafts and furniture; but most of the biomass is left *in situ,* which often results in a fire hazard. Therefore, additional options for utilising this biomass need to be explored.

We explored the opportunity of utilising IAPs biomass for the production of bio-energy. With rapid advancements in renewable energy technologies that can utilise biomass feedstock to produce bio-energy products, there is an urgent need to assess and compare the appropriateness of and preference for these technology options in a given case. This study developed five scenarios based on different bio-energy technology options and the bio-energy services that they can provide. These options were: compressed logs, slow pyrolysis for charcoal, gasification for electricity, combustion for electricity, and decentralised heat and power. The analytical hierarchy process (AHP), a multi-criteria decision analysis (MCDA) method, was used to determine relevant assessment criteria and to identify the preferred scenario (Saaty, 1980). The ranking of scenarios was based on a number of criteria, which were weighted by combining expert opinion with community preferences.

The study area was the Agulhas Plain region in the Southern Cape, South Africa. The region has a land area of 270 000 hectares and a population of approximately 45 000. It lies at the southern-most tip of Africa, between the ocean to the south and the Langeberg mountain range to the north. The area is administered by the Overstrand and Cape Agulhas local municipalities, which form part of the Overberg District Municipality (Naudé *et al.*, 2007).

Recent estimates of IAP species composition and density of invasions (Kotzé et al., 2010) enabled us to estimate a biomass yield of approximately 2.3 million tonnes per annum over a 20 year period for the Agulhas Plain (Table 1), with *Acacia saligna* and *Acacia cyclops* dominating the species composition (De Lange and Le Maitre, 2010).

2 MCDA techniques

MCDA is an umbrella term to describe a collection of formal approaches used to facilitate decision-making for complex problems where there are multiple conflicting criteria (Rozakis et al., 2001, Belton and Stewart, 2002). The aim is to integrate measurement procedures with value judgements in an attempt to make the inevitable subjectivity in complex problems more explicit, while improving stakeholder buy-in and consequently the acceptability of decisions (Eberhard and Joubert, 2002, Joubert *et al.*, 2003, Cherni *et al.*, 2007). The approach facilitates a greater understanding of complex management problems by taking explicit account of criteria used to explore and analyse choices made by stakeholders (priorities, values and objectives) in the context of the problem; the outputs can guide decision-makers to identify a preferred course of action (Mamphweli and Meyer, 2009, Strager and Rosenberger, 2006, Hobbs et al., 1992, Belton and Stewart, 2002). This approach provides a transparent and rational methodology to guide and rank management alternatives based on weighted evaluation criteria (Buchholz *et al.*, 2009, Buchholz *et al.*, 2007). It does not eliminate all subjectivity in the decision-making process, but reflects the trade-offs the respondents are willing to make in a specific context (Stewart *et al.*, 2001, Stewart *et al.*, 1997, Hobbs *et al.*, 1992). A level of subjectivity in decision-making will thus remain, but the process nonetheless facilitates decision-making by making the need for subjective choice explicit, and the process of taking account of this subjectivity more transparent (Stewart *et al.*, 2001, Stewart *et al.*, 1997, Hobbs *et al.*, 1992, Stewart, 2004). Such transparency is important because it enables stakeholder participation and builds confidence in the decision-making process, especially in cases where multiple stakeholders with conflicting views are involved (Starkl and Brunner, 2004).

Different approaches to MCDA can be followed (Belton and Stewart, 2002):

a) Goal programming and reference point techniques are regarded as the original formal form of MCDA. b) Utility and value-function approaches, of which multi-attribute value function (MAVF) and analytical hierarchy process (AHP) are well-known. c) Game theory approaches, which aim to identify solutions that are the most acceptable compromise between stakeholders.

