Vlieland's Renewable Future

A first screening of suitable energy generation technologies on the Dutch island of Vlieland

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Nederlandse samenvatting

Aanleiding

In 2007 hebben de vijf Nederlandse Waddeneilanden in een overeenkomst vastgelegd dat zij in het jaar 2020 zelfvoorzienend willen zijn in hun energiebehoefte. Het eiland Vlieland heeft deze ambitie vertaald naar het worden van een *energie neutraal* eiland, wat betekent dat op jaarbasis evenveel energie moet worden opgewekt als wordt verbruikt. Om dit doel te bereiken is eerder onderzoek gedaan naar duurzame energieproductie technologieën die op een economisch haalbare wijze kunnen voorzien in de energievraag van Vlieland. De conclusie was duidelijk: de 2020 doelen zijn haalbaar, maar alleen met een combinatie van grote windturbines en zonnepanelen. Dit had vooral te maken met het feit dat andere technologieën nog niet competitief waren. Uit vervolgonderzoek bleek dat het installeren van windturbines niet de ideale oplossing was, omdat deze volgens een deel van de eilandbewoners, niet in lijn zijn met de natuurlijke waarde van Vlieland. Veel toeristen komen naar het eiland voor het unieke landschap en de bijbehorende flora en fauna, welke zouden kunnen worden aangetast door de zodanig ervaren horizon vervuiling; het plaatsen van turbines zou toeristen zo mogelijk weerhouden van een eiland bezoek.

Om die reden kijkt dit onderzoek verder dan de huidige mogelijkheden, om te onderzoeken welke hernieuwbare technologieën in de verdere toekomst een optie zouden kunnen zijn voor Vlieland. Dit zijn voornamelijk technologieën die in de ontwikkelingsfase zitten en momenteel niet concurreren met conventionele energiebronnen. Het onderzoek focust op de energiebronnen die het eiland bezit en de technologische mogelijkheden binnen deze bronnen. Daarnaast staat de ‘acceptatie’ van de lokale bevolking hoog in het vaandel. De centrale onderzoeksvraag is: “welke hernieuwbare energie technologieën zijn in de toekomst het meest geschikt voor implementatie op Vlieland?”

Bevindingen

Technologieën

Uit de analyse van de natuurlijke energiebronnen op Vlieland en de bijbehorende technologieën, bleek dat de volgende technologieën potentie hebben voor Vlieland: zonnepanelen, algenproductie voor bio-brandstoffen op land en water, getijdenstroom, getijdenverschil, energie uit golfslag, -golfdeining en -golfoverslag, geothermische warmte en tot slot warmte pompen. Afbeeldingen van deze technologieën zijn te vinden in appendix X.

- Zonnepanelen (PV)

Zonnepanelen zetten direct en indirect zonlicht om in elektriciteit. Deze technologie is momenteel al commercieel te verkrijgen en is al veelvuldig te vinden op Vlieland.

- Golfslag

Golfslag technologie maakt gebruik van energie in de golfslag. Als een golf het apparaat raakt, wordt er lucht uit een kamer gedrukt, door een turbine heen. De turbine die hier wordt aangedreven wekt vervolgens elektriciteit op. De meeste designs worden gebruikt uit de kust, wat ook voor Vlieland het meest geschikt is.

- Golfdeining

Golfdeining energie zet golfbeweging direct om in elektriciteit. Hierbij wordt gebruik gemaakt van geankerde drijvende installaties, welke deinen op het wateroppervlak. Tot op heden zijn verschillende designs ontworpen die in verschillende fases van ontwikkeling zitten.

❖ Golfoverslag

Golfoverslag technologie wekt elektriciteit op door gebruik te maken van het hoogteverschil dat golven met zich meebrengen op zee. Een dergelijke installatie centreert golfslag om golven groter en hoger te maken. Water afkomstig van de golf wordt verzameld in een klein basin, waarna het water vervolgens door een turbine onder invloed van zwaartekracht naar beneden valt.

❖ Getijdenverschil

Getijdenverschil energie opwekking maakt gebruik van het hoogteverschil tussen eb en vloed om elektriciteit op te wekken. Tijdens vloed stroomt een basin vol water, dat wordt vastgehouden totdat een bruikbaar hoogteverschil is bereikt met het water buiten het basin. Op dat moment loopt het basin leeg door een waterkracht turbine, welke elektriciteit opwekt.

❖ Getijdenstroom

Getijdenstroom energie zet beweging van waterstromen met behulp van onderwater waterkracht turbines om in elektriciteit. Een dergelijke waterstroom ontstaat door geografische eigenschappen en eb- en vloedstromen. Door het leegstromen van de Waddenzee worden er relatief hoge watersnelheden gemeten tussen en langs de Waddeneilanden.

❖ Algenproduction op zee

Algen kunnen worden verbouwd om vervolgens biobrandstoffen van te maken die worden gemixt met conventionele brandstoffen. Algen kunnen op verschillende plekken worden gekweekt, bijvoorbeeld op zee in de vorm van zeewier. Het cultiveren van zeewier gebeurt op zeewierboerderij in ondiep water.

❖ Algenproductie op land

Algen, en met name microalgen, kunnen ook worden geproduceerd op land. Het voordeel hiervan ten opzichte van zeewier is dat ze makkelijker toegankelijk zijn en een hogere energie inhoud hebben. Momenteel is de technologie om biobrandstoffen van algen te maken nog niet rendabel en is nog veel onderzoek nodig voordat dit zo ver is.

❖ Geothermische warmte

Geothermische warmte installaties onttrekken warmte uit de ondergrond op honderden tot duizenden meters diep voor direct gebruik voor verwarming. Een dergelijke installatie kan gemakkelijk een wijk of dorp voorzien van warmte, mits een geschikt warmtenetwerk aanwezig is.

❖ Warmtepomp

Warmtepomp installaties gebruiken elektriciteit om op efficiënte wijze warmte te onttrekken uit de omgeving, waarbij de grond en lucht de bekendste zijn. Installaties kunnen direct aan huizen geplaatst worden om direct warmte te leveren, of op een centraal punt warmte onttrekken. Deze technologie is wereldwijd al toegepast op grote schaal, en ook te vinden op Vlieland.

Criteria

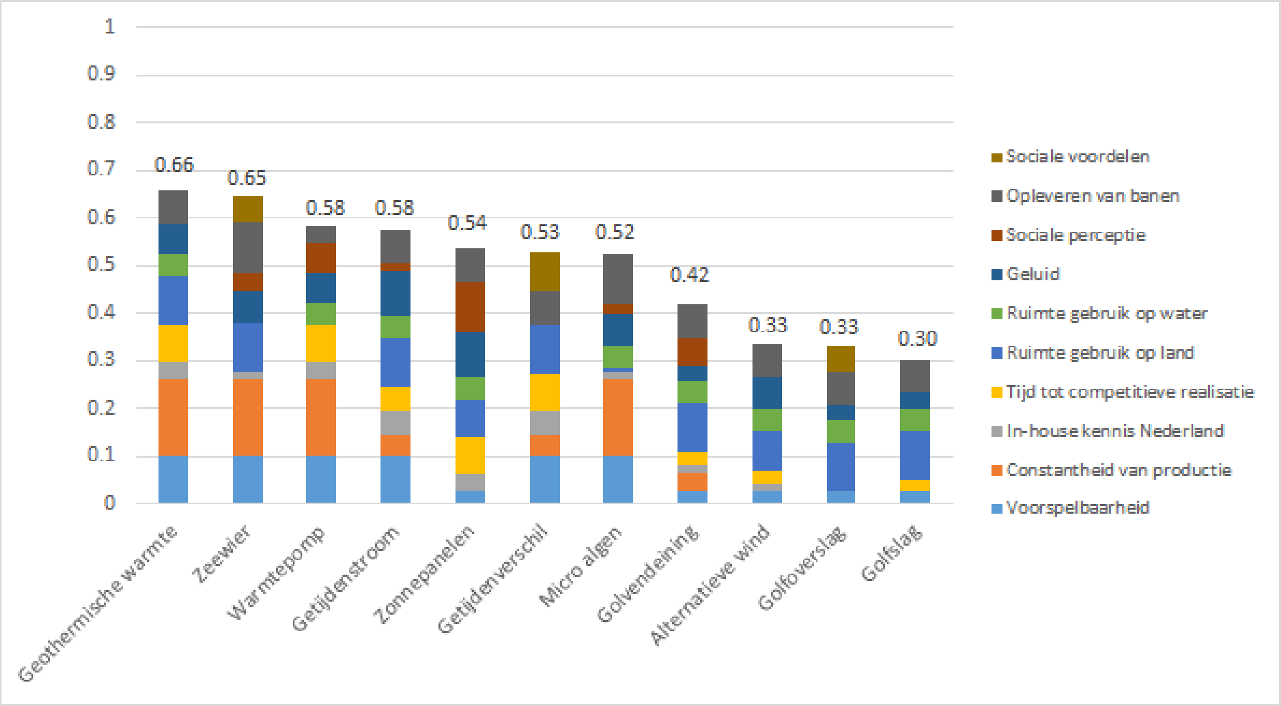
Vervolgens is onderzocht welke karaktereigenschappen van elke technologie belangrijk wordt gevonden op Vlieland; in andere woorden welke *criteria* relevant zijn, en hóe belangrijk ze zijn. Door in disucssie te gaan met belangrijke mensen op of in verband met Vlieland, is een set criteria opgesteld en de onderlinge weging bepaald. De gevonden relevante criteria zijn onderverdeeld in technische, economische, milieu en sociale criteria en te vinden in tabel 1. Daarnaast is de resulterende weging uitgezet van elk criterium, die aangeeft hoe belangrijk de criteria zijn bevonden door verschillende belanghebbende partijen. Een hoge weging voor een criterium betekent dus dat het belangrijker dat technologieën hier goed op scoren.

Tabel 1: Relevante criteria en de bijbehorende weging

Type criterium	Criterium	Weging
Technisch	Voorspelbaarheid van productie	10.2
	Constantheid van productie	15.9
	In-house kennis Nederland	5.2
Economisch	Tijd tot competitive realisatie	7.8
Milieu	Ruimte gebruik op land	10.2
	Ruimte gebruik op het water	4.7
	Geluid	9.7
Sociaal	Sociale perceptie	17.6
	Opleveren van banen	10.5
	Sociale voordelen	8.2
	Totaal	**100**

Resultaten

Vervolgens zijn alle technologieën op ieder criterium gescoord op kwalitatieve en kwantitatieve schalen. Gebaseerd op de toegewezen scores en de wegingen van de belanghebbende partijen zijn tot slot de totale scores berekend [figuur 1]. De totale score geeft aan hoe geschikt een technologie is wanneer alle relevante criteria worden meegenomen. Het is te zien dat geothermische warmte het hoogste scoort, gevolgd door macro algen (zeewier) productie, warmtepompen en getijdenstroom. Deze resultaten impliceren dat aan de hand van de beschouwde waarden deze alternatieven het meest geschikt zijn voor Vlieland. Uit een onzekerheids- en gevoeligheidsanalyse – waar de waardes voor scores en wegingen worden gevarieerd om onzekerheden mee te nemen - blijkt dat de waarschijnlijkheid dat geothermische warmte de hoogste rang krijgt groot is, maar er ook een behoorlijke kans is dat macroalgen de eerste plaats opeist. Daarnaast is er een kleine kans dat zonnepanelen, getijdenstroom, warmtepompen of golfdeining de hoogste notering behaalt als wegingen en scores veel veranderen.



Figuur 1: Totale scores — opgebouwd uit de individuele score per criterium

Discussie

Het resultaat van de MCA geeft een eerste selectie van duurzame energietechnologieën die het beste passen bij Vlieland. Zoals gezegd, scoren op volgorde geothermische warmte, zeewier, warmtepompen en getijdenstroom het best. Echter zijn er veel aannames zijn gemaakt om deze waarden te bepalen en doordat algemene bevindingen toegepast zijn op de situatie in Vlieland, moeten de resultaten niet als definitieve antwoorden moeten geinterpreteerd. Bovendien brengen toekomstige ontwikkeling van de technologieën onzekerheden met zich mee. Daarnaast zijn de toegekende wegingen van de criteria van grote invloed op het resultaat.

Ook heeft het onderzoek enkel gefocust op de productiezijde van de doelstelling. Echter om een energie neutraal Vlieland te bereiken is het essentieel dat de energie vraag ook word meegenomen. Het bestuderen van de energievraag brengt kansen met zich mee om energie te besparen door middel van het inzetten van energie efficiëntie maatregelen. Verder brengt dit de mogelijkheid met zich mee om de vraag naar een vorm van energie te koppelen aan het aanbod van deze vorm van energie, zodat een optimale mix van energie productie technologieën kan worden samengesteld.

Aanbevelingen

Al met al kan aan de hand van dit onderzoek worden vastgesteld dat geothermische warmte, zeewier, warmtepompen en getijdenstroom de meeste potentie hebben voor succesvolle implementatie op Vlieland. De eerste aanbeveling uit deze uitslag betreft om te onderzoeken hoe de gevonden technologieën optimaal kunnen worden ingezet om een energiemix te creëren welke overeenkomt met de energievraag van het eiland.

Aangezien geothermische warmte de beste warmte producerende technologie is, betreft een tweede aanbeveling om te onderzoeken welke locaties geschikt zijn voor het onttrekken van warmte uit de ondergrond. Aan de hand van een dergelijke analyse zal ook bepaalt moeten worden wat de kosten van een dergelijke installatie zijn. Deze zouden eventueel vergeleken kunnen worden met de kosten en impact van de installatie van warmtepompen.

Macro algen op zee is volgens de MCA het beste alternatief voor brandstoffen productie, er zal onderzocht moeten worden of en waar zeewier kan worden gekweekt rondom Vlieland. Mocht dit geen haalbare methode zijn, dan zou gekeken kunnen worden naar de mogelijkheden van algenproductie op land.

Daarnaast is getijdestroom energie productie de beste optie voor elektriciteitsproductie op het eiland. Aangezien in een voorstudie de technisch optimale locatie voor deze technologie al is bepaalt, zal gekeken moeten worden of de technologie daadwerkelijk hier kan worden geïmplementeerd rekening houdende met bestemmingsplannen van de omgeving. Daarnaast kan elektriciteitsproductie eventueel aangevuld worden met zonnepanelen.

Tot slot zullen de ontwikkelingen en mogelijkheden van de overige technologieën gevolgd moeten worden. Dit aangezien technologische vooruitgang voornamelijk met betrekking tot fluctuatie en voorspelbaarheid van energie productie een grote invloed kan uitoefenen op de geschiktheid van een technologie.

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Chapter 1: Introduction

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1. Introduction

In light of global action such as the Kyoto protocol, countries all over the world are urged to reduce their energy consumption and greenhouse gas (GHG) emissions. As a result, more and more energy is produced using renewable energy resources, since these emit no or little GHGs (Ellabban et al., 2014).

The Netherlands are no exception to this renewable trend, as they set a 2020 target of producing 14% of all energy using renewable technologies. Yet by 2014, the share of renewables in the Netherlands was 5.6%, mostly consisting of energy produced through biomass incineration (CBS, 2015). Moreover, the Dutch energy policy has turned strongly towards a focus on sustainability in the *Nationaal Energie Akkoord*.[1] In this agreement, many parties including the provinces have agreed to targets concerning energy use reduction and increased renewable penetration (Interprovinciaal Overleg, 2015). A similar agreement was made amongst the Wadden Islands[2] and the municipality of Friesland in 2007 and further structured in the *Uitvoeringsprogramma Duurzame Waddeneilanden*[3] (2015) in which they agreed to be self-sufficient in terms of energy and water supply by the year 2020. Later, the objective to become self-sufficient was specified as becoming 'energy neutral'. This means the Wadden islands and Friesland intend to produce at least enough energy to account for their own needs in electricity, heat and on-land fuel use (Gemeente Vlieland, nd).

For the island of Vlieland, research concluded that currently the only two ways of cost-effectively reaching energy neutrality by 2020 are through installing 1) two or three large wind turbines or 2) one large turbine combined with solar panels on all suitable rooftops (Hanssen et al., 2014). These technologies are supplementary to a 0.8 ha solar energy field that is planned at the Vliehors (Omrop Fryslân, 2016). Yet, since Vlieland is a unique geographical and ecological destination with nature being its number one tourist attraction (Gemeente Ameland et al., 2015), the visual impact of wind turbines was perceived as undesirable (Lab Vlieland, 2015). This poses the issue that despite wind turbines are not considered the ideal solution to reach the 2020 goal, the deployment of one or more wind turbines is a requisite. On the longer term, future alternatives for these wind turbines could be deployed in order to reach energy neutrality on Vlieland.

1.1. Problem definition

The question remains what the renewable possibilities are beyond wind turbines. These would include technologies that are in earlier stages of development and may not be competitive now, but might be in the future. In other words, rather than considering a short term competitive solution, there is a need for an alternative long term focus. The possibilities of renewable implementation on the long term have not been assessed for Vlieland specifically before. Investigating these possibilities could thus offer a foundation on which a roadmap to an energy neutral system can be based. Furthermore, they could have a scientific value since the methodology and insight into the technologies can be applied to similar locations. It can e.g. act as an example for other small islands with similar visions on energy neutrality, such as the other Wadden islands.

In other words, this research builds on the existing literature and act as a first screening of which developed and developing renewable technologies have potential for *long term* implementation on Vlieland. As mentioned, 'long term' entails that these technologies do not have to be currently economically feasible in order to apply as a suitable option. An important notion here is that a technology should be technically possible and viable, but also accepted and supported by the inhabitants. Therefore, support from the

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[1] The Dutch National Energy Agreement

[2] Texel, Vlieland, Terschelling, Ameland and Schiermonnikoog

[3] Implementation Program Renewable Wadden Islands

community on the island is an essential factor for success that is considered. Subsequently the aim of this report is to answer the question:

What renewable energy technologies are best suited for implementation on Vlieland on the long term?

In order to answer this question, a multi criteria analysis (MCA) is performed which ranks a set of renewable technologies on their suitability for Vlieland. In order to perform such an MCA, three inputs are needed: the possible options, relevant criteria to test them on and performance of each option on these criteria. These three inputs were found by answering the following sub questions:

1. What technologies are suitable for renewable energy generation on Vlieland?
2. Which criteria are relevant for Vlieland and what is their relative importance?
3. How do the suitable technologies score on the relevant criteria?

Answering these three sub questions structurally provided the inputs for answering the main question and therewith provided insight into renewables on the long term.

1.2. Scope and boundaries

Several of demarcations were made in order to determine the scope of this research. The first boundary for the researched technologies is the geographical boundary. The research only considers the island of Vlieland and its surrounding waters, consisting of close to 4,000 ha of land, 66 ha of backwater and 28,000 ha of open water (Gemeente Vlieland, 2013).

Another demarcation entails which type of technologies to include in the analysis. Whereas energy neutrality can be reached by reducing total energy use as well as through producing energy from renewable energy sources (van der Rijt, 2013), this research merely incorporates the latter. Therefore, considered technologies are limited to those who produce renewable energy, as desired by client Lab Vlieland[4]. Technologies that merely provide alterations to existing systems are not considered. Consequently, energy saving measures, storage technologies and integrated system solutions fall outside the scope of this study. Furthermore, it is assumed that the island's energy production can entail energy in any form, either electricity, gas, fuel or heat.

Finally, by default regular onshore wind turbines are not considered in this research; other wind power technologies are however included.

1.3. Report structure

The report structure is as follows: firstly, a fact sheet of relevant data on Vlieland is presented to provide some context regarding the island. Afterwards, the employed research method is set forth and explained. This section elaborates on the MCA steps conducted and the way in which they answer the sub questions. In addition, it discusses the means of data collection and includes the intended output of each step. In the three subsequent chapters the sub questions are answered, providing the inputs for the MCA. Finally, the MCA results are set forth, providing the answer to the main research question. Afterwards, the limitations and implications of the results are included in the discussion. The research results are summarised in the conclusion. Finally, recommendations are given on how the results can be applied in practice.

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[4] G. Reeskamp & T. Couzij, project managers Lab Vlieland, personal communication, April 28, 2016.

Vlieland fact sheet

Figure 1: Map of Vlieland

Table 1: Fact sheet on Vlieland

Fact sheet				
Demographics		**Value**		**Source**
Population		1,100		Gemeente Vlieland, 2013
Population growth		Stagnant		RIVM, nd
Tourist visiting		180,000 /y		VVV Vlieland, 2014
Domestic energy use				
Electricity		8.7[a] GWh/y	748 toe/y [f]	Lab Vlieland, 2016
Natural gas		2.5[b] million m^3/y	1,990 toe/y	Lab Vlieland, 2016
Fuel use (on land)	Petrol	181,900 l/y	272 toe/y	Grontmij, 2011
	Diesel	117,750 l/y		
Fuel use (ferry)[c]	Diesel	2,000,000 l/y	1,960 toe/y	Grontmij, 2011
Domestic energy production				
Solar panels [d]		100 MWh/y	9 toe/y	Lab Vlieland, 2016
0.8 ha solar field (planned) [e]		900 MWh/y	77 toe/y	ECV, 2016; Omrop Fryslân, 2016

[a] 2013 data

[b] 2015 data

[c] Since only the fuel for on-land transport on Vlieland is taken up in the energy neutrality goal, the fuel use of the ferry is only presented to give an indication of other local uses.

[d] Mainly solar panels; a very small part is generated through small wind turbines

[e] A subsidy grant from the Dutch government is currently in application; the solar field is to be constructed towards the end of 2016 (Omrop Fryslân, 2016).

[f] Conversion from heat, electricity and fuels to tonne of oil equivalent (toe) can be found in Appendix V.