The AHP method was chosen for this study since it has been widely applied to determine preferences in complex, multi-attribute problems (Ananda and Herath, 2005, Hobbs et al., 1992, Hwang and Yoon, 1980, Stewart et al., 1997, Belton and Stewart, 2002, Pavlikakis and Tsihrintzis, 2003, Kablan, 1997, Herath, 2004, Duke and Aull-Hyde, 2002). The initial steps in the AHP are to develop and obtain consensus with regard to the goal and criteria hierarchy, against which suitable management alternatives are compared in pair-wise fashion (Ananda and Herath, 2003b, Ananda and Herath, 2003a, Herath, 2004, Kablan, 1997). The aim is to establish the relative preference order of preference for alternatives that are assessed against the goal/objective. Pair-wise comparisons of alternatives simply compare two alternatives with each other and record the relative preference for one above the other in terms of a given criterion on a numerical or descriptive scale. Whenb comparing alternatives with respect to the criterion (i.e. ‘scoring’ the alternatives), participants are requested to express their preferences of alternatives only with respect to a particular criterion. If no clear preference is expressed, an equal score is allocated and the participants move on to the next comparison. The pair-wise comparative scores are captured in a matrix, where the strength of a preference is calculated in terms of a ratio of the scores.

The weighting procedure uses the same pair-wise comparative approach to elicit the relative preferences of decision-makers for the criteria. A Likert scale was used to note and aggregate preferences within sub-criteria groups (sub-criteria are not compared between different criteria groups). A comparison vector is then calculated to present the relative performance of each criterion. The aim is to find the set of values (weights) which approximate the set of ratios derived from the pair-wise comparisons. This is done byeigenvalue analysis of matrices, which aims to extract the eigenvector corresponding to the maximum eigenvalue of the pair-wise matrix. The procedure is iterative and software programs which implement multi-criteria approaches like the AHP, such as "Expert Choice©" (Expert Choice, 2009) are often used to facilitate the analysis. The elements of the vector of scores are then normalised, to allow for the addition and deleting of criteria in a consistent fashion. The criteria weights are multiplied by the score of each alternative against each criterion to present a weighted score for each alternative for each criterion. The aggregated final score of all criteria for each alternative is a ranking which reflects the participants' overall preference, which can aid in decision-making. The weighting procedure for criteria, and scoring procedure for the alternatives, can be done in any order, as long as both are done with the set goal/objective in mind. The effectiveness of the approach depends on the interaction with the participants and the presentation of information in a way that facilitates active participation to enhance understanding, learning and discussion.

3 Method and data inputs for the study

3.1 Incorporation of stakeholders

The Rio Declaration on Environment and Development states that: *''Environmental issues are best handled with the participation of all concerned citizens, at the relevant level''* (United Nations Department of Economic and Social Affairs: Division of Sustainable Development, 2004). The underlying rationale for stakeholder participation in natural resource management decision-making is to accommodate as many opinions and preferences as possible, and to create stakeholder buy-in that represents a consensus in the decision-making process. Public involvement in environmental decision-making is thus recognized as one of the basic requirements of sustainable development, and various studies have been conducted on specific methodologies aimed at effectively accommodating public preferences in decision making. (Iacofano, 1990, Smith, 1984, Renn et al., 1995, Dungumaro and Madulu, 2003, Doelle and Sinclair, 2006, Messner et al., 2006, Renn, 2006, Stagl, 2006, Sowman et al., 2006, Charnley and Engelbert, 2005, Maguire and Lind, 2004, Schemmel, 2004, Buchy and Hoverman, 2000, Davis, 1996, Alvarez-Farizo and Hanley, 2002, Kline and Wichelns, 1998). Such approaches include systems dynamics modelling used interactively in a public forum (Stave, 2003), value function approaches (Ananda and Herath, 2003a), stated preference models (Haider et al., 2002), multi-criteria approval (Laukkanen et al., 2001, Dennis, 2000), direct preference investigation (Kolokytha et al., 2002), the AHP (Duke and Aull-Hyde, 2002, Tzeng et al., 2002, Ananda and Herath, 2003b, Herath, 2004, Hung et al., 2006, Krajnc and Glavic, 2005), photo questionnaires (Ryan, 2002), determination methodologies (Figueira and Roy, 2002), and the social discount rate (Gollier, 2002, Brekke and Johansson-Stenman, 2008, Kaplow, 2006, Du Preez, 2004, Arrow et al., 2003).

There are often questions and debate as to the extent that stakeholder opinion should be incorporated in highly complex decision-making regarding natural resources and other public goods (Wiseman et al., 2003, Maguire and Lind, 2004, Litva et al., 2002, Buchy and Hoverman, 2000, Pateman, 1970, Munro-Clark, 1990). The varied literature on this issue stems from two main sources: 1) political sciences, with discussions around democracy and citizenship, especially within the context of regional and local planning (Pateman, 1970, Munro-Clark, 1990, Davis, 1996); and 2) development theory, especially within the context of sustainable land use (Wignaraja et al., 1991, Rahman, 1993, Nelson and Wright, 1995, Chambers, 1997). Both of these views confirm the importance of stakeholder involvement; because without stakeholder participation, decision makers assume the risk of enforcing compliance on an unwilling public (Maguire and Lind, 2004). However, the appropriate level of involvement is contested, because the debate regarding whether stakeholder preferences have a legitimate role to play in priority setting is highly polarised - sceptics warn against the dictatorship of the uninformed, while advocates proclaim the legitimacy of the stakeholder participatory process (Wiseman *et al.*, 2003, Litva *et al.*, 2002).

Our approach was to incorporate broad-based public participation that facilitated public-private partnerships and was supported by government policy. Therefore, the following stakeholder groups were included in this study: government expanded public works programmes like Working for Water and Working on Fire (see above) and Landcare (Department of Agriculture - aim is sustainable management and use of agricultural natural resources); the Agulhas Biodiversity Initiative (an NGO and pilot landscape initiative of the Cape Action Plan for People and the Environment); land-owners and farmer-associations; local community members and municipality representatives; as well as research organisations (Council for Scientific and Industrial Research and University of Cape Town).

3.2 Structuring and formulating the goal and management alternatives

The goal for the AHP process was to establish the preferred way to enhance the eradication of invasive alien plants by means of processes that utilise all and the whole of such plants (do not leave the smaller trees, unlike the harvesting for other wood products such as timber) for the generation of bio-energy. Furthermore, since the aim is to eradicate IAPs, it implies that the biomass-to-bio-energy options will require decommissioning, relocation or a change in feedstock as an exit strategy if the IAP biomass becomes depleted. Five established and commercial stage technologies were identified that could satisfy this goal- compressed logs, slow pyrolysis for charcoal, gasification for electricity, combustion for electricity, and decentralised combined heat and power). Using a life cycle approach, five scenarios were developed around these technologies, with all scenarios having the following common pre-processing steps: mechanical harvesting, a short haul to stack biomass in windrows to dry in the field, and chipping using a mobile drum chipper. The wood-chips are then delivered to the energy plant for conversion into a bio-energy product, which may be a fuel (such as compressed wood-logs or charcoal), or electricity that is fed into the electrical grid (national or local mini-grid). Pre-processing (drying and chipping) creates a common platform to compare the different scenarios, while increasing the ease of handling; and facilitates uniform and controlled thermal conversion. Although the drying process could increase wear and maintenance on chipper blades, drying of wood increases the energy density, reduces the rate of wood decay, and facilitates improved thermal conversion (which typically requires <30% moisture content). Specifically, drying and chipping typically results in an almost doubling of the energy density; with green wood (45% moisture) having an energy density of 10MJ/kg, and completely dry wood-chips (0% moisture) an energy density of nearly 20MJ/kg (CSIR, 2010a).

Beyond the initial pre-processing, the value chains for the five scenarios proceeded as follows:

1. *Compressed logs* - chipped biomass (ca. 30mm) is further chipped (to ca. 3-5mm), dried in an oven to <10% moisture, and then used to make extruded logs. Extruded

logs are transported to market where they are purchased and used in the household for cooking and space-heating.