Chapter 2: Method


Jan Visser ©

2. Method

The following section outlines the means of data collection and data analysis. The research was conducted by performing a multi criteria analysis (MCA). An MCA is a tool to compare various options, accounting for a wide range of criteria that cannot all be expressed in monetary terms (DCLG, 2009). Performing an MCA is thus effective in rating alternatives on a multitude of criteria with different valuations, in obtaining a ranking of alternatives assessed and subsequently in identifying a single most preferred option (DCLG, 2009). Hence, this method allowed for a ranking of most suitable technologies for Vlieland considering a broad set of criteria.

In general, the first step of an MCA is determining the decision context of the research by clarifying what the aim of the MCA is and who the stakeholders involved are. Afterwards, three steps can be recognised in performing an MCA:

1. Identify all possible options for solving the problem.
2. Identify relevant criteria and determine the scale and standardisation method to be applied per criterion. Also allocate weights to each criterion, to compensate for the diverse order of importance between criteria.
3. Assign scores for each criterion. This is necessary to compare different criteria amongst each other.

These steps relate back to the three sub questions set in the introduction. Consequently, the answer to each of the sub questions acts as an MCA input. Figure 3 shows how these steps are operationalised in this research. The first sub question is answered in chapter 3, resulting in a technology shortlist. The second sub question is answered in chapter 4, encompassing the relevant criteria and their weighting. The score allocation concerns the third sub question and is covered in chapter 5. Afterwards, all the needed MCA inputs are known. The results of executing the MCA are set forth in chapter 6.

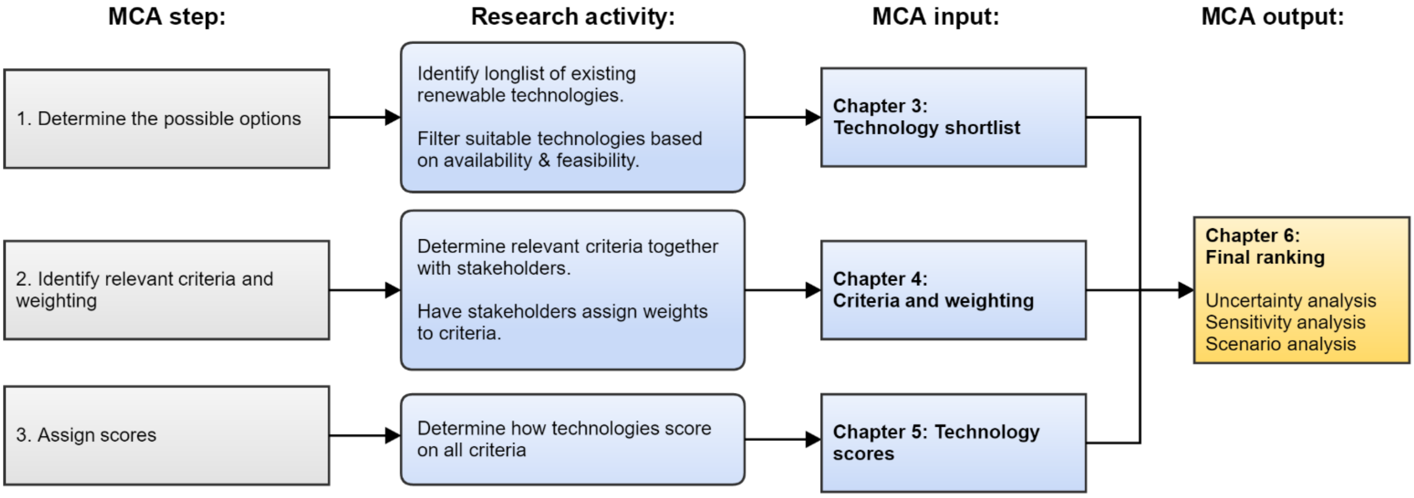

Figure 2: Research outline

2.1. Technology shortlist

The first step was the identification of suitable technologies that could be employed to achieve the objective. In order to make this selection, academic literature on renewable energy technologies was consulted to determine which renewable energy resources exist and which technologies could exploit them (e.g. Twidell & Weir, 2015; NREL, 2012). This resulted in a *longlist* of all possible renewable technologies. However, not every technology is suitable for implementation on Vlieland. Consequently, the longlist was narrowed down into a *shortlist* of suitable technologies by assessing the technologies on two criteria: resource availability and technology feasibility.

The former selection criterion entails that the resource from which energy is extracted had to be present on Vlieland. If the criterion was not met, the technology was not included on the shortlist. The latter criterion entails that implementation would be possible within any restrictions posed by geographical features or any other limitation shown in prior research. In other words, the feasibility considered any other reason why the technology would not be eligible for implementation on Vlieland. If a technology adhered to both criteria, it was listed on the shortlist and was included as an option in the MCA.

Literature that concerned Vlieland specifically was addressed to evaluate the availability and feasibility of the reviewed technology on Vlieland (e.g. Hanssen et al., 2014; Lab Vlieland, 2015; Lab Vlieland, 2016). To further increase reliability and precision of information, this was supplemented with personal communications with experts on Vlieland's lay-out, regulations and culture.

In order to provide background of the technologies on the short list, a technology characterisation was included. This consists of a short description of the operating principles, an assessment on which designs are currently available or being developed and what future developments are expected. Based on the state-of-the-art and predicted technology characteristics (e.g. best efficiencies, highest yield per area or highest coefficient of performance shown possible), an approximation of the energy production potential on Vlieland was calculated. The state-of-the-art characteristics are used as these are expected to be commercially available in the future. Although this was not used directly as an MCA input, it provided a sense of comparison between the potential energy production of the technologies.

2.2. Relevant criteria and weights

The second required input of an MCA is a set of relevant criteria to test the options on. These criteria can either be examined quantitative or qualitative (Jansen & Munda,1999). Secondly, the most suited scale and standardisation method are to be determined for each criterion. Finally, to determine relative importance, weights were allocated to the relevant criteria.

2.2.1. Criteria selection

Criteria which are often reviewed in MCAs were adapted from Wang et al. (2009) and cross-checked with the literature referred to in the article. In this review study, the application of MCA methods in aid for decision making in sustainable energy planning was researched, thus providing a list of well applicable criteria for the MCA. The proposed criteria are divided into social, technical, economic and environmental criteria.

The next step was to determine which of these criteria were relevant for Vlieland and were to be included in the MCA. In order to determine relevancy, an iterative selection process was applied as shown in Figure 4: first of all, the criteria from the literature were checked on relevance in consultation with the client. Irrelevant criteria were removed and missing criteria were added. Then, the criteria were proposed to a selection of local stakeholders to check whether they missed essential criteria [a list of stakeholders can be found in Appendix I]. Their embeddedness in the community on Vlieland supplied them with a reliable view on which criteria could be relevant. Whenever the criteria changed, another discussion with the client was performed. This iterative process resulted in a reliable selection of criteria which were deemed important.

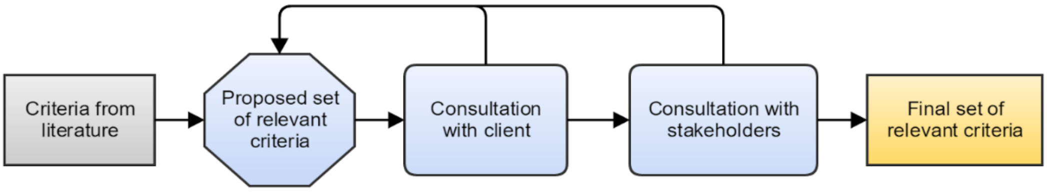

Figure 3: Iterative process of criteria selection

2.2.2. Scaling and standardisation

Each relevant criterion was then supplied with a scale that was best suited for the specific criterion. For each criterion, an argumentation was supplied for the choice of scale, based on literature and practical considerations. Wherever possible, quantified scales were used, but most criteria were scored on scales using pluses and minuses[5]. An exception was the criterion 'social perception', where a survey was performed amongst the islanders.

In the survey, several images of the shortlist technologies were presented [Appendix X]. Respondents were asked to rate their agreement on the following two statements: *I am familiar with this following technology* (answers options range from 1 "not at all" to 5 "completely familiar") and *The technology fits Vlieland's aesthetics* (answer options range from 1 "completely disagree" to 5 "completely agree"). The first question was asked to indicate to what extent the respondents needed an explanation of the picture from the survey taker. The second question indicated their perception of how well a technology would fit Vlieland's aesthetic value.

Simultaneously, all the criteria were assigned a suited standardisation method. In standardisation, all scores are normalised to a score between 0 and 1 which is necessary to compare all the criteria on a similar scale. The different standardisation methods that are used in this report are explained in 0.

2.2.3. Weight allocation

Next, all the resulting criteria were given a weight (or 'weighting factor'), thus assessing the criteria on their relative importance. This is an important step in conducting an MCA, since the allocation will have significant influence on the ranking of each option; it thus needs to be done carefully and accurately. The weights are generally determined by expert judgment, as was done is this research as well.

On the one hand, the weighting factors had to be representative for the client's vision; on the other hand, other stakeholders on Vlieland might have different views and the client aimed to have these taken into account as well[6]. Therefore, the weighting was performed by different relevant stakeholders, categorised in groups according to function. These stakeholder groups allowed consideration of different stakeholder views in the MCA. A distinction was made between four groups of stakeholders, which are 1)

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[5] The plus/minus scales are specified in the results section, since the relevant criteria were themselves already a result of the research.

[6] T. Couzij, project manager Lab Vlieland, personal communication, May 4, 2016.

the client Lab Vlieland, 2) policy makers, 3) Vlieland 2020 group and 4) relevant experts. Lab Vlieland was considered an important stakeholder since they help Vlieland to accelerate towards energy neutrality. Policy makers were considered important since they are closely involved in the spatial planning, strategy and policy making on Vlieland; this group consists of councillors and aldermen of the municipality of Vlieland. The Vlieland 2020 group was considered a key stakeholder since they are a civilian initiative of involved citizens which share the objective to achieve an energy neutral Vlieland by 2020. And finally a group of experts were considered relevant since they were closely involved with Vlieland and possessed more technical knowledge regarding the energy neutrality target and (renewable) energy production in general.

For the weighting, each person was asked to distribute 100 points among the criteria, giving the most important criterion to their judgement the highest amount of points. All individual stakeholders were assumed to be equally important within their group in terms of weighting, so the weighting per group is the average of all respondents in that group. Similarly, the four groups of stakeholders were believed to deserve an equal say in the weighting, so the final weighting is the average of four sub-groups[7] [Figure 5].

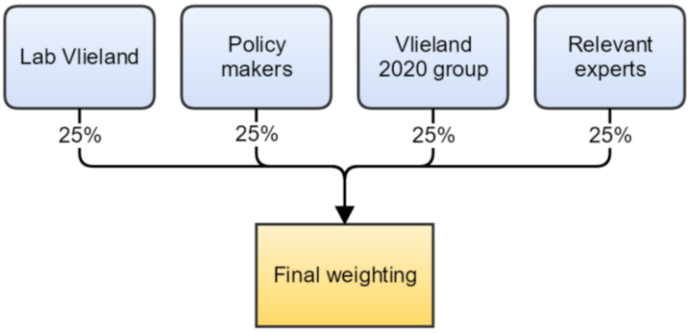

Figure 4: Weighting derivation

2.3. Assign scores

The final input of an MCA consists of the scores of the technologies on each criterion. The determination of scores was done mainly through the review of academic literature and technology briefs. The scores were done on the scales described in step 2 of the MCA [see section 2.2.2]. An argumentation of the applied score was included to support the decision.

2.4. MCA output

After these steps, all the inputs needed to run the MCA had been determined. The results of the MCA consist of the final ranking of technologies as well as a scenario analysis, an uncertainty analysis and a sensitivity analysis. The MCA software 'DEFINITE' was used to execute the MCA, since it offered multiple options for standardisation, weighting mechanisms and graphical representation. Furthermore, it included sensitivity and uncertainty functions (Janssen & Herwijnen, nd).

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[7] It is worthwhile to be noted that the average of the stakeholders per sub-group is not claimed to be representative of the sub-group, since they are still personal opinions which cannot be generalised. Rather, it is interpreted as a reasonable indicator of the group's general vision on Vlieland and therefore gives an indication of the most important criteria for the group. A reasonably justified allocation of weights on the criteria was thus ensured.

2.4.1. Technology ranking

The final score per technology was calculated based on all individual scores and the weighting factors. The MCA software automatically standardised the scores, based on the assigned standardisation methods. The final technology score was an addition of each individual criterion score, multiplied by the weighting factor [Equation 1].

Equation 1: Final score for each technology

$$Final\ score = \sum standardised\ score\ on\ single\ criterion \times weighting\ factor$$

The software then automatically ranked the technologies from high to low score, where the highest was considered the best option. This ranking hence indicated which technology was most suitable for Vlieland considering the relevant criteria and weightings given.

2.4.2. Scenario analysis

Subsequently, a scenario analysis was performed, where the MCA was performed on the basis of the weightings given by each of the individual stakeholder groups. Hence, four additional MCA runs were executed, where the relative importance of criteria was determined by the average of only one of the four groups. This gave insight into what the MCA outcome would be from multiple viewpoints. It therefore showed which technology ranking would apply for each stakeholder group.

2.4.3. Uncertainty analysis

Next, an uncertainty analysis was performed to incorporate uncertainty and unreliability of both the assigned scores and the weights. This allowed an analysis of what the probability is for a technology to receive a certain rank, considering possible variations in scores and weights.

Hence, a percentage of uncertainty was appropriated to each score and weighting. For each criterion, it was argued how uncertain the scores were and an uncertainty level was assigned accordingly. The weight uncertainty of each criterion was determined by comparing the average weight of all groups with the weight per individual group. The group with the highest deviation from the average was taken as the uncertainty for that criterion. It should be noted that an uncertainty level of 30% means that a value could vary between 30% higher and 30% lower than the original input value.

2.4.3. Sensitivity analysis

Finally, the robustness of the MCA outcome was checked by conducting a sensitivity analysis. A sensitivity analysis is conducted to account for weight deviations that could occur when people are asked to translate their personal preferences and values into numerical score (Beinat, nd). In order to do this, a plot was made for each criterion which shows the ranking of technologies as a function of criterion weight. The plot varies the weight between 0 and 100%, giving insight into how much a criterion's weight would have to change in order to alter the ranking outcome. In other words, the sensitivity of the ranking to changes in weighting factors was analysed.

Chapter 3: Technology shortlist

3. Technology shortlist

In this chapter the shortlist of technologies is drafted that will be assessed in the MCA. This provides an answer on the first sub question "what technologies are suitable for renewable energy generation on Vlieland?". The shortlist is found by determination of a technology longlist, which is narrowed down according to resource availability on and feasibility for Vlieland, as discussed in the methods. In addition, a characterisation of the technologies on the shortlist is provided.

3.1. Technology longlist

The technologies found on the longlist concern all the available renewable energy technologies. Available technologies are technologies that are currently at least in a pilot installation or in a further phase of development. The longlist includes all technologies within the renewable resources solar power, tidal power, wave power, biomass, geothermal power, wind power, hydropower, saline power and ocean thermal energy (OTEC) (Twidell & Weir, 2015). An explanation of each resource and the accessory energy production technologies is included in Appendix II. Resulting from this, the longlist of technologies is found in Table 2.

Table 2: Technology longlist

Resource	Technology
Solar power	Conventional photovoltaics (PV), concentrating solar power (CSP), solar water heating (SWH) & concentrator photovoltaics (CPV)
Tidal power	Tidal range, tidal current & hybrid applications
Wave power	Oscillating water column (OWC), oscillating bodies (OB) & overtopping
Biomass	First, second and third generation biomass
Geothermal power	Shallow geothermal (direct heating), deep geothermal, enhanced geothermal (EGS), igneous systems, aquifers & heat pumps
Wind power	Unconventional, offshore & urban wind turbines
Hydropower	Hydro dam
Saline power	Pressure-retarded osmosis (PRO) & Reversed electro dialysis (RED)
OTEC	Ocean Thermal Energy Conversion

3.2. Shortlist selection

This section describes how the longlist was narrowed down to the shortlist. For each technology that did not make it to the shortlist, an argumentation is given why it did not adhere to either of the conditions 1) resource availability on Vlieland and 2) feasibility for Vlieland. The resulting shortlist selection is shown in Table 3.

3.2.1. Resource availability

Firstly, Pressure-retarded osmosis (PRO) and Reversed electro dialysis (RED) technologies were ruled out due to the fact that Vlieland is located in the salty Wadden Sea without any nearby source of sweet water (Ecomare, 2015b). Hence, the possibility of using saline power is absent.

Secondly, an ocean thermal energy conversion plant was disregarded as well, since only coastlines around the equator have the suitable temperature gradient for ocean thermal energy conversion (TU Delft, nd-a). Away from the equator, the only possible installations are large floating installations far away from populated areas (Twidell & Weir, 2015). Thus, this is also not an option within the open waters near Vlieland.

A hydro dam is not included in the shortlist since there is little variation in altitude on Vlieland and no running water or reservoirs (Ecomare, 2015a). Hence, there is not enough available head or moving water to produce hydropower.

Finally, hot igneous systems are not present in the Netherlands (Pawlewicz et al., 1997), so this geothermal technology was disregarded.

3.2.2. Feasibility

Next, the technologies were narrowed down according to feasibility for Vlieland. For each technology that does not adhere to this criterion, a description will follow as to why this is the case.

First of all, solar water heating (SWH) has the potential to fulfil only 2% of the total energy demand (Hanssen et al., 2014). It is therefore not considered to deliver an adequate contribution to the island's renewable energy generation. Concentrated solar power (CSP) is disregarded as well, since it is stated to only be interesting between 40 degrees north and south of the equator (IRENA & IEA-ETSAP, 2013). Finally, concentrating photovoltaics (CPV) are mostly interesting in areas with direct normal irradiation (DNI) over 2000 kWh/m^2, whereas Vlieland's DNI is around 900 kWh/m^2 (Philipps et al., 2016; Geo Model Solar, 2014). For that reason, CPV is also disregarded.

For the tidal resource, hybrid application energy technologies are excluded since it involves the co-creation of a large construction. A typical structure is expected to have an installed capacity in the order of GWs (POWERDTP, nd), which greatly exceeds the energy demand of Vlieland (Lab Vlieland, 2016).

First and second generation biomass are both disregarded as a potential resource for Vlieland. First generation biomass is discarded since there is no arable land for agriculture available (CBS, 2016). The possibility of using second generation biomass (wood chips or waste stream) was rejected by Hanssen et al. (2014). The available wood is scarce and already being used for home heating and the communities' organic waste streams pose little potential. Merely anaerobic digestion of landscape management grass and municipal organic waste were concluded to have potential, but only in insignificant amounts[8]. However, third generation biomass (microalgae and macroalgae) remains a viable option, since these are cultivable on or near the island.

For deep and enhanced geothermal, Vlieland shows significant potential due to the sub surface characteristic (TNO, 1983). However, if a sufficiently deep borehole suitable for electricity production would be drilled (i.e. 5-8 km deep (Hagendoorn et al., 2009)), an installation with an installed capacity of over 100 MW should be deployed (Twidell & Weir, 2015). Since this this greatly exceeds the energy demand on Vlieland, geothermal electricity production is not a suitable option. Hence, deep geothermal technology and EGS are disregarded.

In terms of wind power, urban wind turbines are not considered since prior research determined that over 3,000 turbines would have to be installed on the island, which is undesirable (Lab Vlieland, nd). Moreover, conventional offshore wind turbines are disregarded since they would still be visible for the islanders when built in the open water around Vlieland (Hanssen et al., 2014).

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[8] Less than 1% of the total energy demand in 2020 (Hanssen et al., 2014).

Table 3: Technology shortlist selection

Resource	Longlist technology	Resource availability	Feasibility
Solar power	Conventional photovoltaics (PV)	X	X
	Concentrating solar power (CSP)	X	
	Solar water heating (SWH)	X	
	Concentrator photovoltaics (CPV)	X	
Tidal power	Tidal range	X	X
	Tidal current	X	X
	Hybrid applications	X	
Wave power	Oscillating water column (OWC)	X	X
	Oscillating bodies (OB)	X	X
	Overtopping	X	X
Biomass	First generation	X	
	Second generation	X	
	Third generation	X	X
Geothermal power	Shallow geothermal (direct heating)	X	X
	Deep geothermal	X	
	Enhanced geothermal system (EGS)	X	
	Extraction from hot igneous system		
	Extraction from aquifers	X	
	Geothermal heat pumps	X	X
Wind power	Unconventional turbine designs	X	X
	Offshore wind turbines	X	
	Urban wind turbines	X	
Hydropower	Hydro dam	X	
Saline power	Pressure-retarded osmosis (PRO)		
	Reverse electro dialysis (RED)		
OTEC	Ocean thermal energy conversion		

3.3. Technology characterisation

In the following section, a characterisation of the shortlist technologies is given. Each technology is described briefly but it should be noted that a full elaboration of the technologies including reasoning, assumptions made and calculations applied can be found in Appendix III A-J. This chapter summarises the findings in a similar yet concise fashion: first a short description of the technology is given, then a short review of the current state of development and prospects regarding future development are given. Finally, the calculated estimation of the potential energy production per surface area on Vlieland is.

Solar photovoltaics (PV)

Photovoltaic (PV) panels directly convert solar irradiation into electricity. The technology is widely used and has proven to be economically feasible with current efficiencies of 25% in commercial application (IRENA, 2013b). Recent research has led to the development of a high performance three-junction cell reaching an overall efficiency of 33.4% (Twidell & Weir 2015). Assuming that these panels will be available for commercial use on the long term, and considering the annual average solar irradiation of 1075 kWh/m^2/y on Vlieland, the potential energy production is 215 kWh/m^2/y [Appendix III - A].