2. *Slow pyrolysis for charcoal* - charcoal is produced in modern retort kilns and processed to briquettes with an energy density of approximately 28 MJ/kg. The process of slow pyrolysis to produce charcoal has an established use in domestic and industrial sectors such as the smelting industry, and could replace coal with little or no modification to existing coal-fired power plants. For this scenario, the chipped biomass (ca. 30mm) undergoes slow pyrolysis (carbonisation), and is then ground into a powder, mixed with 5-10% starch and pressed into charcoal briquettes, which are dried before being distributed to the market.
3. *Gasification for electricity* – chipped biomass is fed directly into the gasification process produces syngas which can be converted to liquid fuels, synfuels (energy value of approximately 44 MJ/kg;), or coupled to a gas turbine to generate electricity that can supply a mini- or national- grid. The synfuels are valuable liquid fuels that can replace diesel; they have a higher cetane value and burn with fewer emissions (polyaromatics and sulphur). However, this technology of biomass-to-liquids is not yet at an established commercial stage. Therefore, for the purposes of this paper, this scenario was based on gasification to produce syngas that is scrubbed and fed into a gas turbine for electricity generation to supply the national electricity grid.
4. *Combustion for electricity* – chipped and dried biomass is directly combusted and coupled to a steam turbine to generate electricity to supply the national electricity grid.
5. *Combined heat and power* - chipped biomass is used locally in a small combined heat and power (CHP) unit where the chips are combusted and coupled to a small turbine

to generate electricity (basic electricity for 2-4 lights and cell-phone, radio and television); while the heat is used for cooking, hot-water and space-heating.

3.3 Criteria identification and results of weighing and scoring procedures

Criteria identification is a crucial step in the AHP process. Together with the stakeholders, we identified six main criteria, of which two had sub-criteria. The first criterion focussed on minimising the impacts of the scenario on the natural resource base. This criterion was sub-divided into air emissions, solid waste, water usage and net energy balance. The decision rule was that lower emissions would be preferable. Being a national priority, job creation was the second main criterion, and more labour intensive scenarios were preferred. The development of skills for life, and the certainty that benefits associated with the scenario will reach local people, were also considered important (criteria three and four). The performance of the technology employed in the scenario (criterion five) was sub-divided into the ease of maintenance and reliability of the technology itself. Cost efficiency was the sixth and final criterion.

Criteria weighting, carried out by means of eliciting the preference order of multiple stakeholders during several workshops, was used to construct a criteria tree diagram (Figure 1). Expert Choice© software (Expert Choice, 2009) was used to facilitate all pair-wise comparisons during the workshops and to calculate the weights of the relative preferences for criteria. These weights were combined in a criteria tree diagram, which aggregated sub-criteria (indicated with an “L”) to main criteria (indicated with a “G”) (see Figure 1).

The criterion related to protection of natural ecosystems was ranked highest (0.335) by stakeholders, of which the energy balance and water footprint were considered to be the most important sub-criteria. Job creation was considered to be the second most important criterion, with a weight of 0.224, while cost efficiency was considered least important, with a weight of 0.042. These weights present the relative preference of stakeholders, and were used along with data solicited from various sources to present a weighted score for each scenario that considers the production of the bio-energy product as well as the end-use. The data for the scoring procedures is summarised in Table 2.

The above-mentioned technical data were used as data inputs in the Expert Choice© software to score each scenario. The weights were then applied to these scores and aggregated to yield the preferred ranking as presented in the sensitivity diagram. Figure 2 presents a summary of the results. The weights are presented in the form of the underlying bar-chart, while the line graphs represent the performance of each scenario relative to each main criterion.

Scenario 5 (decentralised combined heat and power) came out to be the preferred scenario for this study area, with scenario 1 (compressed logs) the next best alternative. It was clear from the study that criteria with higher weights (e.g. “minimise impacts on natural resources”(33.5%), “job creation”(22.4%) and “certainty of benefits to local people” (20.8%)) will have greater impacts on the final scoring as compared to, for example “cost efficiency”, which had a relatively low weight (4.2%). This highlights the effect of weighting the various criteria and the need for a sensitivity analysis.