Oscillating water column (OWC)

Oscillating water column (OWC) technologies convert energy in waves that strike against the device, into electricity through the use of turbines (IRENA, 2014b). This technology is far from economically feasible implementation and therefore considered an immature technology (Bull & Ochs, 2013). New state-of-the-art generation turbines reach averages efficiencies of 70% in a random wave environment (Falcão & Henriques 2016). Improvement opportunities that could increase economic feasibility lie in more advanced controls, improved conversion, optimised structural design and array optimisation. The deployment of a single 500 kW OWC installation fixed in the near shore facing the North Sea is expected to generate between 876 and 1,932 MWh per year. However, many turbines could be placed considering the available water area, with a potential energy production of 759 kWh/m^2/y [Appendix III - B].

Oscillating bodies (OB)

Oscillating body (OB) devices convert wave energy into electricity by capturing wave motion using semi-submerged devices (IRENA, 2014b). Several designs of the technology exist and have been both tested and applied. Nevertheless, the technology is still considered to be economically unfeasible. To improve feasible implementation, especially research into power take-off systems is needed (IRENA, 2014b). The deployment of a 750 kW Pelamis system, which has gotten closest to economic feasibility, in the North Sea has the potential to generate between 1.31 and 2.58 MWh on an annual basis. Yet again, multiple installations could be placed in the North Sea, where the potential is 2,682 kWh/m^2/y [Appendix III - C].

Overtopping

Overtopping devices convert wave power into electricity through creating a hydraulic head by collecting water in a small basin (IRENA, 2014b). The level of development of this technology is still in its early stages, meaning that it is not commercially viable yet. Future research and development is expected to concern improved mooring and more intelligent control (Bevilacqua & Zannutigh, 2011; Friis-Madsen et al., 2012). Also survivability of the available devices poses improvement opportunities. The placement of a single 4 MW device in the North Sea could provide an annual electricity production of 12 GWh, resulting in a potential of 308 kWh/m^2/y. Considering the available space in the North Sea, multiple devices could be installed [Appendix III - D].

Tidal range
Tidal range power installations convert tidal range to generate electricity, by storing water in a basin during flood tides creating a head in ebb tides (IRENA, 2014a). This technology has proven to be economically feasible and is considered well-developed since it uses low head hydro power turbines (Montllonch Araquistain, 2010; IRENA, 2014a). Consequently, little technological development is expected in the operating system and technological performance. However, the construction of a tidal lagoon may become more appealing in the future, due to decreasing associated costs (van Berkel, 2014). Implementation of a 10 km^2 tidal lagoon with a bi-directional propeller would have an average power output of 6 MW, producing 51.3 GWh per year with a potential per surface area of 5.13 kWh/m^2/y [Appendix III - E].

Tidal current
Tidal current consists of different technologies which convert (tidal) water current movement into electricity (IRENA, 2014a). Of the available technologies, horizontal-axis turbines are applied and demonstrated most often, therefore considered as the most-developed tidal current technologies (SEI, 2010). However, the technology has not been proven to be economically feasible yet (SEI, 2010). Most development in tidal current is to be done in optimal spatial positioning of turbines, which increases energy output whenever the blockage ratio of a channel is optimized (Twidell & Weir, 2005). The deployment of 10 to 15 turbines near Vlieland's docking area could generate 3.07 GWh per year (Gardner, 2012) and has a potential of 153 kWh/m^2/y [Appendix III - F].

Third generation biomass: macroalgae
Macroalgae (seaweed) are multicellular plants cultivated in salt or fresh water ponds that can be converted into biofuels. There are several macroalgae species suitable for large-scale cultivation and energy production, by conversion into bioethanol, biodiesel and biogas production (Hochman et al., 2015). Macroalgae are widely cultivated for several purposes but cultivation for energy production is merely being tested and currently not commercial (Hughes et al., 2012). However, combined production of different products and secondary energy carriers is expected to be feasible in the future (Reith et al., 2005); with controlled nutrient addition in cultivation, algae yields could reach up to 50 tons/ha/y (dry weight) (Reith et al., 2009). Furthermore, it has been found that there is a large potential for marine macroalgae cultivation in the North Sea (Reith et al., 2005). Production merely for energy use (bioethanol) the potential of macroalgae at sea is estimated at 19.2 MJ of bioethanol/m^2/y [Appendix III - G].

Third generation biomass: microalgae
Microalgae are unicellular organisms that can be cultivated on land for biofuel production. Currently, commercial algae production is mainly aimed at high-value products for niche markets (de Visser, 2015). Although microalgae are already used as a resource for secondary energy carriers, yields are currently considered too low to serve as competitive energy production alternatives (Hochman et al., 2015). In order to increase the yield and scale up production, innovations are needed. Microalgae strain development via genetic modification could contribute to this (Rodolfi et al., 2009). Also, optimizing the operation and design of photo-bioreactors in which the algae are grown can increase production yields (AlgaePARC, 2015). A large potential lies in the combination of energy production and coproducts (e.g., wastewater treatment), that make large-scale algae biofuel production economically viable on the long term (Hochman et al., 2015; Parmar et al., 2011). For Vlieland the potential production of biodiesel produced by microalgae on land is estimated at 210 MJ of biodiesel/m^2/y [Appendix III - G].

Geothermal direct heating

Geothermal direct heating is applied by extracting shallow geothermal heat from the subsurface and directly utilising it for heating applications. Direct heating application of geothermal energy is already broadly applied and commercially available on both small and large scale with an overall worldwide installed capacity of 15.3 GW_{th} (Twidell & Weir, 2015). Therefore, it is considered as a well-developed and mature technology. However, the performance of the pumps, heat exchangers, re-injection technology and storage tanks is expected to improve, increasing efficiencies and decreasing drilling costs (IEA, 2011). A 6 MW_{th} installation with a depth of 1,700 meters is expected to greatly exceed total energy demand for heating on Vlieland[9] (van Leeuwen et al., 2010). As geothermal direct heating cannot be exported to the mainland, overproduction for energy use compensation is not viable and the maximum energy production is equal to the energy demand for heat, which is 2.5 million m^3 of gas for heating per year [Appendix III - H].

Geothermal heat pumps

Geothermal heat pump (GHP) systems use electricity to transfer heat from the subsurface or the environment to heating or cooling appliances (Çengel & Boles, 2015; IRENA, 2013a). Heat pumps are widely used and are economically feasible worldwide, so GHP systems are a mature technology (Elzenga & Ros, 2014). Nevertheless, technological system advancements are expected due to increasing deployment and research. Consequently, efficiency is expected to increase by 30 to 60% for heating applications and 20 to 50% for cooling systems in the coming thirty years, leading to cost reduction and increasing the viability of the system (IRENA, 2013a). Besides, more accurate and improved specific site GHP system placement could augment the heat pump functioning (IRENA, 2013a). Geothermal heat pumps have the ability to generate all heat demand at Vlieland but it will increase the electricity demand. The potential per surface area of land is 50 $kWh/m^2/y$ [Appendix III - I].

Unconventional wind

Unconventional wind turbine designs convert kinetic energy from the wind directly into electricity. As a large amount of turbine designs exist, the performance of one design is reviewed; the INVELOX system was chosen as ample performance data were available on this design. This system is being tested and not economically feasible yet (Allaei & Andreopoulos, 2014). Further research and development and increased testing and deployment should improve performance, reduce costs and therewith enable the INVELOX to be commercially available in time. The potential energy production is 272.6 $kWh/m^2/y$ [Appendix III - J].

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[9] van Wees, J.D., Lecture: geothermal Energy: an introduction to an important RE. Presented at the course fossil resources: past, present and future, 07-04-2016, Utrecht University.

Chapter 4: Relevant criteria and weighting


Jan Visser ©

4.1. Criteria selection
4.2. Scaling and standardisation
4.3. Weight allocation

4. Relevant criteria and weighting

This chapter provides an overview of the criteria that are deemed important for Vlieland when assessing implementation of renewable energy technologies. Subsequently, it provides answer to the second sub question "What criteria are deemed important for Vlieland?". First an argumentation for the selection of criteria is presented, followed by a definition of each criteria. Afterwards the methods of scaling and standardisation are described. At last, the weight allocation by stakeholders is presented.

4.1. Criteria selection

This section concerns the criteria that are included in the MCA. As stated in the method section, most of the criteria were adapted from Wang et al (2009) and verified through discussion with Lab Vlieland and other stakeholders. The resulting relevant criteria were divided into four categories: technical, economic, environmental and social, and are summarised in Table 4. A short definition of the criteria is given afterwards. Whenever criteria were suggested by one of the stakeholders, an argumentation is supplied as to why it was either included or excluded.

Table 4: Relevant criteria

Technical	Economic	Environmental	Social
- Predictability - Intermittency - In-house knowledge	- Time to commercial realisation	- Land area use - Water area use - Noise	- Social perception - Job creation - Social benefits

Technical criteria

Wang et al. (2009) proposes the technical criterion 'reliability of energy supply'. This criterion measures both the continuity and predictability of the performance of a technology (Beccali, Cellura & Mistretta, 2003). Since these are considered to be separate features and vary depending on the assessed technologies, the criterion was divided into the two criteria predictability and intermittency.

The stakeholder discussions furthermore resulted in the selection of one additional technical criterion, which is the level of in-house knowledge in the Netherlands. The criterion was put forward by Lab Vlieland, since it could influence how likely it is Vlieland would be a potential location for employing a technology.

Predictability:

The predictability of the technologies concerns the extent to which energy output of the technology can be predicted. It is often dependent on a specific resource, e.g. the possibilities of forecasting weather conditions to predict solar irradiance, wind speed or wave heights. Predictable energy generators are considered better substitutes for the well predictable, and even controllable, fossil-based energy generation units that they replace (Weber, 2010). As part of electricity trading is done on a day-ahead basis (APX, nd), predicting generation can furthermore benefit the owner of the technology, i.e. the seller of the energy. Hence, a well predictable technology will be benefit future renewable implementation on Vlieland and is thus included.

Intermittency

Intermittency entails the level of continuity in energy output for a technology. E.g. photovoltaics produce more electricity when solar irradiation is higher, causing fluctuations in electricity output. Although exact matching of energy supply and demand is not a requirement, some consideration was expected regarding the intermittency of a technology[10]. Such consideration should be done since intermittency influences costs and the operation of renewable energy systems (Gowrisankaran et al., 2015). Thus, a highly intermittent is less preferable for future implementation into an energy system than a technology with constant energy output.

Level of in-house knowledge in the Netherlands

This criterion considers to what extent the knowledge in a technological field is indigenous; in this case, occurring in (or in close relation to) the Netherlands. Knowledge can either concern (fundamental) research or the fact that many companies are involved in the field. The reason that location of knowledge can matter, is that a technology may rather be tested close to home when possible. Hence, if much research is done indigenously, Vlieland is ought to be a more attractive testing location than a foreign country.

Economic criterion

An economic criterion proposed by stakeholders was an estimation of the costs for each technology. Cost estimation for a future point in time was however shown to be difficult and remain too hypothetical due to the immaturity of technologies. Also this research did not consider a specific time horizon, complicating the comparison of costs at a certain point in time. Hence, this was reformulated into a related indicator, being expected time to commercial realisation as explained below.

Expected time to commercial realisation

In this research, non-competitive technologies as well as fully developed technologies are considered. According to van Sark et al. (2010), there are several stages in the development of an innovation where the relation between the costs of production and the price of the product variate accordingly. Consequently, technologies that are in a further phase of development are expected to be cheaper and thus closer to commercial realisation. Since Vlieland has the objective to become energy neutral on the short term by deploying renewable technologies, the sooner a technology will become commercially available, the better. Subsequently, expected time to commercial realisation is considered an indicator of economic viability.

Environmental criteria

The environmental criteria adapted from Wang et al. (2009) are land use and noise. Yet, land use was split in land area use and water area, as some technologies are not land-based.

Another proposed environmental criterion was the level of ecological impact. It was not incorporated due to a number of factors: ecological impact is highly dependent on the location of a technology. Thus, an ecological impact assessment would only make sense if actually assessed for one specific location. Moreover, impact studies are elaborate assessments (see e.g. CIEEM, 2016) and not feasible within a reasonable time scale. Finally, some impacts were poorly known for technologies such as wave technologies.

The criterion ‘CO_2 emission’ was also suggested. However, emission reduction is not a primary objective within this research, as it is not part of Vlieland’s definition of energy neutrality. Furthermore, since the MCA concerns renewables, the difference in emissions will be limited in most cases.

Land area usage

Many energy technologies use land in one way or another, affecting among others the human quality of life, ecosystems and animal habitats. This is especially relevant since Vlieland has limited amounts of space

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[10] T. Couzij, project manager Lab Vlieland, personal communication, May 4, 2016.

available and the islanders wish that the environment, flora and fauna, and landscape are affected to a minimum extent.

It should be noted that land area usage can be interpreted in different ways. Most simply, it entails surface area used for the installation itself. Yet, some technologies use up space indirectly by limiting the functionality of a certain area; e.g. solar panels use the surface on which they are installed, but also cast shadows so they cannot be placed directly behind one another. Finally, one could also include land used in processing the energy source, such as electricity cabling or refineries. Which of these definitions is adhered is specified per technology wherever necessary.

Water area usage

Whereas some technologies are implemented on land, others use up space only at sea, either at sea or close to shore. Since water area might be valued different than land use, the use of space in water was a new resulting criterion. Water area usage is still considered as negative, since it might affect aquatic flora and fauna or be a nuisance for shipping routes. Similar to land area usage, it should be noted that some technologies utilise water surface in more ways than merely the surface used for the installation. This is again specified per technology.

Noise

Noise is defined as undesirable sound caused by aerodynamic or mechanical movement. The level of noise is dependent on the technology, plant size and distance from the source (Cavallaro et al., 2005). Only noise during operation was considered and not any sound related to construction or maintenance, as these are temporary nuisances. Noise during operation is a constant nuisance for human and animal inhabitants.

Social criteria

Three criteria adapted from Wang et al. (2009) concerning social factors are social acceptability, job creation and social benefits. Social acceptability was specified to social perception since the acceptability of technologies on Vlieland is mainly determined by the aesthetic value of the technologies.

Social perception

This criterion involves the perception that society, or in this case the local community, has of a certain technology. Social perception can influence the acceptability of a technology and thus influence rates technology implementation. As social perception is hard to quantify, it is rather expressed in a qualitative manner (Cavallaro et al., 2005; Chatzimouratidis & Pilavachi, 2008). Since the inhabitants of Vlieland treasure the island's natural environment, they tend to be cautious regarding the implementation of new technologies (Lab Vlieland, 2015). Hence, the social perception is relevant criterion to consider.

Job creation

This criterion concerns job creation due to the implementation of an energy system, including jobs for the local innovation and development, construction, operation and maintenance (O&M), and decommissioning of the energy technologies. As the economy in Vlieland is dependent on tourism, job creation was interpreted as a benefit (Banning, 2008).

Social benefits

This criterion entails social benefits that result from technology implementation. The criterion expresses social progress that is booked in a region following the introduction or development of an energy project. They could include benefits for local population's social lives, income or tourism attractiveness. This was concluded to be important since both islanders and tourist e.g. valued educational/commercial purposes that a technology could bring (Lab Vlieland, 2015).

4.2. Scaling and standardisation

In this section the scale and standardisation is specified and supported for each criterion. An explanation of the used standardisation methods is given in 0.

Predictability

Predictability of energy generation is best measured on a qualitative scale. Quantifying the time ahead when energy output can be predicted (e.g. on an hourly basis) is highly complex and requires elaborate techniques for every technology (Banos et al., 2011). In addition, this research considers some pilot phase technologies, increasing the difficulty to accurately determine the predictability. Since resource availability is not influenced by technological developments, this criterion is based on the predictability of the resources.

"The resource can be predicted…"	
--	less than a day ahead
-	days ahead
0	weeks ahead
+	months ahead
++	years ahead

The standardisation method that is used is the maximum standardisation. This method is applied when absolute minimum and maximum scores can be given to a scale. This same argumentation goes for every other --/-/0/+/++ scale.

Intermittency

The intermittency of energy supply is commonly evaluated in literature on a qualitative scale (Troldborg et al., 2014). A proposed scale by Tsoutsos et al. (2009) measures intermittency or reliability of energy supply on a scale ranging from (1) highly discontinuous to (5) continuous or stable. The applied scale is based on this scale, but specified to --/-/0/+/++ where:

"The energy output…"	
--	always fluctuates
-	fluctuates daily
0	fluctuates per season only
+	is mostly constant
++	is constant

The standardisation method used is maximisation standardisation.

Level of in-house knowledge in the Netherlands

This criterion evaluates how involved the Netherlands are in a specific technological field. Especially the activeness in development of a technology provides insight into the level of in-house knowledge. Hence, the scaling considers the presence of research institutes (including universities) and companies (for e.g.

production) within a technological field. The scale applied to this criterion was 0/+/++/+++; although in-house knowledge is a benefit, its absence is not necessarily a disadvantage.

"In the production/research of a technology…"	
0	there are no research institutes and/or companies active
+	there are a few research institutes and/or companies active
++	there are many research institutes and/or companies active
+++	the Netherlands is involved in fundamental research

The scores are standardised using maximisation standardisation.

Expected time to commercial realisation

The scale that is applied to assess the expected time to realisation is the technology readiness level (TRL), adapted from Mankins (1995; 2009) and Ruehl & Bull (2012). The TRL assesses the maturity of technologies on several objective characteristics in order to allow for comparison between different options (Mankins, 1995). The phase of development therefore represents how far the technologies are from commercial competitiveness; technologies that scored low are expected to need more time to become competitive, while high scoring technologies are closer to or already competitive.

"The technology is on technology readiness level…"	
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof-of/concept
4	Component and/or breadboard validation in laboratory environment
5	Component and/or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
7	System prototype demonstration in the expected operational environment
8	Actual system completed and "qualified" through test and demonstration
9	Actual system "flight proven" through successful mission operations

The standardised scores for this criterion are assigned using the interval standardisation method, starting from TRL 6. Since all technologies scored above TRL 6, interval standardisation ensured more distinct separation between the scores of each technology.

Land area usage

The total amount of land that is necessary for the generation of one unit of energy differs per technology (Evans et al., 2009). This criterion can be expressed in m^2/kW of installed power (Becalli et al. (2003). However, since power plant capacity does not consider the actual energy production this was considered an inappropriate unit for evaluation. Moreover, since Vlieland aims to become energy neutral and has limited space available the criterion should allow evaluation of the total amount of land needed. Therefore, this criterion was scaled quantitatively to the total amount of land area (in hectare) that is necessary for a technology to cover the whole annual energy demand on Vlieland.

The land usage is derived from the energy production potential per surface area, calculated in Appendix III A-J. In order to allow comparison of technologies that produce different forms of energy (electricity/heat/biofuels), a conversion method was formulated. The comparison method from IEA key world energy statistics is used, where all energy forms are converted to tons of oil equivalent (toe) (IEA, 2015). The energy conversion factor of 1 TWh = 0.086 Mtoe (Million tonnes of oil equivalent) is stated for electricity. For geothermal heat, it is stated to be 1 TWh = (0.086/0.5) Mtoe. For liquid biofuels, the conversion factor is 1 EJ = 22 Mtoe (IEA, 2010). The production converted to m^2/toe is then multiplied by the total energy consumption of Vlieland (in toe) and converted to hectares. For the calculation on the total energy use on Vlieland in toe, see Appendix V.

The maximization standardisation was used for this criterion.

Water area usage

Water area use is defined similarly to the use of space on land. Subsequently, the scale is a ratio scale measured in hectares needed of the technology to cover for the entire energy demand on Vlieland. The standardisation method that was used for this criteria is the maximization standardisation as well.

Noise

Noise can be quantitatively scaled and evaluated in decibel (Wang et al., 2008). However, such a scale does not allow for distinction between more and less disturbing noises due to the location of the technology. Moreover, due to limited deployment of some of the technologies reviewed, such specific data (in terms of exact decibels) are limitedly available in literature. However, as literature has provided good indications of noise levels and how far from inhabitants the technology can be applied, an alternative qualitative scale was resulted using ---/--/-/0.

"The operation of the device produces…"	
---	a lot of noise and close to a populated area
--	a lot of noise but possible in an isolated location
-	little noise but is close to a populated area
0	little noise and possible in an isolated location

The standardisation method used is maximisation standardisation.

Social perception

The scale applied to evaluate the social perception of the technologies is based on Troldborg et al. (2014). In their research a qualitative scale was utilised where (1) indicates strong general resistance and (5) indicates strong general support". As the reason for the resistance against wind turbines was its visual impact (Lab Vlieland, 2015), this scale was specified to how well a technology fits Vlieland's aesthetic value. Respondents were asked to provide their perception of a technology based on a visual indication of each technology [Appendix X]. The respondents indicated their perception on a 1-5 scale where:

"The technology's aesthetics seem…"	
1	completely unfit for Vlieland
2	not really fit for Vlieland
3	a good nor bad fit for Vlieland
4	a good fit for Vlieland

5	a perfect fit for Vlieland

Here, the scores were standardised using a goal standardisation. Any technology that is perceived as unfit by the public will be considered insufficient for social acceptability. Hence, the goal is a score >3 and any score below this value is assigned a minimum score. The maximum score is the highest possible score of 5.

Job creation

Job creation is commonly expressed in jobs per unit of power installed (Chatzimouratidis & Pilavachi, 2008). However, exact determination of the amount of jobs proved difficult for underdeveloped technologies and is dependent on the amount and size of installations. Hence, a scale based on Wei et al. (2010) is used, which considers the frequency of potential job creation: never or temporarily (construction or decommissioning), occasionally (maintenance), continuously during operation and continuously even beyond operation (in fuel extraction and processing). Hence, the scale is given as 0/+/++/+++, where:

"The technology creates jobs…"	
0	never, or only during construction/decommissioning
+	occasionally, in maintenance
++	continuously, in maintenance and operation
+++	continuously, in maintenance, operation and processing

The standardising is done using maximisation standardisation.

Social benefits

The addition of social benefits is considered to be a qualitative characteristic which cannot be expressed as a measurable figure (Mourmouris & Potolias, 2013). Therefore, the possibilities were assessed and evaluated on the following 0/+/++/+++ scale:

"The technology has the potential to provide..."	
0	no additional social benefits
+	a small additional benefit (to be specified)
++	either commercial/touristic/educational benefits
+++	commercial, touristic and educational benefits

For this criterion is also the maximisation standardisation method used.

4.3. Weight allocation

The following section includes the weighting factors for the criteria, as determined by the stakeholder groups; Lab Vlieland, policy makers, Vlieland 2020 group and relevant experts. The weighting factors for each group is shown in Table 5 and the resulting average is graphically represented in Figure 5. The individual weight allocation from the stakeholders can be found in Appendix VII.

Table 5: Group weightings

	Lab Vlieland	Policy makers	Vlieland 2020 group	Relevant experts
Predictability	8.9	8.3	10	13.6
Intermittency	8.5	20.0	15	20.0
In-house knowledge	7.7	3.3	2.5	7.3
Expected time to commercial realisation	8.6	6.7	5	10.8
Land area use	13.9	5.0	10	11.8
Water area use	6.8	5.0	2.5	4.6
Noise	8.9	15.0	7.5	7.6
Social perception	9.1	18.3	30	12.8
Job creation	15.3	8.3	15	3.3
Social benefits	12.2	10.0	2.5	8.2

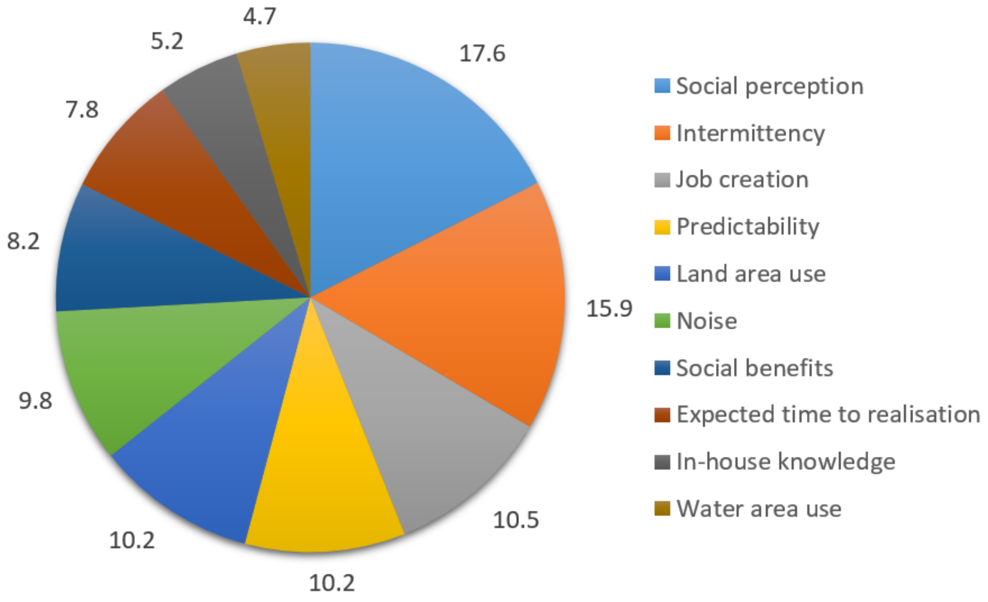

Figure 5: Pie chart showing relevant criteria and their weighting (%)

Chapter 5: Assign scores

5. Assign scores

This chapter argues how each technology scores on the relevant criteria. The results provide an answer on the third sub question "how do the technologies score on the relevant criteria?" and are presented in Table 6. The argumentation of technology scoring per criterion is supplied in the following section.

Table 6: Scores of technologies on the relevant criteria

	Solar PV	Wave OWC	Wave OB	Wave overtop-ping	Tidal Range	Tidal current	Macroalgae	Microalgae	Geothermal direct heating	GHP	Unconventional wind
Predictability	-	-	-	-	++	++	++	++	++	++	-
Intermittency	--	--	-	--	-	-	++	++	++	++	--
In-house knowledge	++	0	+	0	+++	+++	+	+	++	++	+
Time to commercial realisation	9	7	7	6	9	8	6	6	9	9	7
Land area use (ha)	16.3 ***	0	0	0	0	0	0	65.1 **	0.01 *	70.0 *	12.8 *
Water area use (ha)	0	4.6*	1.2 *	11.4 **	682.3 ***	22.9 ***	712.6 **	0	0	0	0
Noise	0	--	--	--	---	0	-	-	-	-	-
Social perception	4.21	2.56	3.65	2.68	2.47	3.18	3.47	3.24	2.85	3.71	2.65
Job Creation	++	++	++	++	++	++	+++	+++	++	+	++
Social benefits	0	0	0	++	+++	0	++	0	0	0	0

* Merely considers the area use by installations; excluding the space required in between installations or any subsurface area usage

** Merely accounts for agricultural surface needs; surface needs for processing in a refinery is excluded

*** Accounts for total direct and indirect area usage by the technology

Predictability

Solar resource forecasting is not yet very mature. Even though the course of the sun through the sky is known, other factors such as cloud coverage are unpredictable (NREL, nd-b). The yield of solar PV technologies is therefore only predictable on a daily basis, about one day in advance. So solar PV was given a '-'.

Wave conditions vary every day and are predictable only on a day ahead basis, where the forecast gets less accurate as the time horizon increases (Chozas et al., 2013). Therefore the wave OWC, OB and overtopping devices all were rated a '-'.

The tidal range and the tidal current are predictable up to years ahead (Iyer et al., 2013; NREL, 2012). Both these technologies therefore scored a '++'.

The biofuels made from algae can easily be stored and be deployed whenever necessary; the predictability of biofuels is thus high (An et al., 2011). Moreover, the algae can be harvested in batches year around, which replenishes the stock continuously (Schenk et al, 2008). This predictability (for macro- and microalgae) were therefore scored with a '++'.

Geothermal energy for direct heating applications is very predictable, since the heat comes from the centre of the earth where chemicals decay in a constant rate (Twidell & Weir, 2015). The amount of energy that can be generated is therefore predictable and was rated a '++'.

The temperature of the subsurface that is tapped into with geothermal heat pumps is not subject to seasonal variations and is therefore very predictable (Twidell & Weir, 2015). Therefore, this technology was thus rated a '++'.

Wind is an unpredictable resource. Predictions are only fairly accurate on a day ahead basis (Chozas et al., 2013). Therefore unconventional wind was given a '-'.

Intermittency

Solar PV output is highly intermittent since it fluctuates between day and night and is influenced by e.g. cloud cover (NREL, nd-b). Hence, it not only fluctuates daily but energy output varies constantly. The score is thus '--'.

Energy output of wave energy converters is dependent on wave motion, which correlates strongly with variations in wind speed. Wave power output is therefore constantly intermittent (Chozas et al., 2013). The scores for wave OWC and overtopping were therefore allocated a '--'. Wave OB technology is an exception, since power output can be smoothed through the use of gas accumulators or the use of multiple moving parts. Hence, power output is smoother than in other wave technologies, but still fluctuates daily and per season (Kramer, 2006). The received score was thus '-'.

The tides come in and go out twice per day, resulting in a constantly changing tidal current speed throughout the day. Furthermore, the water height at absolute low and high tide is also dependent on the position of the moon, resulting in variating water heights per tidal cycle (Freris & Infield, 2008). The produced output thus gradually changes on a daily basis. Both tidal categories therefore received a '-'.

Intermittency is not an issue for biomass technologies, since the option to store the energy is present (An et al., 2011) and energy output can be controlled to wish. Both algae technologies are therefore scored a '++'.

The earth's heat is generated at a constant rate and can be extracted at a similarly constant rate (Twidell & Weir, 2015). Geothermal direct heating and geothermal heat pumps, which both make use of this heat, were thus given a '++'.

The output of a single wind turbine is variable (NREL, nd-b). Variations in wind speed within minutes, i.e. turbulence, affect the output that wind power technologies deliver (Albadi & El-Saadany, 2011). The score for this category was therefore a '--'.

Level of in-house knowledge in the Netherlands

Solar energy is considered a 'top consortium' by the Dutch government. Many companies and multiple universities in the Netherlands are combining their knowledge and creating value for the Dutch economy (TKI Solar Energy, 2014). However, the Netherlands is not specifically a leading country in the field. Solar PV therefore was ranked a '++'.

OWC and overtopping devices have not yet been deployed within the Netherlands (Nelson & Starcher, 2015) and have not been the focus of much research. They were therefore allocated a '0'.

Wave OB devices however have received some attention by universities, such as the research and development of the Archimedes Wave Swing (TU Delft, nd-b). It therefore scored a '+'.

Several Dutch institutions are involved in the development and deployment of tidal range power (Topsector water, 2015). Moreover, Pro-Tide is currently constructing a tidal range power testing centre at the Grevelingendam. This tidal centre will test (ultra-) low head tidal range power turbines (Pro-Tide, nd). Due to Vlieland's low head (Hanssen et al., 2014), similar turbines will have to be deployed on Vlieland; therefore, tidal range was ranked '+++'.

Tidal current has been developed on a larger scale already and companies and universities are working together on developing tidal current installations on the Oosterschelde and Afsluitdijk (Tocardo, 2015; TU Delft, nd-c). Furthermore, a Dutch company employed world's first grid-connected tidal current device (van Hoeken, 2016), so the score was determined to be a '+++'.

While seaweed is cultivated all over the world for food and other products, seaweed production for energetic purposes in the Netherlands is in the test phase. Research institutes, public bodies and companies are developing a seaweed farm in the North Sea (Noordzeeboerderij, nd). It was given a '+'.

The same counts for microalgae, where Wageningen University is testing and developing strains and photo-bioreactors (AlgaePARC, 2015). Microalgae thus also scored '+'.

Multiple universities research geothermal heating and an NGO platform has been created with support of the Dutch government (Verhagen, 2011). Therefore, it was rated a '++'.

Geothermal heat pumps are not researched extensively, but are produced in the Netherlands (Kleefkens, 2014). Therefore, the technology scored '++'.

Unconventional wind power is a field of research that has received some attention. Even though not much power is generated by unconventional wind turbines in the Netherlands, Dutch universities are developing new concepts and exploring new designs (TU Delft, nd-d; Terschler, 2012). Therefore it was rated a '+'.

Expected time to commercial realisation

Photovoltaic solar cells are a proven concept that are currently installed on a wide range of locations (Dincer, 2011). The technology was therefore determined to be in technology readiness level (TRL) 9.

Wave energy technologies are currently in different phases of development, due to the large amount of projects that are simultaneously being executed. According to SI Ocean (2012), OWC is in TRL 7. The OB installation Pelamis has been tested for long periods of time in both Portugal and Scotland (Falcão, 2010). SI Ocean (2012) classifies the device in TRL 7. The Wave Dragon, an overtopping device, has been tested on a 1:4 scale for several years in open sea (Tedd & Kofoed, 2009). Since small scale testing belongs to TRL 6, overtopping was assigned to TRL 6.

There are currently several commercially operating tidal range installations around the world (Rourke et al, 2010). The TRL for this technology was therefore given in TRL 9.

Around the world there are several tidal current projects in operation, one of which is in the Netherlands (Bluewater, 2016). All of these installations are in the test phase on full scale (IRENA, 2014a). This is typical for TRL 8 and so it was classified in this readiness level.

Production of biofuels from both microalgae and macroalgae is currently in the development phase (EC-JRC, 2011). According to de Visser (2015) it will take at least 10 to 15 years before they are suitable as bulk material for biofuels. Biofuel production was therefore estimated at TRL 6.

Geothermal heat pumps and direct application of geothermal heat are mature practices and have been applied on a broad scale worldwide (Lund et al., 2005). Both technologies are at TRL 9.

There are multiple different kinds of unconventional wind turbines, which are in different stages of development (Manwell et al., 2010). However, the technology that was under review in this study, the INVELOX, is in the testing phase at full scale (Allaei et al., 2015). This technology is thus at TRL 7.

Land area use

First of all, the wave and tidal energy technologies are located at sea and therefore have no land usage. Macroalgae are also cultivated at sea. These technologies therefore all scored 0 ha. The land use of the bio refinery needed for processing both the macro- and microalgae is neglected in this research. Underlying information and calculations regarding the land use can be found in Appendix III A-J.

Solar PV in a solar field uses land directly. Yet, due to array spacing to avoid shadows, the land surface for a solar field is larger than just the area of the PV modules. The land use of a ground based solar field system is estimated at 215 kWh/m^2/y. This corresponds to 5.4 m^2/toe/y using the conversion method described in Appendix V. Thus, 14.8 ha of solar PV is necessary to account for Vlieland's yearly energy consumption.

The yield of microalgae on land is 210 MJ/m^2/y of biodiesel (Mata et al., 2010). This corresponds to 21.6 m2/toe/y. The total amount of land that is necessary then becomes 65.1 ha of microalgae cultivation area. Only the land needed for cultivation is considered, excluding the surface space needed for the refinery.

Geothermal direct heating would extract all necessary heating for Vlieland from one single well system, which is covered by an installation of about 100 m^2 (derived from Platform Geothermie, nd). The needed subsurface area does not hamper usability of land area and can be deployed for other purposes; hence, this is excluded in the land use.

Geothermal heat pumps produce 50 kWh/m^2 heat, according to Twidell & Weir (2015), which equals 11.6 m^2/toe/y. Consequently, 70.0 ha is required to fulfill the entire energy demand. Similar to geothermal direct heating, the subsurface area use is not included in this area.

The unconventional wind turbine INVELOX on land produces 272.7 kWh/m^2/y. This corresponds to 4.26 m^2/toe/y and the entire energy demands would require 12.8 ha of land. This merely considers the space needed for the installation and does not account for the land area needed between to installations since this surface area can be deployed for other purposes.

Water area use

The land based technologies are Solar PV, microalgae, geothermal direct heating, heat pumps and unconventional wind; These technologies do not use any space in the surrounding waters of Vlieland and thus all score 0 ha. Calculations on which the water area use for the remaining technologies is based, can be found in Appendix III A-J.

A 500 kW wave OWC installation takes up 1154 m^2 (i.e. 0.12 ha; Lee, 2014). The annual power output of such a device on Vlieland is 759 kWh/m^2/y/. The output per water area is then 1.5 m^2/toe/y, leading to 4.6 ha required for fulfilling the whole energy demand. However, the estimated surface water area does not include any area needed between the multiple installations.

The Pelamis oscillating body installation is 0.049 ha big and is likely to produce 1,314 MWh on an annual basis on Vlieland. The production of this device will thus be 0.4 m^2/toe/y, which leads to a required 1.3 ha to fulfil the whole demand. Similar to OWC, this area merely accounts for the direct water surface usage.

The overtopping device called the Wave Dragon takes up 3.9 ha of space and is able to generate 12 GWh/y, which comes down to 3.8 m^2/toe/y. The total water area needed to produce all of Vlieland's energy, excluding the water surface area needed in between the devices, then adds up to 11.4 ha.

A tidal range power generation station could generate up to 51.3 GWh/y, covering 10 km^2 (i.e. 1000 ha) in water area. The total power output of this system is thus 226 m^2/toe/y, which requires a total area of 682.3 ha. Although the basin in a tidal range area can possibly be deployed for other functions, such as agriculture and recreational activities, this area is considered as water usage since alternative options for deployment are limited due to severe restrictions.

A tidal current installation of 20,000 m^2 near Vlieland of 100 kW capacity will produce 153 kWh/m^2/y, which leads to a water area use of 7.6 m^2/toe/y. The total necessary water area then becomes 22.9 ha, including the space needed in between turbine placement.

For the cultivation of macroalgae, the annual yield is around 19.2 MJ/m^2/y. This is equivalent to 236 m^2/toe/y. The total area required for cultivation of the macroalgae then becomes 712.6 ha, excluding the area needed for the placement of a biofuel refinery.

Noise

Solar PV panels do not make any noise, as they contain no moving parts. Furthermore, they can be installed far from inhabitants, as e.g. shown in the solar field on Vlieland. Hence, they received a '0'.

For wave technologies, little data are available on noise levels in real sea conditions (Patricio et al., 2014). Especially underwater noise, potentially harming animals, is hard to determine. However, noise is expected to be produced by moving parts, turbines, flows and/or friction (Patricio, 2012). Yet, since most wave devices are placed away from the coast, all three types received a '--'.

For tidal range installations, it is expected that that the turbines produce continuous tones (Martin et al., 2012). Since tidal range technologies are placed attached to the coastline, it scored a '---'.

Furthermore, tidal current technologies are expected to produce low levels of noise due to low operation speeds (Fraenkel, 2006). Moreover, they are generally located away from shore, so the allocated score is '0'.

For both types of algae, the extraction of algae and the operation in a bio refinery is likely to only cause some limited noise for workers or people within a small radius (as DOE (2011) shows for a bio refinery in the US). The bio refinery for microalgae would however be on land and the one for macroalgae on the shore, so they are likely to be close to habitation. Also, continuous biomass transportation is needed, which may lead to some nuisances. The technologies were rated a '-'.

The noise during operation of a geothermal plant is very limited, and only a nuisance when inside or right beside the plant (Lund, 2007). However, the geothermal direct heating plant is based on land and can be close to inhabitants. Consequently, the score '-' was given.

Although geothermal heat pumps are installed directly near a house, their noise levels (on a 5m distance) are on the same level as a normal conversation (MasterTherm, 2016) and thus not a large nuisance. It therefore scored '-'.

The unconventional wind turbine INVELOX claims to produce very low noise levels (Sheerwind, 2016a), even though no testing data are available. Yet, the technology uses a moving turbine, which thus has the potential to produce some noise. It therefore scored a '-'.

Social perception

The social perception was measured by a public survey amongst the residents of Vlieland, of which 34 respondents participated. Figure 6 summarizes the results on this survey for each technology. The survey questions, background information and additional comments are given in Appendix XI. The score behind each bar indicates the average score, which is the input score for the MCA.

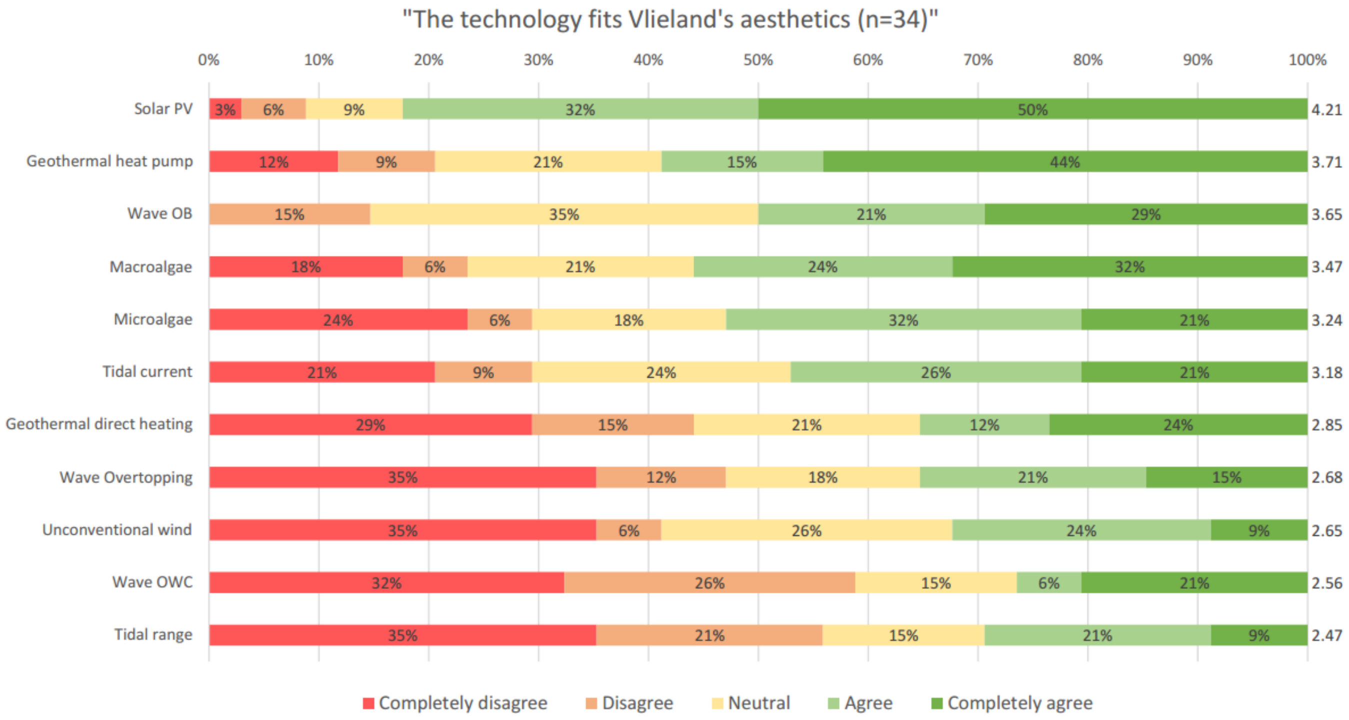

Figure 6: Social perception survey results

Job creation

Both the placement of solar PV panels on rooftops and the construction of solar fields require jobs during installation and O&M (Wei et al., 2010). Consequently, PV job creation received '++'.

Wave farms and tidal farms will create jobs during construction, O&M and for onshore needs; however, farm monitoring and therefore processing does not require any permanent jobs (Bahaj & Battan, 2007; Soerensen & Weinstein, 2008). Therefore, all the wave and tidal energy technologies were given '++' for job creation.