4 Sensitivities

Sensitivity analysis is used, to explore the effect of a decision maker's uncertainty about their values and priorities, or to offer a different perspective on the problem. Saaty (1980) developed a consistency index which compares the scores/weights to a value derived by generating random reciprocal matrices of the same size, to give a consistency ratio which is meant to have the same interpretation no matter what the size of the matrix. A consistency ratio of 0.1 or less is generally seen to be acceptable. It has been suggested that instead of direct pair-wise comparisons of scenarios, a so-called 'absolute measurement mode' should be used in order to eliminate the need to laboriously present the performance of alternatives with painstaking accuracy. This 'absolute level' of performance for each criterion is predefined, which facilitates the comparison of alternatives by means of relative instead of absolute scores (Belton and Stewart, 2002, Saaty, 1980). An advantage of the absolute measurement mode is thus that the resultant scaling of the scores for each criterion is independent of the alternatives and may be similar across criteria, which enables the interpretation of criteria weights more effectively. However, reported applications of AHP seldom refer to the use of absolute measurement (Belton and Stewart, 2002, Hung *et al.*, 2006, Pavlikakis and Tsihrintzis, 2003). We carried out sensitivity in absolute measurement mode by altering the weighting of the criteria, with the aim ofidentifying the absolute level of a particular criterion that will cause a change in the ranking of scenarios as presented in Figure 2. For example, "minimising impacts" will need to be decreased in relative importance from 33.5% to 23.4% in order to make scenarios 5 and 1 equally preferable. Likewise, "certainty of benefits" will need to be decreased in importance to 10.4% to make scenarios 5 and 1 equally preferable. The relative importance of "cost efficiency" will need to be increased to 21.8% in order to make scenarios 5 and 1 equally preferable. If the importance of "cost efficiency" is increased to 100%, scenario 1 will become the preferred scenario with scenario 5 in second place at 29%. However if "cost efficiency" is of no importance (0%), the hierarchy will stay the same. “Job creation” will need to be increased in importance to 29.9% to balance out scenarios 5 and 1. If the importance of “job creation” is increased to 100%, scenario 1 will become the preferred scenario, scenario 2 will take second place and scenario 5 will drop to last place. Lastly, “technology performance” will need to be increased to 15.4% to balance scenarios 5 and 1. It should be noted that each of the proposed changes will affect the whole weight structure of the criteria tree and that none of these changes can be executed without a well structured argument and participant agreement to the proposed change.

5 Discussion and conclusions

It is argued that the financial burden of clearing invasive alien plants in the Agulhas Plain could be reduced by utilising IAP biomass for bio-energy. However, this could be done in several ways, and choosing the most acceptable option is a complex problem which includes numerous trade-offs between different stakeholders (landowners, business, government, civil society and communities in the Agulhas Plain). We applied a multi-criteria decision analysis decision-support process in order to assess different IAP technology options and stakeholder preferences associated with each, simultaneously. A multi-stakeholder engagement process (the analytical hierarchy process) was used to develop and weigh criteria that can be used to guide the assessment and management of the options. The AHP is a structured approach to trade-off analysis that requires active participation from stakeholders in order to facilitate discussion and understanding, which helps to ensure accountability and transparency. Such transparency increases stakeholder buy-in and acceptance of the outcome, simply because of the nature of the participatory process. However, care must be taken to make the subjectivity associated with the process as explicit as possible. AHP does this by presenting pair-wise comparisons to stakeholders as a stimulus for debate, which is arguably an efficient way to engage subjectivity.

Several criteria were identified to assess the different IAP to bio-energy scenarios: minimise impacts on natural ecosystems, job creation, skills development, certainty of benefits to locals in the Agulhas Plain, technology performance and cost efficiency. The scenarios, incorporating different IAP biomass to bio-energy technology options, were assessed by means of a weighted score, which revealed the following preferred order: decentralised combined heat and power (CHP), compressed logs, pyrolysis for charcoal, gasification for electricity, and combustion for electricity. The order was largely determined by the preference for localised benefits and minimum impacts on the environment. Options scored higher when benefits tended to be localised, and when impacts to the environment were minimised. Smaller, modular technology approaches which are more appropriate in the localised context, namely using wood-chips or compressed logs in efficient combined heat and power stoves, also have the advantage of developing local skills and capacity in their manufacture, sales and maintenance. Since this assessment approach considered the entire value chain, changes in end-use practices can greatly influence the overall ranking of scenarios. Furthermore, in practice, in any scenario in which IAPs will be utilised for a specific purpose, it is important to be aware of the risk of creating adverse dependencies which could lead to incentives for ‘farming’ these plants, thus perpetuating their invasion potential. Therefore, in any such scenario, it is important to take steps to avoid this by synchronising the technology lifetime with the IAP stock.

One particularly important limitation of the study was that the risk of wildfire on bio-energy from IAPs is uncertain. A wild fire would cause a loss of biomass in the short term, but would densify most of the prominent IAPs in the long term which is regarded as a benefit from a financial perspective. This creates a dilemma from an IAP control perspective and remains a contentious debate. Also, we have found that the current supporting legislative and institutional structures in South Africa are ill equipped to enable the uptake of green energy derived from IAPs. The uptake of decentralised technologies is particularly problematic in a developing country context such as South Africa, mainly because the conventional approach towards energy supply is a centralised one and developments in rural energy supply have often been donor driven, i.e. external agencies determine the 'suitable technology' for a particular location. Furthermore, government policy often has contradictions and fundamental differences with regard electricity supply and management. While it is recognised that 100% coverage of dwellings would be physically impossible to achieve because of the migration patterns in deep rural areas, the macro economic policy of the country strongly argue for 100% coverage; yet the dominant electricity supplier (covertly) discourages dispersed generation as do municipalities, because of much needed revenue streams.

This study suggests that investments in remote and rural energy markets need to be approached in an interactive way to account for the preferences of the target community and to increase the probability of successful uptake. AHP, to a large extent, facilitates this participation process and thus has an important role to play in the successful uptake of policy and management strategies and long-term planning. We have demonstrated and tested the process in the form of a case study on the Agulhas Plain, where different options for utilising IAPs for energy purposes were compared. The rankings as obtained in this study are context-bound, which implies that the findings only have limited application to areas with similar biophysical and socio-economic characteristics. However, the method itself is fully generalisable, and the same prioritisation process can be followed in any study area.

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Table 1: Estimated biomass available from various species in the Agulhas Plain coastal lowlands based on mapped data of these areas (De Lange and Le Maitre, 2010, Kotzé et al., 2010).

Density class	Total area (ha)	Biomass (t/ha/yr)	Biomass (tonne/yr)
Closed	16414	95	1 559 318
Dense	12638	60	758340
Total	29052		2317658

Table 2: Summary of the input data variables for the scenarios. Refer to footnotes for explanation of technical assumptions and calculations. Data and assumptions from footnotes was sourced from CSIR (CSIR, 2010a, CSIR, 2010b)

Scenario name	Description of technology	Energy balance (considers the energy input required to generate the energy product (excludes distribution) (%)	Description of energy product	Capacity factor (% of time the technology operates at maximum capacity)	Lifetime (years)	Capital outlay (ZAR'000)	Operating cost (ZAR'000/yr) expenditure excludes biomass feedstock supply, marketing and distribution of the energy product as these cost are accounted for separately.	EROI (kWh/ZAR)break even point in brackets (years)
Compressed logs (SC1)	Hammer mill; Drier; Compressed log machine	53 (see note 1)	3854 tonnes of wood-chips are used to produce 3066 tonnes of compressed logs per year (see note 4); which is equivalent to approx. 2 MW energy output per year as used in household stoves for cooking and space-heating.	86	10	ZAR350	ZAR30	6.06 (1)
Slow pyrolysis for charcoal (SC2)	Slow pyrolysis retorts; Briquette machine; Drier	26 (see note 2)	Three retorts use 10950 tonnes wood-chips and produce 4928 tonnes charcoal briquettes per year (see note 5) which is equivalent to approx. 4 MW energy output as charcoal used in household stoves for cooking and space-heating.	86	10	ZAR1650	ZAR330	2.73 (1)
Gasification to electricity (SC3)	Gasification-gas turbine	26	150 KW electricity	75	20	ZAR3000	ZAR150	1.99 (6)
Combustion to electricity (SC4)	Combustion-steam turbine	21	5 MW electricity	75	20	ZAR123000	ZAR2700	1.54 (11)
Decentralised combined heat and power (CHP) (SC5)	Household CHP unit	90 (see note 3)	IAP biomass (4 kg capacity) directly combusted. CHP unit rated at 5 KW. Heat for cooking, hot-water and space-heating. Electricity for 4 LED lights, radio and cell-phone charging.	25 (see note 6)	10	ZAR11	ZAR1	4.74 (1)