Biomass cultivation for energy production creates jobs during installation, O&M, and extraction and fuel processing (Wei et al., 2010); subsequently both micro- and macroalgae were rated with '+++'.

Only the installation and O&M of a geothermal direct heating system requires jobs (Wei et al., 2010). Therefore, it was scored with '++'.

Geothermal heat pump deployment creates jobs merely during installation as O&M does not require structural jobs (Ragwitz et al., 2009), so it was rated with '+'.

As the operating system for an unconventional wind turbine is similar to a conventional wind turbine (Sheerwind, 2016b), it is assumed that the effect on job creation is also similar. Since Wei et al. (2010) state that wind power creates jobs during installation and for O&M, unconventional wind was scored with '++' as well.

Social benefits

Solar PV was not found to have any additional social benefits and was scored a '0'. Similarly, geothermal heat pumps and geothermal direct heating were allocated the same score of '0'. Though they are new and innovative, the wave technologies OB and OWC, tidal current, unconventional wind and microalgae were not found to create additional benefits for Vlieland as well, since no examples or projections were found in literature.

Macroalgae do have additional social values. Several food products are already produced (Reith et al, 2009). Furthermore, the multi-functionality of energy production with food production and shellfish and fisheries provide additional social benefits (Noordzeeboerderij, nd.). It thus scored a ‘++’.

Overtopping devices have the opportunity of combining the device with aquafarming (Bevilacqua & Zannutigh, 2011). The spread of the device causes calm wave conditions behind the device. Here, fish or seaweeds can be cultivated, so this technology scored a ‘++’.

Tidal range was given a score of ‘+++’ as it has the ability to provide commercial, touristic and educational benefits. Commercial and touristic benefits may include combining the tidal lagoon with sporting and recreational activities. Besides, the tidal lagoon could be created in combination with an agricultural farm and combined with educational programs at all levels (Tidal Lagoon Swansea Bay, nd).

Chapter 6: MCA results


Jan Visser ©

6.1. Final ranking
6.2. Scenario analysis
6.3. Uncertainty analysis
6.4. Sensitivity analysis

6. MCA results

This chapter sets forth of the results of the performed MCA. Note that the MCA input consisted of the inputs found in chapter 3 through 5. First, the final ranking is set forth. Subsequently, the robustness of these results is assessed in a scenario, an uncertainty and a sensitivity analysis respectively.

6.1. Final ranking

Adding all the standardized scores and considering the weights, the final ranking of the MCA was calculated, as shown in Figure 9. The figure stacks the scores per criterion to produce the final overall score. The best suitable technology therefore has the highest stacked score, whereas the least suitable technology achieved the lowest overall score.

Firstly, the figure indicates that geothermal direct heating has the highest overall score. The very closely second ranked technology is macroalgae, followed by a shared third place for geothermal heat pumps and tidal current. Compared to the other technologies, the success of these technologies is greatly attributable to the criteria predictability and intermittency.

Solar PV, tidal range and microalgae follow with reasonably high scores as well. Compared to the top four, solar PV especially lacks due to a low score on intermittency and predictability. Especially social perception and noise are beneficial factors for PV. Tidal range also receives a decent score, but lags on social perception and intermittency. Microalgae does score high on intermittency, but scores especially low on land area use.

Furthermore, it can be recognised that OB, unconventional wind, overtopping and OWC are the least suitable alternatives for Vlieland. These technologies score particularly low on social perception, intermittency and predictability.

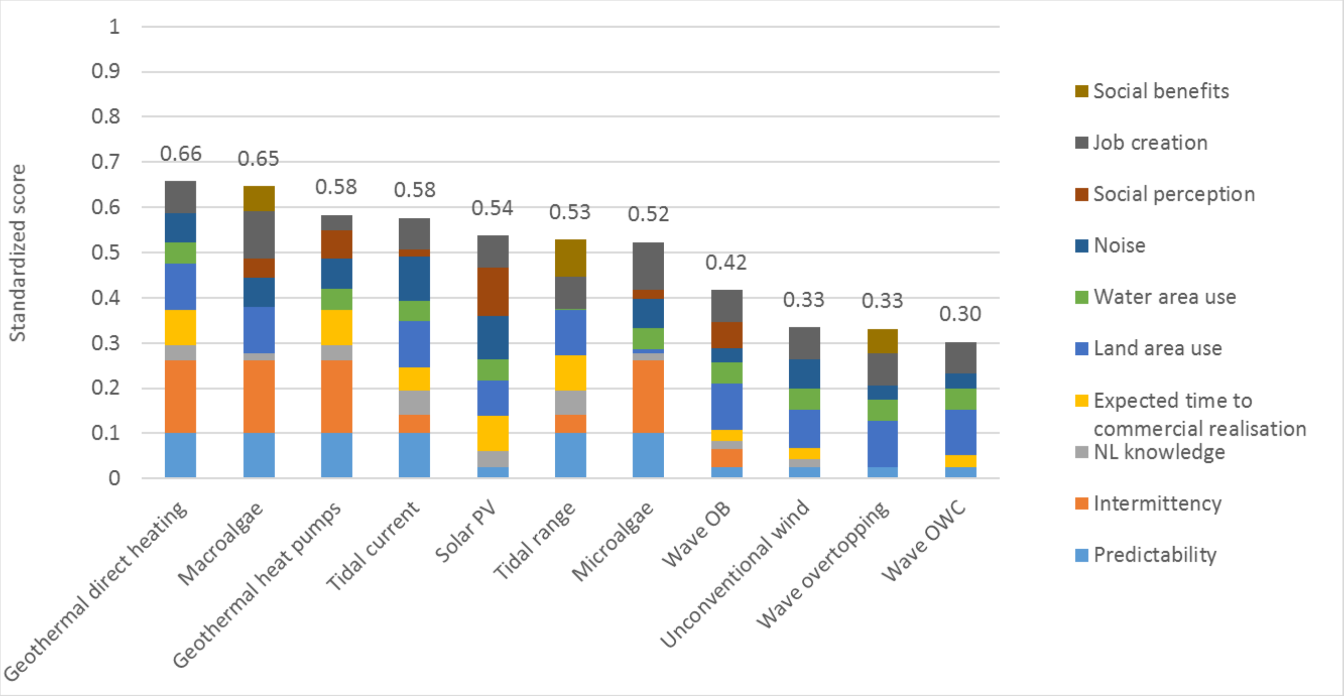

Figure 7: Final Technology Ranking

6.2. Scenario analysis

To enable comparison between different stakeholder groups, the MCA was performed using only the weightings given by individual stakeholder groups. The results can be found in Figure 10.

Considering the weights given by Lab Vlieland, geothermal direct heating is still the highest ranking technology. However, notably tidal current, solar PV and tidal range have overtaken geothermal heat pumps as a more suitable option. Geothermal heat pumps and microalgae scored similarly. These changes are caused by a decreased weight allocation to technical criteria and improved importance of economic and environmental criteria.

The Vlieland 2020 group weighting results in a very similar ranking as was found with the average. Apart from macroalgae taking the highest ranking position, the ranking did not change. Furthermore, the margins between technologies have changed very slightly, especially at the lower regions of the ranking.

In the ranking for the policy makers, it can be noted that social perception has gained importance in the ranking, causing solar PV to move up significantly. Macroalgae has risen to the highest rank. Tidal current and tidal range have dropped a few places, while microalgae has moved two places up in the ranking.

For the weighting of the experts, not many changes can be recognised. Only solar PV drops two places and is overtaken by tidal current and tidal range in the process. Yet, the top four all score quite similar to the average ranking.

In conclusion, the ranking does not change significantly considering the different viewpoints. The two highest scoring technologies, geothermal direct heating and macroalgae, remain first and second. OWC, OB, overtopping and unconventional wind remain the four lowest performing technologies in all scenarios. In the middle range of ranks, a shift of technologies ranking can be seen since their scores lie close together.

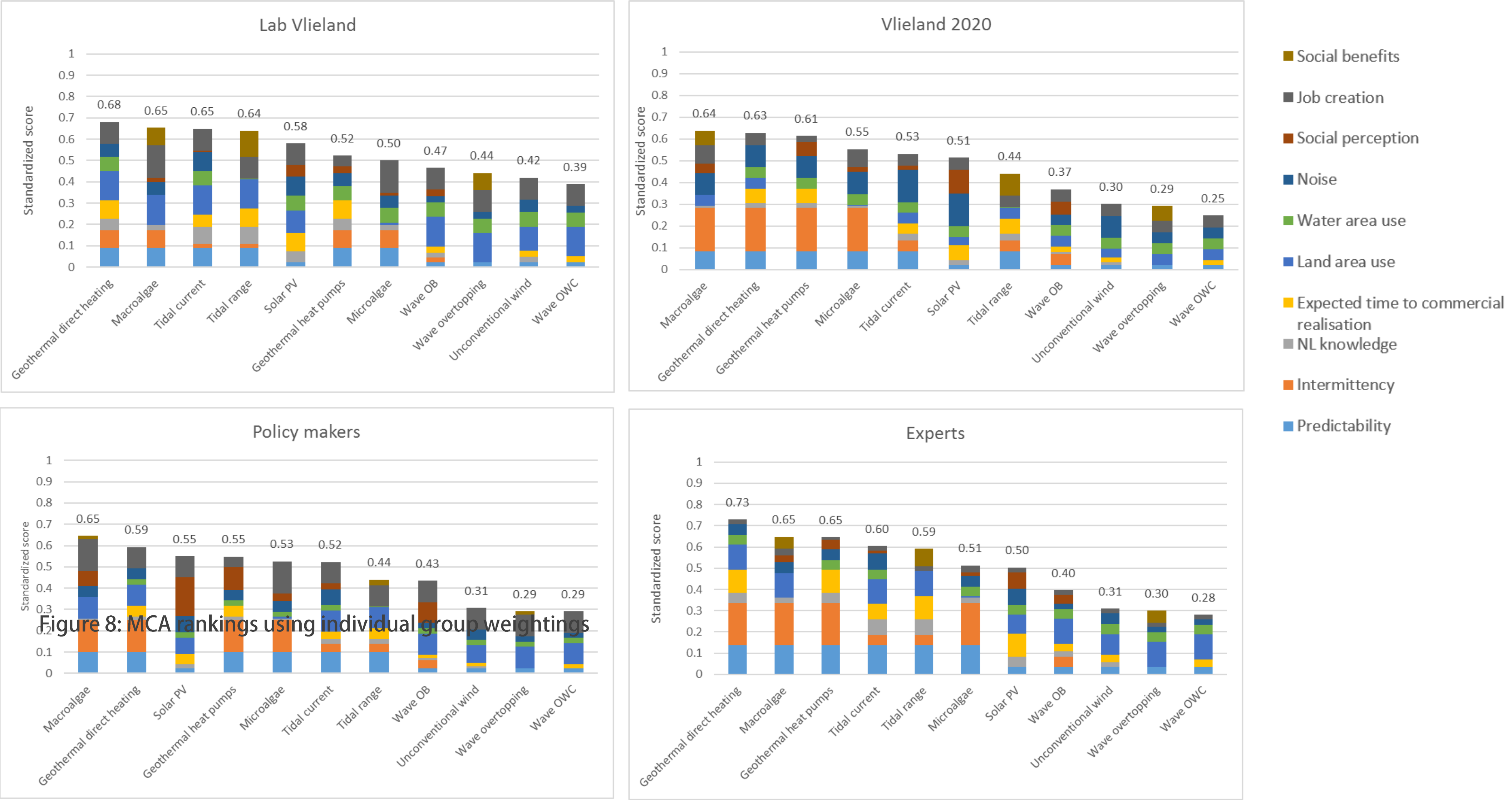

Figure 8: MCA rankings using individual group weightings

6.3. Uncertainty analysis

A level of uncertainty is argued for the scores and the weighting factors. The uncertainty levels can be found in Appendix IX. The following section will outline how these were determined.

According to Janssen & Munda (1999), ordinal data have a low information level and therefore a high certainty level. Subsequently, predictability, intermittency, level of in-house knowledge in the Netherlands, noise, job creation and social benefits were assigned a score uncertainty of 10% in the uncertainty analysis. Expected time to commercial realisation is an exception since the information on the technology readiness level (TRL) of the different technologies was not always recent; this makes undocumented technological advances into the next TRL possible. The uncertainty was therefore assigned to be 30%. The scores on land and water use were based on calculations that were not site specific for Vlieland. Deviations from these values were thus expected and an uncertainty of 30% was assigned. Finally, due to small sample size in the survey on social perception, also high uncertainty was assumed in for this criterion. Therefore 30% uncertainty was assigned.

Figure 11 shows what the probability is that the technology gets a certain ranking, incorporating the stated uncertainties. The total score indicates a weight sum of the probabilities, where the technologies that receives the highest score is most likely to end up on a high ranking. Geothermal direct heating has the highest probability to be ranked first. Although unlikely, variations of scores and weights exist where macroalgae, GHP, tidal current, solar PV and tidal range could rank first as well. The latter is indicated by the presence of a small bubble on rank one for these technologies.

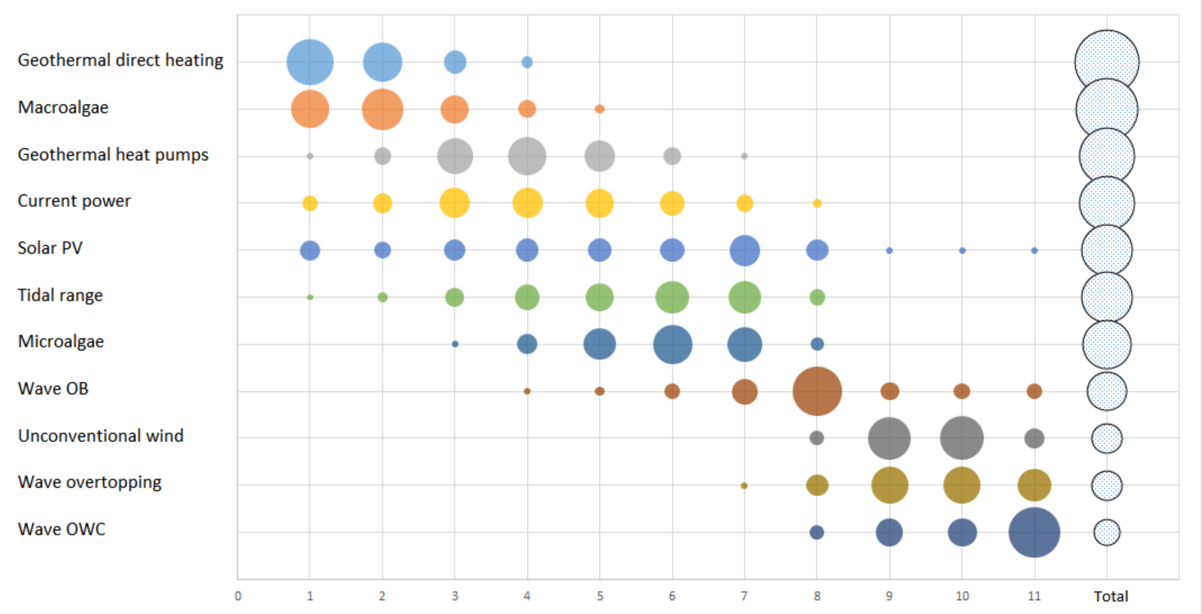

Figure 9: Probability chart of final technology ranking

Note that the size of the bubbles represents the probability that a technology achieves a certain ranking. The final column indicates overall ranking.

6.4. Sensitivity analysis

The results of this sensitivity analysis are depicted in the form of graphs, where the allocated weight to a certain criterion is plotted on the x-axis against the final score per technology [Appendix XIV]. Figure 12 shows such a graph for the criterion intermittency. An intersect between two lines indicates that two technologies swap in rank.

The relative sensitivity of the criteria can be determined by comparing the average absolute slopes of all the lines in the graph of each criterion. This comparison determined that water area use is the most sensitive to the shift in weights (0.56[11]), followed by land area use (0.54), while level of in-house knowledge in the Netherlands (0.23) and noise (0.21) are the least sensitive criteria. However, this number only says something about the final score of the technologies rather than about how the ranks of technologies change relative to one another.

For the criterion predictability, the final ranking was relatively insensitive to changes in weight. Only solar PV varies between rank three and rank six, ranking lower with increased weight; all other rankings are independent of weight variation.

For all other criteria, multiple shifts in ranking occurred. An example of this is visible in Figure 11. for intermittency. When the weight is decreased by 5%, only the two highest and three lowest technologies remain on the same rank.

The highest ranking option changes from geothermal direct heating to macroalgae whenever the weight allocation is decreased for the criteria water area use, expected time to commercial realisation or in-house knowledge, and increased for social perception, social benefits or job creation. When the weight of social perception e.g. is increased by only 5% of the original weight, macroalgae production overtakes geothermal direct heating. For water area usage, this already happens if the weight is decreased by 1%. Hence, the first rank is sensitive to a shift in weight allocation. However, for the criteria noise and intermittency, a large shift of weight has to occur for the geothermal direct heating to lose the highest rank to macroalgae.

This analysis shows that the outcome of the MCA is sensitive to changes in weights for all criteria except predictability. Also, the highest scoring technology is sensitive to the weight allocation. Consequently, this means that geothermal direct heating is not always considered to be the most suitable renewable energy technology for Vlieland but is subject to the weight allocated to the criteria.

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[11] Average (absolute) shift in final score when the weight for this criterion varies between 0 to 100%.

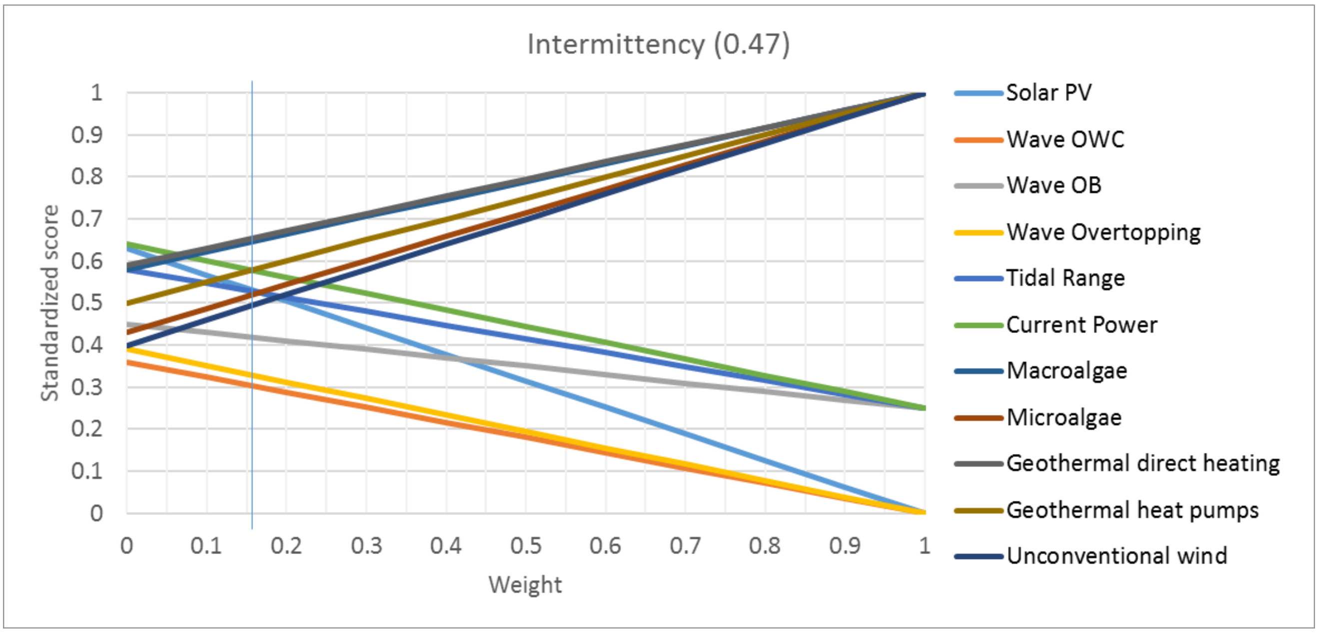

Figure 10: Sensitivity analysis for intermittency criterion

NOTE: The vertical blue line indicates the original weight. E.g. geothermal direct heating remains on the highest rank, unless the weight of this criterion shifts below 0.05, where tidal current takes over.

Chapter 7: Discussion

7. Discussion

This chapter describes the quality and limitations of the research, as well as the theoretical implications.

7.1. Data quality and research limitations

The results of the research come with certain limitations and implications. Firstly, the implications of the research regarding energy neutrality are described. Then, more specific remarks are set forth on the reliability of criteria selection, scaling and scoring as well as on the outputs of the MCA.

Energy neutrality

First of all, a main side note to the research lies in the ultimate problem it aims to solve, namely making Vlieland an energy neutral island through the implementation of renewables. Achieving an energy neutral island is more complicated than merely generating renewable energy. Rather, both consumption and production are to be considered; i.e. a system integrated approach is essential in a successful sustainable energy system according to professor Ad van Wijk [Appendix XIII]. Subsequently, the ranking cannot be interpreted as a single best solution for reaching energy neutrality and should therefore not be considered as such. However, the consideration of merely energy producing technologies in this research does provide valuable output. The drafted shortlist of renewables that meet the criteria availability on and feasibility for Vlieland form a first screening for implementation of a renewable energy system.

Another limitation lies in the objective as it was assumed that energy generation on the island could exist in any form, either fuel, heat or electricity. This would entail that all energy generated on the island could be in one single form; e.g. all energy consumption is compensated by biofuel production. However, this may not be the ultimate solution since fuel use on the island is very limited. Most produced biofuel would then have to be exported[12] whereas the electricity and heat demand are still to be fulfilled through imports. Another issue could arise if all energy generation would entail heat production, as heat is not an exportable form of energy due to the distance to the mainland. It would thus be preferable if the energy produced on Vlieland matches the form of energy demand. The results imply that this is in fact possible by combining technologies to produce energy in different forms. Hence, the research poses a foundation for the production side of system integrated research.

Criteria selection and weighting

The criteria were selected in an iterative process where literature was consulted and the perspective of the client and stakeholders were considered. This provided a reliable selection process for including as many relevant criteria as possible. Moreover, this process composed a set of criteria that were in agreement with the four stakeholder groups. It therefore acts as a general set of criteria that are important for Vlieland and can be considered in future research as well.

The weighting of the criteria has significant influence on the results of the MCA. The stakeholder response was ample and personal communication was conducted with almost all intended stakeholders. Hence, the weighting factors were assumed to give a reliable indication of the perspective of different stakeholders on the island. It should be noted however that each stakeholder group consisted of only a few respondents, which limited the possibility to make any generalised comments on the view of a whole group.

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[12] Fuel demand only consists of fuel use by the ferry service and some on-land transport, and biofuel is currently used in a mix with fossil fuels (Hansen et al., 2014). Moreover, the fuel for the ferry service is not included in the energy neutrality target.

Of all criteria, social perception was allocated the highest weight. Hence, the social aspect of a technology was included as an important input of the MCA. Including this in an evaluation of suitable technologies poses a valuable implication of the research, as it ensures inclusion of the islanders' opinion from the start.

Furthermore, it appeared that the stakeholders weighed intermittency relatively heavily. One could doubt whether it indeed weighs so heavily over other factors since highly intermittent technologies have also been proven to be widely applicable (such as wind and solar PV). Moreover, intermittency is a drawback that can be limited by designing an energy system in an effective way. Considering this, high intermittency is not per definition a drawback of an individual technology as is assumed.

Scaling and scoring

A less reliable input concerns the scaling applied in the MCA. Although criteria are preferred on a quantified scale, such specifics were not available in many cases (e.g. noise level in dB). Hence, most criteria were scaled qualitatively using pluses and minuses. The separation between scores was thus less distinct. E.g. job creation considered merely the jobs created per phase (installation, O&M and fuel extraction/processing), not an absolute amount of jobs. Similarly, the criterion 'expected time to commercial realisation' lacked some accuracy. After trying to apprehend a ratio scale (in 'years') for expected time to commercial realisation, this proved infeasible. Then a scale using only four phases of development was attempted but this left little separation between stages of technological development. Hence, the nine stages of technology readiness level (TRL) seemed the best alternative scale.

The only quantified criteria were land and water area use. However, these calculations entailed many assumptions, affecting the reliability of the inputs. For example, some technologies included consideration of the installation position (e.g. shadow effects for solar PV), whereas this was not included for others. Hence, these inputs are to be interpreted as estimations. Consequently, the actual values may differ significantly.

The criterion social perception was scaled from 1 to 5 and scored using a survey. The scale used supplied ample differentiation between personal opinions. However, the survey that was conducted had 34 respondents. Considering the population of over 1,100 inhabitants, the survey results cannot unreservedly be generalised to the islanders. Consequently, the survey may present a biased view of the technologies assessed. Also, some of the surveys were conducted with two people simultaneously; the impression was raised that the respondents influenced each other's opinion in one way or another. Finally, the choice of pictures shown and descriptions given with each technology may have influenced the surveys outcome. All these influences may undermine the reliability of the survey results.

Overall, the data quality was adequate, due to the presence of ample academic literature which allowed for cross-checking between sources. The only exception here concerns the INVELOX since all relevant literature here could directly be linked to the company developing the device. For the other technologies the available literature posed a reliable data source for the scaling and scoring process. Yet, sometimes specific data were hard to acquire and argumentations were given based on the best available literature. Moreover, for some purposes more generalised data were used, e.g. in determining the potential energy production on Vlieland due to a lack of location specific data.

MCA output

The MCA output comes with a certain level of reliability. The scenario, uncertainty and sensitivity analysis were used as tools to analyse how certain the results actually are.

The scenario analysis showed that the ranking outcome was relatively insensitive to the weighting of different stakeholder groups. Geothermal heating and macroalgae remained the two most suitable options in all scenarios. Similarly, the four least suitable options were the same four in all scenarios. Yet, it was shown that tidal current and tidal range power have the potential to move up in ranking if land use area is weighted heavier, which resulted in solar PV to descent a few ranks.

On the contrary, the sensitivity analysis suggested that the ranking is sensitive to changes in weight. For most criteria, the ranking changed significantly with changing weights. However, the ranking generally changed significantly at weights of 30-50%. Such high weights were not assigned to any of the criteria and can be considered exceptional. Hence, within reasonable weight variation, the ranking is presumed to be reliable.

The uncertainty analysis further showed that when uncertainties in both the weight and the scores are taken into account, the ranking remains relatively constant. Although technologies tended to move up one or two places in ranking, there was a general trend visible of high ranking and low ranking technologies. Especially for geothermal direct heating, macroalgae, unconventional wind, wave overtopping and wave OWC, the place in the ranking is relatively reliable. However, the rank of solar PV, tidal current, tidal range and wave OB, however, are more susceptible to uncertainty, as there is high probability that they end up on a variety of ranks. It can thus be concluded that the ranking results are reliable. Although variations do occur between rankings, the analyses show a general trend of suitable and less suitable technologies.

7.2. Theoretical implications

The research and obtained results provide theoretical implications as well.

The long- and shortlist selection that is made describes general resource availability on Vlieland and subsequently assesses possible technologies that qualify for implementation. As a result, a shortlist of technologies that may be deployed on Vlieland was drafted. This list adds to literature as it provides a concise and well-structured overview of available resources and feasible renewable technologies. The technology characterisation further describes the operating principles, summarises the state-of-the-art of the technology and discusses future prospects. Hence this poses insight into the key characteristics of each technology and can thus be used as a reference for other researches concerning renewable technologies.

The method for criteria selection can be exemplary to other studies. The iterative nature of the criteria selection can be considered a relatively easy yet reliable way of combining literature and stakeholder judgement. It addresses all criteria that were deemed to be important as little mentionable remarks were made upon the criteria selected by the client nor the stakeholders. In addition, the resulting relevant criteria can be interpreted as a good indication for variables deemed important by the islanders. Consequently, these criteria provide an indication of different stakeholders values that occur on the island.

Chapter 8: Conclusion

– Jan Visser ©

8. Conclusion

This research aimed to determine what renewable technologies are best suited for implementation on Vlieland on the long term. Subsequently, the research answered what technologies could be deployed on the island, which criteria are deemed important for Vlieland and how the technologies rank on these criteria accordingly.

It was concluded that the most suitable technologies are geothermal heating, macroalgae, geothermal heat pumps and tidal current respectively. Yet, also solar PV, tidal range and micro algae were found to be relatively promising. On the other hand, the wave technologies OB, overtopping and OWC seem less suitable options, as well as unconventional wind power technology.

These results were found by executing the MCA on three inputs. The first input existed of a selection of renewable energy generating solutions that can be deployed on Vlieland. This resulted in a list of the eleven suitable technologies. The second input was a set of relevant criteria and their relative level of importance. The resulting relevant criteria were intermittency, predictability, in-house knowledge, expected time to commercial realisation, land and water area use, noise, job creation, social perception and social benefits. Finally, the research assessed each of the technologies, scoring them on the criteria [Appendix VIII].

It was further concluded that the ranking of the technologies does not change significantly per stakeholder group. Elaborating on that, geothermal direct heating and macroalgae retain the first two positions in the ranking for all stakeholder groups. In addition, OWC, OB, overtopping and unconventional wind remain the four lowest performing technologies in all scenarios. However, the ranking does alter more significantly when the criteria weightings are adjusted with larger variations than were found between the stakeholder groups. In the uncertainty analysis it is found that macroalgae, geothermal heat pumps, tidal current, solar PV and tidal range can be the most suitable option under certain circumstances.

Chapter 9: Recommendations

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9. Recommendations

In this section, recommendations will be set forth regarding the steps that can be taken to use and apply the research results in practice.

In general, the screening of renewable technologies for Vlieland provides a foundation for designing a future energy system. Additionally, the discussed benefits and hurdles of different technologies can be used as a handhold in determining the next steps towards such a system. Simultaneously, this research can aid in limiting resistance from society, since social involvement was ensured in an early stage and information was reduced to understandable and concise content. Therefore, the road forward from this research seems investing time and money into further exploring more exact possibilities of implementing the high scoring technologies. It is essential to conduct site specific studies to find exact energy potentials, determine cost developments and identify bottlenecks for implementation of each technology.

Overall, it was found that geothermal direct heating received the highest score in the MCA. This means that it is currently considered as the most suitable technology for achieving an energy neutral Vlieland. However, geothermal direct heating can only produce heat, which cannot be exported to the mainland. Overproduction of heat can thus not compensate for the electricity and fuel use. As a consequence, Vlieland can become energy neutral by deployment of only geothermal direct heating and will need to implement a different energy resource to become energy neutral. The most suitable options for fuel and electricity production are found to be macroalgae and tidal current respectively.

Following from this, the first advice is to consider technologies that produce energy in different forms and consider the demand to limit export and import needs. Rather than one individual technology, Vlieland should employ an energy mix in order to become energy neutral. Hence, it seems fruitful for further research, to move beyond an analysis of individual technologies and optimise a renewable generation mix. This could even include the opportunities for the implementation of energy efficiency measures and the potential for energy storage facilities. This research could act as a solid starting point.

Nevertheless, geothermal direct energy is considered as the most suitable technology and should be further assessed on implementation potential. The first step to be taken seems to determine which specific locations are most suitable for a geothermal well. Research should assess the required depth and location of drilling, since this influences both the economic feasibility and the energy output of the geothermal installation. The best option to evaluate this would be test drilling to assess the drilling depth and the accessory energy that can be extracted. Hence, geothermal seems more of a long term solution, since an elaborate trajectory is needed until implementation is possible. A short term solution may therefore be heat pumps, which score only slightly lower. These are independent of location and relative easy to install. Moreover, heat pumps are already deployed on Vlieland.

Since macroalgae are ranked second in the MCA, this technology should be further assessed on implementation potential for fuel production. The first step to be taken seems to determine which specific locations are most suitable for a macroalgae farm. Specifying possible locations will enable an investigation of the precise ecological impact of realising a macroalgae farm on Vlieland, which was not assessed in this research. The estimation of water area use showed that macroalgae may well use up a vast amount of water area. This may lead to more extensive ecological impacts or problems due to regulatory restrictions affecting the potential of macroalgae production. Besides, it is to be assessed how macroalgae impact aquatic ecosystems or water quality. An important consideration is that the calmer wave climate south of Vlieland seems most fit for algae farming; yet this is Natura 2000 area (Ministerie van Economische Zaken, 2016) so care has to be taken that implementation is in line with regulation. To assess these impediments, it is recommended to perform a feasibility and impact studies for the assigned locations. Furthermore, since microalgae serve the same purpose of biofuel production but score lower, it is recommended to first examine the possibilities for macroalgae. If done without success, microalgae can always be resorted to as an alternative.

Subsequently, other technologies may be deployed for electricity generation. The highest ranking electricity generating technology is tidal current. The most suitable location has already been determined to be an area of 2 ha near the docks. Yet, this location is situated between the docks and an area that is in used for military purposes[13], so it may be fruitful to investigate whether implementation would not interfere with either. Furthermore, selecting one most suitable type of installation is to be done to provide a more specific energy potential for the chosen location. E.g. a floating installation like the BlueTec installation near Texel may be considered, or alternative forms such as a tidal fence. Finally, a determination of the amount of installed capacity should be done; considering the 2 ha of space, multiple devices should be possible, but an on-site evaluation considering annual currents observed at multiple depths will give definite numbers.

Electricity generation could be further supplied with solar photovoltaics, which was ranked slightly below tidal current. The technology's value has already been recognised on Vlieland and implementation is in a developed stage as is e.g. shown by the planned solar field. Hence, PV may not need as much research as the other technologies. Yet, any research may focus more on possibilities of implementing higher efficiency panels. The potential estimated in this research was done using highest laboratory efficiency shown; monitoring when such efficiencies become available for commercial use may augment photovoltaic yields on the island.

Regarding the remaining technologies, the ranking indicates low suitability for Vlieland in respect to the technologies discussed above. The bottom line is thus that they should not be the centre of attention when mapping future renewable implementation. However, it is not to say they should be discarded as options completely. These technologies were still determined to be suitable for Vlieland based on availability of resources and feasibility. lowest ranked technologies wave OB, unconventional wind, overtopping and OWC performed low on intermittency, predictability and social perception. When storage facilities are installed in the future, the intermittency of a technology might be a criterion of less importance, making these technologies more suitable. All these technologies are highly developing, so people are less familiar with these technologies. If these technologies get deployed more, people familiarity could increase for these technologies, which may have a positive effect on the social perception of a technology. The bottom line is that these technologies remain suitable for Vlieland's energy production but other technologies currently seem more favourable.

In conclusion, this report should be used as a starting point for further research on energy neutrality on Vlieland. Relevant criteria for Vlieland are indicated as well as the technologies which could contribute on the energy production side. For each technology it is shown how it performs on specific criteria, with that specific obstacles are indicated. However, these scores can and will alter in the future, so technologies and criteria should be evaluated over time.

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Appendix

Noventus

Energy revisioned.

11. Appendix

Appendix I Key stakeholders that were interviewed, including their function and relevance to the research.

	Name	Function	Reason
Experts	Prof. Dr. Ad van Wijk	Professor in Future Energy Systems	Has insight into renewable energy systems their future developments
	Antoine Maartens	Sustainable Wadden Island projects at Urgenda	Has experience with implementation of renewables on the Wadden islands
	Allard van Hoeken *(lecture TU Delft)*	Blue Water Energy Services	Lecture on "Oceans of Energy: Renewable Energy Solutions for Islands"
Stakeholders	Tijl Couzij & Govert Reeskamp	Project managers Lab Vlieland	Experience and close interaction with (sustainable) projects on Vlieland
	Jan van der Veen	Owner camping Stortemelk	Expert judgment on weighting factors; embedded in local community on Vlieland
	Henk Visser	Alderman Vlieland (Energy and sustainability policy)	Expert judgment on weighting factors; knowledge of policy Vlieland
	Marco Bakker	Vlieland 2020 group	Expert judgment on weighting factors; embedded in local community on Vlieland
	Jan Roelof Witting	Rijkswaterstaat and member of city council Vlieland	Expert judgment on weighting factors; knowledge of boundaries/limitations of Vlieland and Wadden Sea
	Jan den Ouden	Energie Cooperatie Vlieland (ECV)	Expert judgment on weighting factors; sustainable projects Vlieland; implementation of PV plant and possible other renewables (process and bottlenecks)

Appendix II Renewable resource descriptions and technologies

A. Solar heat and power

Solar power generation entails all energy conversion techniques that transform (in)direct solar radiation into electricity or heat. The most applied and developed techniques include solar photovoltaics (PV) and concentrating solar power (CSP) to generate electricity, and solar water heating (SWH) for space and water heating purposes. These techniques are already widely proven to be economically feasible at various locations around the world (NREL, 2012; Twidell & Weir, 2015).

PV installations convert solar irradiation (either direct or diffuse) directly into electricity by diffusion through photovoltaic cells. They can be installed locally in the form of installations of up to 200 W or clustered to form large power plants in the order of a few hundred MWs. A recent variation on PV is *concentrator photovoltaics* (CPV), where solar irradiation is concentrated onto expensive yet high-efficient cells (Phillips et al., 2016). For CPV, a high direct normal irradiation (DNI) is needed.

CSP converts direct solar radiation into electricity through creating a concentrated solar beam with mirrors that transposes its heat to a liquid or gas. CSP plants have a big advantage that heat can be temporarily stored (for hours) with the purpose of generating electricity at night or at relatively low solar intensity. The plant size is usually in the order of several hundred MWs to enhance economic viability and are often placed in regions with relatively high DNI.

Finally, SWH comprises various techniques that convert solar radiation into heat or hot water through capturing radiation in a solar thermal collector. SWH installations are often locally implemented in small scale installations to provide heat or hot water directly to the producer or customer (Twidell & Weir, 2015).

Technologies:

- Photovoltaics (PV)
- Concentrator photovoltaics (CPV)
- Concentrating solar power (CSP)
- Solar water heating (SWH)

B. Wave power

Wave power energy conversion extracts energy that is stored in the movement of waves; both in the deep and shallow waters. The energy potential depends on their crest height, wave height and wave period (NREL, 2012). Yet, the restless characteristics of the ocean and weather conditions pose many challenges for extracting wave power. Generators should be able to cope with e.g. irregular wave patterns, harsh weather conditions and low wave frequencies (Twidell & Weir, 2005). Hence, understanding wave motion is highly difficult yet essential for power extraction. There are three main classes of wave energy conversion technologies: oscillating water column (OWC), oscillating bodies (OB) and overtopping (Falcão, 2010).

OWC technologies are characterized by waves that strike into a fixed water column, which in turn forces air through a turbine (Falcão, 2010). An advantage of this system is that with both the striking and withdrawal of the wave, electricity is generated (Cruz, 2008). These technologies can either be installed as floating devices, attached to the seabed or built on the coast.

OB technologies are floating or attached bodies that are subject to the movement of the waves (Twidell & Weir, 2015). The displacement of (parts of) these devices convert wave energy into electricity. Some OB devices characterize by harvesting energy at one point in the wave only (point absorbers), while others capture the energy as the wave passes the entire length of the structure (line absorbers) (Cruz, 2008).

Overtopping technologies are characterized by an elevated reservoir, where waves are being forced into by using a ramp (IRENA, 2014b). Wave concentrators direct waves to the direction of the ramp, which increases wave height. When the wave hits the ramp, it gets forced onto an elevated reservoir, storing the wave energy as potential energy. When a sufficient water level in the reservoir is reached, the water is released through a hydropower turbine which generates electricity (Twidell & Weir, 2015).

Technologies:
- Oscillating water column
- Oscillating body
- Overtopping

C. Tidal power

Due to the gravitational effects from the sun and moon, and the earth's rotation, bodies of water experience one tidal movement per 12 hours and 25 minutes. These movements cause energetic potential that can be harvested; especially at geographical locations where (natural) "narrow passageways between oceans and large estuaries or bays" occur (NREL, 2012; ch.9, p.5). Tidal power generation technologies can be divided into three main categories, which are tidal range technologies, tidal current/stream technologies and hybrid applications (IRENA, 2014a). The tidal range concerns the vertical difference of water levels or available head between low and high tide, whereas the tidal current/stream is the horizontal difference (NOAA, nd). Moreover, hybrid applications concern all tidal technologies that can be integrated in new infrastructure for coastal zones (IRENA, 2014a).

Tidal range technologies consist of a natural or man-made barrage deployed with hydropower turbines to harvest potential tidal power that is available due to the head difference that occurs between flood and ebb tide. The technologies employed are similar to hydropower technologies and therefore well-developed and proven to be commercially feasible for varying plant capacities all over the world (0.4 MW - 254 MW) (IRENA, 2014a).

'Tidal current' or 'tidal stream' technologies refer to underwater tidal turbines that harvest the kinetic energy of tidal streams. This kinetic energy depends on the strength of the tidal current and can be harvested by applying different energy conversion techniques (IRENA, 2014a).

Hybrid applications are tidal range technologies that can be combined in their design and deployment with large new or refitted infrastructural structures. These structures are multi-purpose and have a great potential. Currently the deployment of hybrid tidal applications is in an early development and innovative stage (IRENA, 2014a). Examples of such structures include combined electricity generation and coastal defence infrastructures or road passages. Another possible multi-purpose structure is dynamic tidal power (DTP), which would involve the construction of a large T-shaped dam-like structure of 30-60 km long with an expected installed capacity in the order of several GWs (POWERDTP, nd).

Technologies:
- Tidal range technologies
- Tidal current or tidal stream technologies
- Hybrid applications

D. Biomass

Biomass is defined by Twidell & Weir (2015) as "The material of plants and animals, including their wastes and residues" (p. 351) and thus comprises a variety of resources. Biomass can generally be divided into first, second and third generation: first generation encompasses arable crops, where energy is produced of sugars and vegetable oils. Second generation includes energy crops (such as willow, miscanthus and wheat) where energy is produced using lignocellulosic biomass and waste streams (such as woodchips from industry waste and green waste). These feedstocks do not compete with food production in terms of land use. Third generation includes all micro- and macroalgae used for energy applications. All forms of biomass are energy carriers and can thus be used to produce work or electricity by combustion or chemical reactions. The main driver of bioenergy production is solar irradiation, since it causes photosynthesis and thus the production of harvestable energy in ecological systems (Twidell & Weir, 2015).

Biomass can be converted into various different energy carriers by many different conversion methods. Biomass can either be turned into heat, through e.g. direct combustion or pyrolysis (anaerobic or partly aerobic combustion) or it can be turned into bio-chemicals through (an)aerobic digestion, alcoholic fermentation or bio-photolysis (i.e. splitting water using light). Finally, it can be used to produced biofuels, such as bioethanol and biodiesel (Twidell & Weir, 2015).

Biomass is not per definition a renewable, since agricultural and waste resources are limited and can be depleted. Hence, Twidell and Weir (2005) state that "If biomass is to be considered renewable, growth must at least keep pace with use." (p. 352) This means that in order to use biomass renewably, it has to be grown, harvested and re-grown. This causes the need for land to be extensive and poses risks for forest degradation, for both first and second generation biomass. Furthermore, it can result in a competition for land use between food production and bioenergy production in the case of first generation biomass.