<u>Abbreviations</u>: W- power in **Watts**; J- Energy in **Joules**; g- Mass in **grams**; h- time in **hours**; Multipliers: M- Mega (10^6); K- kilo (10^3);

Note 1: A 33.5KW mill uses wood chips at 440kg/h (20% moisture @ 18MJ/kg) to produce 350kg/h of compressed logs (5-10% moisture @ 20MJ/kg). Most of these logs are used in a household wood stove which operates at 20% efficiency. The remaining 80% energy is lost as space heat and 40% of this could be recovered as household space-heat. Therefore, the net efficiency is (60/100)*88=53%. Note that this ignores the opportunity to modify the stove to utilise the heat for heating water.

Note 2: Energy efficiency of 70% (10 tonnes wood @18MJ/kg) produces 4.5 tonnes charcoal @ 28 MJ/kg. However, starch (5-10%) and water (25%) are used as binder and must be dried to 5% moisture. As the water specific heat capacity is 4.18 KJ/kg; the latent heat of evaporation of water is 2260 KJ/kg; to raise temperature from 20-80^{o}C : E1=0.2*4.18*60=50 KJ. To evaporate the water: E2=0.2*2260=452 KJ. Therefore, the energy to dry 1 kg charcoal: E1+E2=0.5MJ. Since each briquette contain 5-10% starch, some of the energy content of briquettes comes from this starch (starch energy value of 18 MJ/kg) and this is an external energy input. Each kg contains minimum 0.05kg starch equivalent to 0.9MJ. Since charcoal has an energy value of 28MJ/kg the addition of 5% starch and the drying of the briquettes represents an energy cost of (0.5+0.9)/28 or 5%. The overall process efficiency is therefore estimated at 65%. The energy balance assumes that charcoal will be used equally in an outdoor grill and indoor household stove. The same assumptions is applied to the household stove as mentioned in Note1.. The outdoor grill is used to cook food at 5% efficiency and 15% of the space heat captured and valued giving net efficiency of 20%. The average overall usage efficiency is (60+20)/2=40%. The energy balance is therefore 0.4*65%=26%. Note also that this ignores the opportunity to modify the stove to utilise the heat for heating water.

Note 3: Energy efficiency is 90% for the stove @ 5KW (2KW for cooking, 2KW hot water geyser and 1KW space-heat). Assumes that <2% of the energy will be used to generate electricity, 38% used to cook, 40% hot water geyser and 20% is space heat. Approximately half of this space heat (ie 10%) will be valuable. Therefore, the net efficiency is 90%.

Note 4: Assume that 350kg/h compressed logs (@ 5-10% moisture) produced from 440kg/h IAP feedstock (20-30% moisture). The energy content of logs is 20 MJ/kg, so output is equivalent to 1.94MW

Note 5: Three retorts utilise 30 tonnes biomass to produce 13.5 tonnes charcoal briquettes per day with an energy content of 28 MJ/kg. Charcoal output is equivalent to 4.34 MW, however 5-10 % of the briquettes is starch binder so the net energy content of the char product is approximately 4MW.

Note 6: Maximum output would require loading 4kg biomass fuel every 4h (i.e. 6 times per day). However, a 25% capacity factor assumes that the use of the stove will primarily be driven by the need to cook and therefore will be loaded 1.5 times per day (a half load of 2kg in morning and full load of 4 kg in the evening).