Technologies:

- First generation
- Second generation
- Third generation

E. Geothermal heat and power

Geothermal energy is energy in the form of heat harvested from the crust of the earth. Heat can either be extracted from natural aquifers, hot igneous systems (semi-molten magma near surface) or by fracturing dry rock. The amount of energy that can be extracted from dry rock is amongst others dependent on the depth of the heat source, the rock density, heat fluxes and specific heat capacities of the rock (Twidell & Weir, 2005). After (sometimes necessary) fracturing, water is pumped down, seeping through the hot rock, aquifer or igneous system and afterwards pumped up again as heated water. This water can be used for direct heating of houses/industries or, at high enough temperatures, be turned to steam and power in a turbine.

Only at certain geographical locations the heat flow is large enough to provide commercial amounts of heat. Between 50 and 70 degrees Celsius, geothermal heat is mostly suitable for direct building or process heating. As Twidell & Weir state: "[...] the energy demand for heat at <100°C is usually greater than that for electricity, and so the direct use of geothermal energy as heat is important. Electricity generation will probably be attractive if the source temperature is >300°C, and unattractive if <150°C." (2005, p. 481).

Furthermore, at these lower temperatures, the same principle can be applied. In this case, geothermal heat pumps (GHPs) can transfer heat from very shallow ground surfaces to provide direct heating for houses. For these shallow ground surfaces, no extensive drilling is needed. Although these heat pumps do need electricity to work, they result in a net gain in energy.

Geothermal energy technologies are all based on the same principle, extracting (thermal) energy from the earth's surface. Three distinctions are made between geothermal systems; the depth of the geothermal well, the extraction formation (aquifers-, hot igneous-, dry rock- or fractured rock systems) and electricity conversion or direct use.

Technologies:

- Hydrothermal power plant (aquifer)
- Hot igneous systems
- Dry rock fracturing
    - Shallow
    - Deep
    - Enhanced (EGS)
- Geothermal heat pump

F. Wind power

The wind turbine is a well-established technology. Since onshore wind turbines are disregarded by default, this alternative is not included and merely other forms to harvest wind power were assessed. These alternatives include offshore wind turbines, urban wind turbines and other alternatives designs. Large offshore wind turbines can be deployed to harvest a great amount of wind power (Twidell & Weir, 2015).

Furthermore, a variety of smaller turbines, either horizontal or vertical axis, focusses on use in urban areas. Hence, they are called urban wind turbines and generally produce between 0.5 and 20 kW of output (Cace & ter Horst, 2007). Due to their small size, they do not pose as much visual pollution. Also, they can be adapted to many shapes and sizes, something that can be more appealing to society. Hence, the development of unconventional wind turbine designs is widespread and includes bladeless designs, air-suspended designs and collecting technologies (e.g. INVELOX; for other designs see MNN (2013)). Cace & Ter Horst (2007) from the 'Urban Wind' initiative considered an average urban wind turbines to be a 2.5 kW wind turbines with a rotor area of 10 m^2 as an average.

Technologies:

- Off shore wind turbines
- Urban wind turbines
- Unconventional turbine designs

G. Hydropower

Although hydropower could be seen as all power derived from water, Twidell & Weir define it as "the generation of shaft power from falling water" (p. 238). Hence, it is differentiated from other water power sources such as tidal and wave power. Power is extracted by running falling water through a hydro dam with turbines inside, which can be of different shapes and sizes (e.g. Pelton wheel or Francis wheel). The amount of power output is especially dependent on flow rate and the vertical fall (the *head,* including head loss due to pipe friction). Hydropower can also be used as a form of energy storage: overproduced power can be used to pump water uphill, creating potential energy. Subsequently, water can be released downhill through the turbines to produce power (Twidell & Weir, 2005).

Technologies:

- Hydro dam

H. Ocean thermal energy conversion (OTEC)

OTEC is an energy conversion technology driven by the natural occurrence of a temperature gradient between the ocean surface and the subsurface or deep ocean water layers. This gradient is caused by solar energy absorption. The heat difference captured can be exchanged to vaporize and condense a working fluid and thereby used to drive a Rankine-cycle which enables electricity production. In practice, the efficiency of this technique depends on the temperature difference between the top and bottom layer, which should be at least an annual average of 20°C to be considered viable. This means that the warmer surface water (upper 20 meters) should have a temperature of around 25°C, whereas the cold subsurface or deep ocean water must have a temperature of about 5°C, which generally occurs at a depth of 1,000 meters. Consequently, OTEC is only considered to be feasible around the equator, as such required temperatures only occur in this region (NREL, 2012).

Technologies:

- OTEC plant

I. Salinity gradient power

Salinity gradient power is based on the energy that is released when two water streams with different saline concentrations mix (NREL, 2012). In nature this phenomenon occurs at river mouths, where freshwater mixes with salty ocean or sea water. Such a saline gradient can also be artificially created between dense industrial waste water streams and freshwater. The two different techniques to capture this potential energy are pressure-retarded osmosis (PRO) and reverse electro dialysis (RED) (Post et. al, 2007). In both techniques fresh and saltwater are used as input, and brackish water and energy are produced. At the moment these two techniques are intensively researched, in a pre-commercial phase, and tested at pilot plant sights.

Technologies:

- PRO installation
- RED installation

Appendix III Technology characteristics of technologies on the shortlist

Introduction to Appendix III A-J

This part of the appendix gives more background information on the technologies that are selected on the shortlist as a result of section 3.2. The technologies are described on specific aspects. First the general working principles are discussed, then the current state of the technology and its prospects are provided. Lastly, insights and assumptions are given concerning the potential of the technology on Vlieland by calculating the potential energy production per surface area.

This potential takes into account natural restrictions, basic geographical suitability and technical restrictions such as conversion efficiency (Hoogwijk & Gaus, 2008). Determining the potential of certain technologies was done by looking into the available resource and the conversion efficiencies of the technologies. An estimation was made with information retrieved from previous studies and other data resources available in order to give insight into what the production potential per surface area of a specific technology could be on Vlieland[14].

The relevant formulas and assumptions are discussed per technology in the section A-J. For solar PV, the irradiation per surface area and relevant efficiencies were used to calculate the potential energy production. For overtopping, tidal current and geothermal heat pumps, literature on demonstration projects or current uses was used to assess the potential. For both types of algae, the maximum yields of biofuel per surface area retrieved from literature and the energy contents of these biofuels were used.

For oscillating water columns, oscillating bodies and unconventional wind, the annual energy production was calculated using an adaption of the following formula from Blok (2006):

Equation 2: Capacity factor

$$Capacity\ factor\ (\%) = \frac{Annual\ production\ (\frac{kWh}{y})}{Nominal\ capacity\ (kW) \times 365\ \left(\frac{days}{y}\right) \times 24\ (\frac{hrs}{day})} \times 100\%$$

For this calculation, the nominal capacity of the technology and the load factor were needed. The values used are argued in each sub-section. Besides the capacity factor (CF), for wave and tidal technologies, a relevant availability factor (AF) was also taken into account. The AF concerns the time that the installation can produce energy, e.g. influenced by maintenance (Energy Mag, nd). Rewriting and including the AF, the resulting formula is:

Equation 3: Annual energy production

$$Annual\ production\ \left(\frac{kWh}{y}\right) = Nominal\ capacity\ (kW) \times CF \times AF \times 8760\ (\frac{hrs}{y})$$

To get to the potential per surface area, for all technologies the potential was divided by the surface area of the system that generates the energy. For geothermal direct heating however, an exception was made as is explained in due time.

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[14] It should be noted that there may be discrepancy between the calculated potential production per surface area and the real-life potential that can be realised on the island, due to the assumptions made and any other limitations (by e.g. the municipality of Vlieland, the province of Friesland, Staatsbosbeheer and Natura 2000). Hoogwijk & Gaus (2008) define the real potential that can be realised on a specific place as the market potential. This potential is subject to competing technologies, policies and measures, economic limitations and the demand for energy. Assessing such potential of a technology is an extensive study by itself.

A. Solar PV

Operating principles

Photovoltaic (PV) panels directly convert light or solar irradiation into electricity by conducting a number of solar cells (IRENA, 2013b). The conversion is based on the photovoltaic effect, which exist of both a chemical and physical reaction (Twidell & Weir, 2015).

Current state

PV is widely employed and has proven to be economically feasible and competitive to fossil energy resources. On a global scale, the most popular current PV technologies are thin-film (TF) and crystalline silicon (c-Si) cells as set out by IRENA (2013b). The best commercial cell available has around 20% efficiency but high-end modules have reached 25%. One c-Si module generally has an area around 7 m^2/kW and "[...] is typically made up of 60-72 cells, has a nominal power of 120-300 W_p and a surface of 1.4-1.7 m^2" (IRENA, 2013b, p. 9). Furthermore, the market consists of over 1000 PV producers and a few producers of the basic materials (IRENA, 2013b).

The state-of-the-art entails cells made from different materials, which are designed to absorb a broader solar spectrum and utilise multiple cell junctions. Efficiencies of such cells can reach over 30% (Twidell & Weir, 2015; NREL, nd-a).

Prospects

Increasing utilization of solar PV panels and ongoing research and development will allow for increasing efficiencies along with improved economic feasibility of PV panels (Reichelstein & Yorston, 2013). Besides conventional PV panels, several newer variations are coming into play. These include emerging PV, single-junction GaAs and multi-junction cells. The technologies differ in the way in which solar irradiation is converted into electricity, potential and efficiency. The highest (non-concentrating) cell efficiency reached is 37.9%, consisting of three-junction cells (NREL, nd-a). Although concentration techniques can be employed to reach even higher efficiencies, concentrator technologies are not considered as an option for Vlieland since high direct irradiation is essential.

Potential energy production per surface area

Considering the fast development of PV in recent years and an achieved lab efficiency of 37.9%, for this research it is expected that PV panels with a similar efficiency will become available for commercial use. Hence, this efficiency will be used to calculate the potential energy production. Furthermore, the annual net electricity output of PV installations depends on the PV system efficiency and the annual radiation influx, and can be expressed by (Twidell & Weir, 2015):

$\text{Potential (kWh/m}^2\text{/y)} = G_{ann} * \eta_{system} * \text{surface area coverage (\%)}$
Where:
G_{ann} = annual local irradiation (kWh/m^2/y)
η_{system} = the PV system efficiency
Surface area coverage = percentage of land area that is covered by solar panels in a solar field (%)

The annual local irradiation on Vlieland is estimated to be 1075 kWh/m^2/y (SolarGIS, 2014). The overall PV system efficiency depends on the module efficiency, conversion efficiency and other losses defined by Hansen et al. (2014) as "typical" losses. These typical losses account for all other losses that occur in any of the PV system components. The overall PV system efficiency can be calculated by the following formula from Twidell & Weir (2015):

$\eta_{system} = \eta_{conversion} * \eta_{module} * \eta_{other}$

Other PV system component losses are determined to be 10%, resulting in an efficiency of 90%. The conversion efficiency is estimated at 98% (Hansen et al., 2014) and according to NREL (nd-a) the current maximum achieved module cell efficiency is 37.9%. These account to an overall system efficiency of 33.4%. The solar panel coverage in a solar field is approximately 60%, meaning that 40% of the surface area is needed as space between the panels in order to avoid losses by shadows (Debets, 2014). The potential per surface area is therefore:

Potential (kWh/m^2/y) = G_{ann} (kWh/m^2/y) * η_{system} (%) * surface area coverage (%)
= 1075 kWh/m^2/y * 0.334 * 0.6 = **215 kWh/m^2/y**

B. Oscillating water column

Operating principles

Oscillating water column (OWC) technologies convert wave energy into electricity. The technology consists of a chamber of trapped air with a column of water underneath. When a wave strikes, the water column rises, pushing the air out of the chamber through an air turbine. When the wave retracts, air is sucked through the turbine and back into the chamber. This reversing motion generates the electricity (IRENA, 2014b). This technology is either placed on shore at the water side or off shore in front of the coast.

Current state

Wave power is generally far from being commercially viable, having not been proven to work above installations of 10 MW (Bull & Ochs, 2013). Although attempts to install 1 MW installations have failed, a successful 500 kW installation has been deployed recently on Jeju Island (Falcão & Henriques, 2016). Examples of OWC technologies are the GreenWave, Ocean Energy Buoy, Oceanix, Pico Plant and the Wavegen Limpet.

The state-of-the-art is hard to determine, as developments are immature. Yet, the extensive research on wind turbines provides a good basis for determining generator requirements for OWC technology since it utilises air turbines. Air turbines - of which the Wells turbine is most common - cause beneficially increased flow rates from wave to air flow and reaches relatively low efficiencies of 60-65% (Drew & Sahinkaya, 2009). However, Falcão & Henriques (2016) state that "[...] peak efficiencies close to 80% and average efficiency in random waves above 70% can be attained by new-generation turbines" (p. 1421).

Prospects

The most promising technological advances lie in more advanced controls, improved conversion, optimised structural design and array optimisation, as described by Bull & Ochs (2013). Of these, more advanced controls is stated to be the most probable option for cost reduction. Furthermore, issues concerning air compressibility are to be resolved, especially through more advanced model testing.

Potential energy production per surface area

A near-shoreline fixed structure seems most fit for Vlieland, since integration with breakwater keeps operation requirements, construction and costs relatively low (Falcão & Henriques, 2016). The 500 kW deployment of a shoreline fixed structure on Jeju Island (measuring 37 x 31.2 m), was the largest shown feasible and the device is stated to work well in shallow waters (KCTV, 2013). Since Vlieland is surrounded by relatively shallow waters (Kilometerafstanden, 2016), this type of installation is used for the potential calculation.

The potential calculation for wave is very location specific and can be immensely complex (see e.g. Cahill & Lewis, 2014; Twidell & Weir, 2015). To simplify yet still give an indication, Equation 3 was used. Furthermore, an availability factor was considered.

Although no capacity factors (CF) and availability factor (AF) specifically for Vlieland were found, values of 25% and 80% respectively can are used: according to the marine technology roadmap by ETI/UKERC (2014), UK wave energy currently has an availability of up to 80%. The capacity factor of OWC is around 25% according to Nelson & Starcher (2015). Assuming the given values, the potential is as follows:

Potential (kWh/m^2/y) = (Nominal capacity (kW)/surface area (m^2)) * CF (%) * AF (%) * 8760 hrs/y
= (500 kW/(37*31.2 m)) * 0.25 * 0.80 * 8760 hrs/y = **759 kWh/m^2/y**

C. Oscillating body

Operating principles

Oscillating body (OB) technologies are floating or submerged devices that convert wave motion into electricity, as the device captures the movement of the waves. Systems can e.g. include a hydraulic pump or a piston pump that is set in motion by the waves (IRENA, 2014b). These devices are generally meant for off shore regions with a minimum depth of 40 to 50 meters (IRENA, 2014b; Guedes Soares et al., 2014).

Current state

Many OB systems exist which can mainly be categorised in different forms of movement. Examples are heaving, pitching, surging or swaying (Falcão, 2010; IRENA, 201b). Although the induced level of mechanical movement is highly variable due to the wave variation, the electricity output can be smoothed through the use of gas accumulators (Falcão, 2010).

OB technology is still in the development phase and only some devices are in the full-scale demonstration phase (Falcão, 2014). The Pelamis is a floating OB technology which is closest to commercial deployment. In this system, wave motion causes joints in the device to move hydraulic cylinders, which in turn pump fluid to produce power. Accumulators are installed to levelise the output of electricity, which is rated at 750 kW (i.e. three 250 kW modules per Pelamis). This installation has a water surface area of 140 by 3.5 meters. Other devices include the PowerBuoy, the Oyster, Seatricity, Pelamis and Wave Star (IRENA, 2014b).

Prospects

OB technologies are considered to be complex (Falcão, 2010). To improve the economic feasibility of the technology, especially research into power take-off (PTO) performance[15] is needed (IRENA, 2014b).

Potential energy production per surface area

For the potential calculation the same counts as described in OWC technology, where power output was calculated using the capacity factor, availability factor and the nominal power. Since the 750 kW Pelamis system is closest to commercial operation, it will be used a reference for calculating the potential production. The device is stated to have a capacity factor of around 25% (Ocean Power Delivery, nd). As this is in a similar range as the OWC technology, it is assumed availability factors will also be of a similar range. Hence, the 80% is assumed for the AF.

Potential (kWh/m^2/y) = (Nominal capacity (kW)/surface area (m^2)) * CF (%) * AF (%) * hrs/y
= (750 kW/(140*3.5 m)) * 0.25 * 0.80 * 8760 hrs/y = **2682 kWh/m^2/y**

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[15] I.e. the mechanism which converts mechanical energy into electricity.

D. Overtopping wave power

Operating principle

Overtopping converts wave power into electricity by conducting either floating or coastal-fixed devices. Electricity is generated by creating a head of 1-2m in a basin which is sent through a hydro turbine if enough water is collected. This head is created by concentrating waves, which are subsequently spilled over a ramp into a small basin (IRENA, 2014b). Waves can be concentrated by conducting collector arms.

Current state

The development of the technology benefits from existing coastal engineering research into overtopping across dikes (Bevilacqua & Zannutigh, 2011) and existing low head hydro power turbines. Examples of developing overtopping devices are the WaveDragon, Seawave Slot-Cone Generator and the WaveCat (IRENA, 2014b). The Wave Dragon is considered the most developed, rated at 4-10 MW depending on wave climate (Bevilacqua & Zannutigh, 2011). A shoreline fixed device that has been tested empirically is the Sea Wave Slot Cone Generator, providing about 320 MWh/y (Margheritini, 2009).

Yet, most overtopping systems are no different from other wave technologies in their development, and also still in early stages of development.

Prospects

Developments can include improved mooring systems and increase survivability of the devices, which have to withstand large loads and struggle with fatigue. Furthermore, as with the other wave devices, improved mooring and intelligent control pose opportunities for development (Bevilacqua & Zannutigh, 2011; Friis-Madsen et al., 2012). Thirdly, empirical evidence is needed “to analyse the response of the Wave Dragon to environmental and mooring loads for extreme wave conditions” (Friis-Madsen et al., 2012, p. 4)

Apart from performance development, cogeneration activities on overtopping sites pose possibilities for development. This is due to the still waters that are caused behind a floating overtopping device, which pose recreational activities or aquafarming (Bevilacqua & Zannutigh, 2011).

Potential energy production per surface area

Devices are generally quite large, operating at higher wave energy contents: the Wave Dragon can measure as much as 300m by 170m (Soerensen, 2006) and output is only given above wave energies of 24 kW/m (Soerensen, 2006). However, the device is scalable to 4 MW, stated to be suitable for North Sea conditions (Friis-Madsen et al., 2012). It should be noted Schiermonnikoog’s wave climate was measured to average at only 7.44 kW/m (Beels et al., 2007) so the device will need to be further from the coast. Furthermore, sandbanks in front of Vlieland’s shore hamper the wave climate[16] and thus disadvantage a device close to shore.

A 4 MW device, with a surface area of 150 * 260 m, in the North Sea will produce approximately 12 GWh per year (Friis-Madsen et al., 2012), depending on location and wave climate. The potential is therefore:

$$\begin{aligned}\text{Potential (kWh/m}^2\text{/y)} &= \text{Annual production (kWh/y) / surface area (m}^2\text{)}\\ &= 12 \cdot 10^6 \text{ kWh / (150 m * 260 m)} = \mathbf{308\ kWh/m^2/y}\end{aligned}$$

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[16] Witting, J.R., Rijkswaterstaat on Vlieland, personal communication, May 27th, 2016

E. Tidal range

Operating principle

Tidal range power temporarily stores water during flood tides in a basin and releases this water through low head hydropower turbines during ebb tides (IRENA, 2014a). There are three forms in which tidal range power can be captured: (1) one-way power generation at ebb tide; (2) one-way power generation at flood tide; (3) two-way power generation, which combines (1) and (2) by using reversible turbines. These two-way power generating turbines have on the one hand in theory the ability to double the energy production and production is better distributed over the day. On the other hand, it comes with extra investments and technical requirements (van Berkel, 2014).

There are several different methods to create a basin for tidal range power production and those can be categorized into: tidal barrage/dam, tidal reef, tidal fence and tidal lagoon (IRENA, 2014a). However, considering the geographical limitations and absence of natural estuaries (Hansen et al., 2014) only the construction of a tidal lagoon at or near Vlieland is possible and will be considered.

Current state

Tidal range power is a well-developed electricity production technology, and has proven to be economically feasible for decades in varying capacities and available heads at numerous locations around the world (Montllonch Araquistain, 2010; IRENA, 2014a). Commercial production of tidal range power plants varies between installed capacities of 0.4 to 254 MW and have an available mean head of 2.4 to 10.7 meters (Montllonch Araquistain, 2010). Moreover, Pro-tide is developing a tidal testing centre in the Netherlands, to commercialize a tidal plant with an available head of 50 cm (Pro-tide, nd).

The efficiency of state-of-the-art one-way turbines reach over 90% for low available head. Bi-directional propellers are claimed to have an efficiency of 85% at a hydraulic head of 1 meter (van Berkel, 2014).

Prospects

Due to the far stage of development, tidal range power is considered as well-developed and therefore little to no technological improvements in terms of efficiency or increased output are expected (IRENA, 2014a; van Berkel, 2014). Improvements can still be made in terms of costs of the lagoon infrastructural design.

Potential energy production per surface area

Since bi-directional propellers have the largest electricity output, in this research the implementation of such a turbine is considered as the power production is maximized and there are no apparent limitations to the implementation of these turbines.