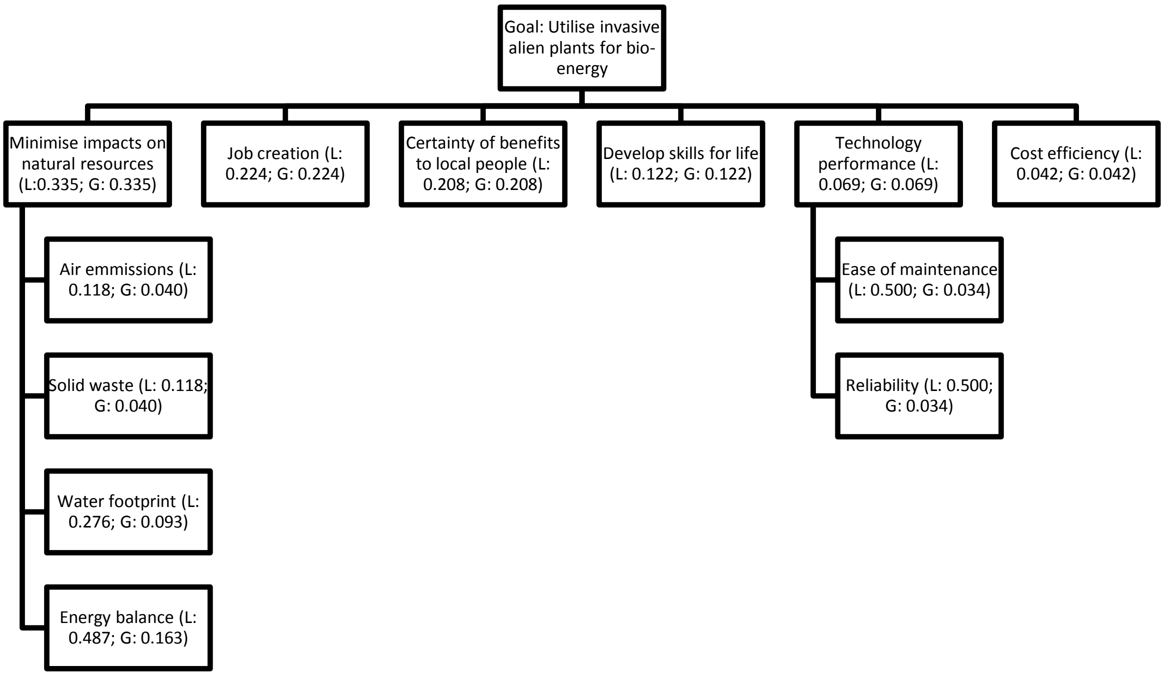

Figure 1: Weighted criteria tree as used in the AHP model. Sub-criteria ("L") is aggregated to main criteria and the goal ("G").

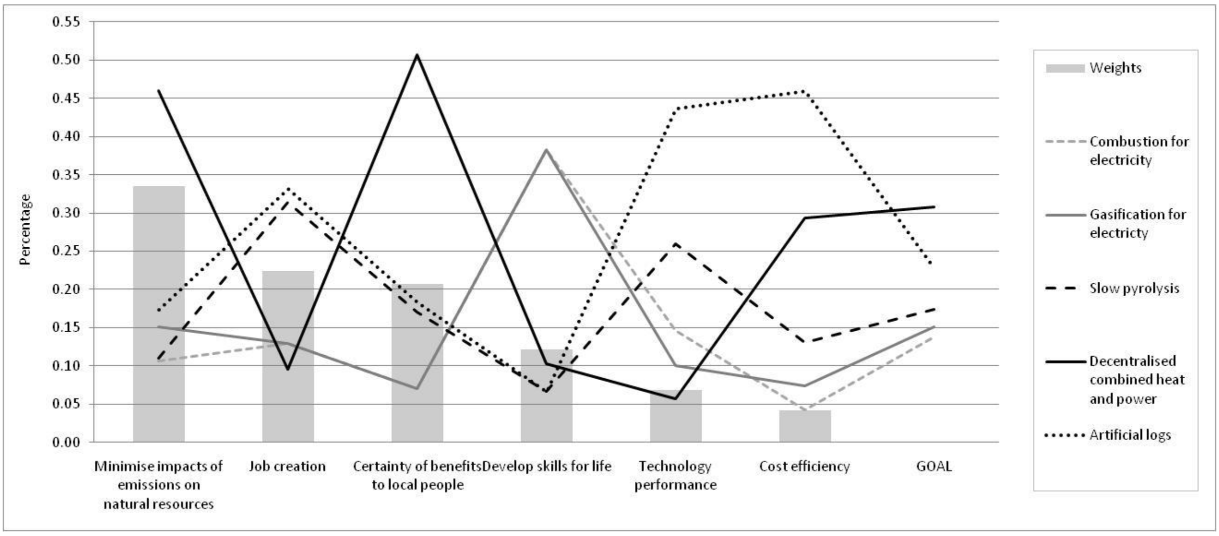

Figure 2: Results of the AHP