The average potential power production of a one-way tidal range power installation is given by Twidell and Weir (2015) as:

$P_{average} = (\varrho * A * g / 2t) * R^2_{average}$

Where:

$P_{average}$ = the average potential power production per tide (W)

ϱ = density of water (kg/m^3)

A = area of the basin (m^2)

g = gravitational constant (m/s^2)

t = tidal period

$R_{average}$ = average range of tide (m)

Considering a bi-directional tidal range power production this formula can be described as:
$P_{average} = 2 * (\varrho * A * g / 2t) * R^2_{average}$

Including the turbine efficiency (η), an availability factor of 90% (IRENA, 2014a), an observed average annual tidal range of 1.84 m and assuming a tidal range basin of 10 km^2 (Hansen et al., 2014) the annual electricity production can be described as:

E_{output} (GWh/y) = AF (%) * 2 * η * (ϱAg/2t) * $R^2_{average}$ * 8760

$\eta = 85\%$
$\varrho = 1025$ kg/m^3
$A = 10$ km^2
$g = 9.81$ m/s^2
t = 12hrs25minutes
$R_{average} = 1.84$ m
AF = 90 %

E_{output} = 0.9 * 2 * 0.85 * (1025 kg/m^3 * 10 km^2 * 9.81 m/s^2 / 2 * 12hrs25minutes) * 1.84^2 m * 8760
= 51.3 GWh/y

Installing an adequate bi-directional propeller with an average optimal power output of 6.5 MW would have the potential to generate 51.3 GWh per year, exceeding the total energy demand of Vlieland. The potential per surface area is:

Potential (kWh/m^2/y) = Yearly production (kWh/y) / surface area (m^2)
= 51.3*10^6 kWh / 10 km^2 = **5.13 kWh/m^2/y**

F. Tidal current

Operating principles

Tidal stream power converts horizontal water movements caused by tidal currents, into electricity. Tidal stream can be generated using (1) horizontal and vertical-axis turbines (2) reciprocating devices and (3) alternative designs (IRENA, 2014a). Horizontal/vertical-axis turbines capture energy by letting water flow pass through turbines, where the blades are oriented parallel and perpendicular to the current respectively (EMEC, nd). Reciprocating devices consist of a hydrofoil attached to an oscillating arm, which is set in motion by the tidal stream. The movements of the arm in turn drives a rotating shaft that enables electricity production (EMEC, nd). Finally, there are various alternative designs such as rotating screw-like devices and tidal kites (IRENA, 2014a; EMEC, nd).

The maximum potential of tidal current technologies depends on the channel blockage ratio of the turbine and is in theory bounded by the Betz limit, which is expressed as a maximum rotor power coefficient ratio of 16/27 (Twidell & Weir, 2005). However, research by Vennel (2013) states that this upper limit can be exceeded if operating tidal turbines are placed alongside each other in a channel, due to the presence of a lower and upper boundary. According to Vennel, the Betz limit in "[...] very small channels, e.g. 2 km long and 20 m deep" (P. 285) cannot be exceeded as bottom friction dominates the channel dynamics.

Current state

At the moment, 76% of all current tidal stream power plants use horizontal-axis flow turbines for energy conversion (IRENA, 2014a). Moreover, these are currently considered as most-development and closest to economic feasible implementation (SEI, 2010). Therefore, from the devices discussed only the power generation of state-of-the-art horizontal-axis flow turbines is considered.

To date there are only horizontal-axis flow turbines in operation in the order of single MWs (Vennel, 2013). These turbines reach efficiencies of 25 to 35% on site locations and 55% under lab conditions, considering the total available tidal current power (Ballard, nd). The most efficient commercial tidal power turbine reaches a turbine efficiency of 89%. Taking into account the Betz limit, this turbine has an overall efficiency of 52.7%.

At the moment, current velocities lower than 2 meters per second are considered as not viable, but it is expected that further technological research and development, and deployment should enable economic feasible implementation of turbines at lower velocities in the future (SEI, 2010).

Prospects

Horizontal-axis tidal stream turbines are well developed as it is based on the established propeller turbines used for low head hydro power installations. Moreover, most gains in increasing output is to be made by local, site specific, optimization. Moreover, optimal placement could increase efficiency leading to exceedance of the Betz limit (SEI, 2010; IRENA, 2014a).

Potential energy production per surface area

Highest currents found in Vlieland are induced by tidal streams and local accelerations of water stream due to the presence of the Wadden Islands. A tidal current study for the Wadden islands by Gardner (2012) resulted in three potential locations for the placement of tidal current turbines in the Wadden island area. One of these is near Vlieland and concerns an area of 100 m x 200 m located in front of the docking area, east of Vlieland. In this area, 10 to 15 turbines with a diameter of 8 to 10 meters could be placed, adding up to a nominal capacity of 1000 kW. The capacity factor is mentioned to be 0.35 but no availability factor is mentioned (Gardner, 2012), so it remains unclear whether it is incorporated into the stated calculations;

AF is therefore set to 1. Following the calculations from Gardner (2012), the potential energy production then becomes as follows:

Potential (kWh/m^2/y) = (Nominal capacity (kW)/surface area (m^2)) * CF * AF * hrs/y
= (1000 kW/(100*200 m)) * 0.35 * 1 * 8760 hrs
= (3.066 * 10^6 kWh/y) / (100*200 m^2) = **153 kWh/m^2/y**

G. Third generation biofuels

Operating principles

Third generation biomass is fundamentally different from first and second generation biomass. Where first generation biofuels compete directly with food crops and second generation biofuels are produced on arable land, biofuels from algae are considered as a possible solution. Algae also do not compete with food or feed crops, and can be produced on non-arable land or in water. Algae can produce many chemicals, pharmaceutical products and biofuels.

A distinction is made between macroalgae (seaweed) and microalgae. Many different production routes and product outputs are possible, including the conversion techniques pyrolysis, anaerobic digestion, aerobic digestion, alcoholic fermentation and bio-photolysis. Roughly, the conversion methods for biofuels can be categorized in three basic principles: directly (by burning dry algae), extracting oils (to produce biodiesel) or by fermenting the algae (to produce bioethanol).

Besides several conversion routes to energy carriers, there are also different cultivation methods described by Resurreccion et al. (2012). For macroalgae, the main cultivation method is offshore/marine cultivation in sea. Microalgae can be cultivated in both salt and fresh water in ponds (open/raceway) or in photo-bioreactors (that can be tubular, flat plate, vertical column or use algal biofilm).

Current state - Macroalgae

Macroalgae (seaweed) are multicellular plants. They are currently mainly used for the production of food and for the extraction of hydrocolloids (e.g., agar, alginates, and carrageenans) which are used in the pharmaceutical and cosmetic industries. Conventional crops and conversion methods do not have the ideal traits for biofuel production, because the sugar content and seasonality of the production cycle is not good enough; yet, strain development of for instance Laminaria causes better characteristics for biofuel production (Hughes et al., 2012).

There are now several species that are suitable for large-scale cultivation and energy production, where the macroalgae produce bioethanol and biodiesel (Hochman et al., 2015). It was also already found in 2005 that here is a large potential for marine macroalgae cultivation in the North Sea (Reith et al., 2005).

Prospects - Macroalgae

While offshore cultivation of seaweed for solely bioenergy is not yet developed, combined production of different products and secondary energy carriers is expected to be feasible in the future (Reith et al., 2005). With controlled nutrient addition, the yield can go up to 50 tons/ha/y (dry weight) (Reith et al., 2009). However, the impact of large scale-seaweed cultivation on the North Sea ecosystem is a critical success factor (Reith et al., 2009).

Potential energy production per surface area - Macroalgae

An area of 2,500 km^2 in the North Sea would be able to provide 10 million tonnes dry biomass annually, yielding close to 2 billion litres of bioethanol according to Hughes et al. (2013). Assuming an energy content of 24 MJ/litre of this ethanol, this would be 48 $*10^9$ MJ per year. The potential of bioethanol on sea is then calculated by:

$$\begin{aligned}\text{Potential (MJ/m}^2\text{/y)} &= \text{Yield (L bioethanol/m}^2\text{)} * \text{Energy content bioethanol (MJ/litre)}\\ &= 2 *10^9 \text{ L bioethanol/}(2500 *10^6 \text{ m}^2) * 24 \text{ MJ/litre bioethanol} = \mathbf{19.2\ MJ/m^2/y}\end{aligned}$$

Current state - Microalgae
Currently, commercial algae production is mainly aimed at high-value products for niche markets (de Visser, 2015). Algae production yields are too low to serve as energy production alternatives. Therefore, only 10,000 tonnes of microalgae are estimated to be produced yearly (Hochman et al., 2015).

Prospects - Microalgae
In order to increase the production yield and scale up the production, lots of innovations are needed. Microalgae strain development via classical selection methods or by genetic modification could contribute to this (Rodolfi, 2009). Also, optimizing the operation of the bioreactor and improvement of the design of photo-bioreactors in which the algae are grown can increase the production yields (AlgaePARC, 2015). De Visser expects the time for commercial realisation of large scale algae production as bulk material to be 10 to 15 years (de Visser, 2015). A large potential lies in the combination of energy production and coproducts (e.g., wastewater treatment), that make large-scale algae biofuel production economically viable on the long term (Hochman et al., 2015; Parmar et al., 2011).

Potential energy production per surface area - Microalgae
Assuming the theoretical biodiesel productivity of low oil content microalgae of 52,000 kg/ha/y by Mata et al. (2010) and a heating value of biodiesel of 41 MJ/kg (Rawat et al., 2013), the estimated potential is:

Potential (MJ/m^2/y) = Yield (kg biodiesel/m^2) * lower heating value biodiesel (MJ/kg)
= 52,000 *10^4 kg/m^2 * 41 MJ/litre biodiesel= **210 MJ/m^2/y**

H. Geothermal direct heating

Operating principles

Geothermal energy is energy in the form of heat, located in the crust of the earth. By drilling a hole into the ground, this energy can be extracted (Twidell & Weir, 2015). The thermal heat is then extracted by pumping a heat carrier (often water) into the ground, which is pumped back to the surface. The heated water is then used directly for heating applications, after which the cooled carrier is reinjected into the ground to maintain the initial conditions[17].

Current state

Direct heating application of geothermal energy is applied on a broad scale around the world, with an overall installed capacity of 15.3 GW_{th} (Twidell & Weir, 2015). The technology is used for different purposes, such as space heating, greenhouse heating, bathing and swimming pool heating and agricultural drying (Lund & Boyd, 2015). Geothermal direct heating on an industrial scale has been applied since the beginning of the 19th centuries (Goldstein & Gerardo, 2011). Taken the overall installed capacity, it can be argued that geothermal direct heating is a well-developed and mature technology.

The temperatures used in direct district heating are close to the actual process temperatures and range from 60 °C to 120 °C (Goldstein & Gerardo, 2011). For this application, a hole is to be drilled varying in depth from 2 to 4 km, since subsurface temperature increases on average by 30°C/km (Twidell & Weir, 2005).

Prospects

Improvements are expected on several components of the systems for geothermal direct heat use (IEA, 2011) Firstly, it is expected that the performance of the pumps, heat exchangers, re-injection technology and storage tanks will increase. Also, higher efficiencies can be achieved by implementing a cascade system. It is expected that drilling cost will go down because of the research and tests that focus on this aspect nowadays (Goldstein & Gerardo, 2011).

Potential energy production per surface area

The potential for geothermal energy on Vlieland will be assessed by looking into the geothermal project in Bleiswijk, the Netherlands. The temperature at the subsurface on Vlieland is around 60°C at 1700 m depth, which is similar to the subsurface temperature in Bleiswijk (Berendsen, 2004; de Boever et al., 2012). The installation in Bleiswijk uses geothermal heat for direct heating of greenhouses with a temperature of 60°C and has an output of 6 MW_{th}(van Leeuwen et al., 2010), with a capacity factor of around 91%[18] with an installation of 100 m^2 (derived from Platform Geothermie, nd).

Potential (MWh/y) = Power (MW_{th}) * capacity factor (%) * hours in a year (h)
6 MW_{th} * 0.91 * 8760 hr/y = 48000 MWh_{th}
Potential (MWh/m^2/y) = Potential (MWh_{th}) / area (m^2)
48000 MWh_{th}/ 100 m^2 = 480 MWh_{th}/m^2/y

The potential of this project is roughly 2000 times the heat content of the total amount of natural gas that is used on the island on a yearly basis (Lab Vlieland, 2016).

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[17] van Wees, J.D., Lecture: geothermal Energy: an introduction to an important RE. Presented at the course fossil resources: past, present and future, 07-04-2016, Utrecht University.

[18] Idem.

In order to meet the demand on Vlieland (since overproduction of heat cannot be exported to the mainland (Twidell & Weir, 2015)), a smaller system can be used and the drilling could be more shallow (<1700m), in order to not succeed its demand by so much. In order to only produce the heat that is currently used on Vlieland, the following power extraction from the subsurface is necessary

Power (MW) = Potential (MWh/y)/capacity factor (%) / hours in year (h)

$22.86\ \text{MWh}_{th} / 0.6 / 8760 = 4.35\ \text{kW}_{th}$

From this it is concluded that the potential for geothermal heat on Vlieland is plentiful.

A side note on the similarities between the area of Bleiswijk and Vlieland is the permeability of the subsurface. The permeability of the subsurface of Vlieland is expected to be much less than the sandstone that is accessed in Bleiswijk (TNO, 1983). This means that water can penetrate the subsurface less easily and less water can be extracted at similar pressures. This either makes the energy extraction rate lower or asks for fracturing of the sandstone to improve the permeability. When the sandstone is fracked to such an extent that it gets the same permeability as the project in Bleiswijk, a comparison can still be made.

I. Geothermal heat pumps

Operating principle

Heat pump systems are systems that displace heat from one location to another. Heat can be extracted from low temperature locations and be delivered to a high temperature location, but they can also be reversed to work in an opposite direction (Çengel & Boles, 2015; IRENA, 2013a). Different heat sources can be used such as soil, groundwater, seawater and air. All heat pump systems work in a similar fashion; coils filled with a working fluid are installed in the energy source and the building where the temperature is controlled. A compressor and expansion valve system then compress and expand the working fluid in the right location in order displace the energy (MacKay, 2009).

The performance of heat pump systems is highly dependent on the temperature of both the source and the sink, where the highest energy returns can be achieved when these temperatures are close together (Çengel & Boles, 2015). Hence, it is useful to have a low temperature heating system installed in the location that needs to be heated (which is currently not common) (Kleefkens, 2011) and have a source that has a relatively high temperature.

Current state

Heat pumps are substantially present in the Netherlands. In 2013 there were over 70,000 heat pumps installed in the Netherlands, most of which are air source heat pumps in the form of an air condition system (Elzenga & Ros, 2014). There are several Dutch producers involved in the heat pump market, such as ATAG, Inventum & Techneco (Kleefkens, 2014), even though the Dutch market is still in its infancy (Kleefkens, 2011).

Prospects

Heat pumps are globally a mature technology, but their efficiency is expected to increase by 30 to 60% for heating applications and 20 to 50% for cooling in the coming thirty years (IRENA, 2013a).

Potential energy production per surface area

The technologies with the highest potential for heating purposes on Vlieland are the soil, groundwater and seawater systems. The air heat pump systems have the problem that they can cause *frosting* in wintertime, which means that so much energy is extracted from the air that the water in the air starts to freeze and the accumulate on the evaporator coil (Çengel & Boles, 2015), which is a relevant problem on Vlieland due to the relative humidity on Vlieland year round (Weather Online, nd). Furthermore, they also have the lowest efficiency of all systems (Twidell & Weir, 2015). Ground source geothermal heat pumps, which tap into the soil or shallow lying aquifer, have the advantage that the temperature at a depth of 2 to 50 meter does not experience seasonal variations in temperature, where the seawater system does experience season variations.

According to Twidell & Weir (2015) a typical ground source heat pump installation extracts around **50 kWh/m^2/year** of heat from the ground. One single heat pump system with a COP (coefficient of performance) of 7, which is among the highest efficiency of these systems (IRENA, 2013a), delivers 7 unit of heat per unit of electricity that is put into the system. For the extraction of 50 kWh/m^2/year of heat, 7.14 kWh/m^2/year of electricity is therefore necessary.

J. Unconventional wind power

Operating principles

As urban wind turbines and conventional wind turbines have been disregarded, the most promising alternative design based on the current level of development and energy generating potential is considered, which is determined on available literature to be the INVELOX system developed by Sheerwind. The INVELOX wind power generator converts wind energy into electricity, using concentrated wind and a turbine system (Sheerwind, 2016b).

More specifically. the system works by taking in wind from all directions with an elevated concentrator, after which the wind is directed through a funnel. Subsequently, the wind gets accelerated as the funnel narrows; this is the Venturi effect, explained by the effect of forcing a fluid true a narrow area leads to an increase in pressure (Sheerwind, 2016b). The accelerated wind then drives an air turbine (or multiple placed in series), which in their turn generates electricity. Finally, the wind is slowed by a diffuser and returned to the open environment.

Current state

The INVELOX is still in its testing phase. Sheerwind has so far build three demo units and two commercial units. These systems are constantly monitored, tested and evaluated on the operations and maintenance (Sheerwind, 2016b). Research by Allaei & Andreopoulos (2014) showed that increased wind velocities (using the INVELOX design) lead to significantly higher power output compared with a reference turbine. It should be noted that the INVELOX's structure is significantly bigger than the reference turbine. Also, the costs of installing an INVELOX are higher compared to the reference turbine.

The rated power of the INVELOX system depends on size of its design and can in theory vary from 500 W to 25 MW. However, INVELOX has been tested with a 600 kW rated power turbine. An advantage of the INVELOX compared to a reference turbine was proved by demonstrations and entails lowering of the cut in speed. The reference turbine has a cut in wind speed of 4 m/s while the INVELOX had a cut in wind speed of 1 m/s, leading to a higher capacity factor. Other advantages described by Allaei & Andreopoulos (2014a) comprise lowering of the turbine placement simplifying operation and maintenance work, usage of smaller turbine blades saving costs and the absence of any visible moving parts from the outside.

Prospects

As stated before, five pilot systems have been realised, but more widespread testing is needed to prove its viability. Consequently, the INVELOX wind power system is still in its developing phase and more pilots are planned. For example, in the Netherland a wind power plant for a rooftop is designed with a rated power of 25 MW. Furthermore, there is an ambition to build a 220 KW and 2.2 MW rated power INVELOX system by the end of 2016 (NedPowerSWH, 2016).

Potential energy production per surface area

The potential of the unconventional wind turbine design on Vlieland depends the available wind and the available space to install a certain amount of capacity. In the research done by Hanssen et al, (2014) it was found that, based on the local wind data, a conventional wind turbine with rated power 2 MW, would produce 10.4 GWh per year. An INVELOX system of 1.8 MW needs about 10 acres of land.

Assuming a 10 acres (=40,469 m^2) installation of 1800 kW and a capacity factor (CF) of 0.7 (Sheerwind, 2016), the potential is :

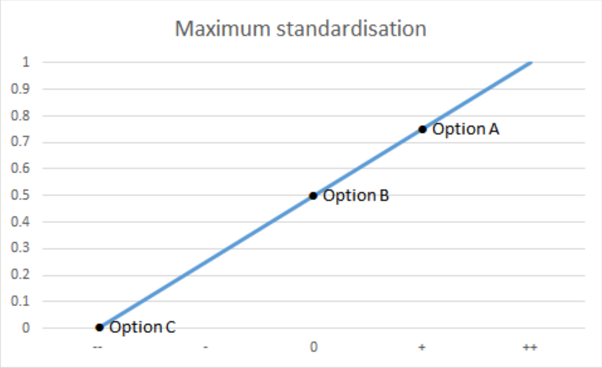
Potential (kWh/m^2/y) = (Nominal power (kW)/surface area (m^2)) * CF * hrs/y
= (1800 kW/40,469 m^2) * 0.7 * 8760 hrs = **272.7 kWh/m^2/y**

Appendix IV Description of standardisation methods

For the standardisations used in the research, there is a linear difference between values across the range of scores. This means that the impact that a difference between two values has on their standardised scores, is constant over the whole scale.

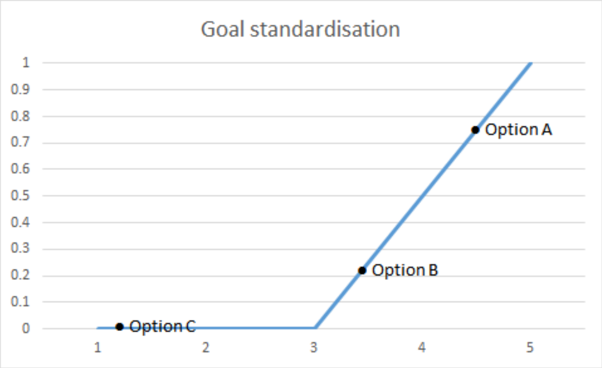
Maximum standardisation

In this method there is an absolute point of most and least favourability (as shown in the figure as '++' and '--' respectively). These point gets the standardized score of 1 and 0. The option that performs worst, C, gets a standardized score of 0. The options that are performing anywhere between the two extremes are scored on a linear scale based on their performance relatively.



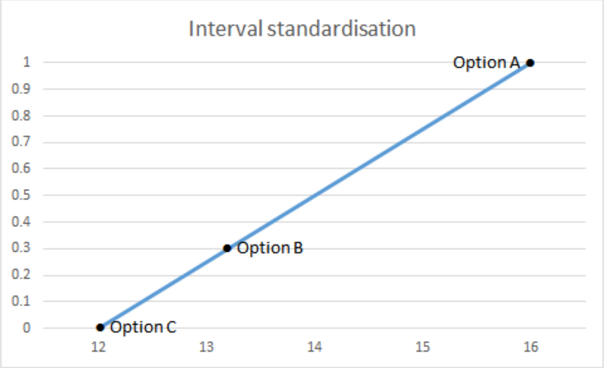
Goal-standardisation

In the situation where there is a minimum and/or maximum acceptable value that an option has to achieve, this method can be used. All options that have an unacceptable value (below the threshold) will not adhere to the 'goal' and receive a standardized score of 0 (option C in the figure). The other scores will be standardised linearly between the goal and the absolute best score that can be achieved (1).



Interval standardisation

For interval standardisation, the scores are standardised between the best and worst scoring options (option A and C in the figure). The best option scores a 1 and the worst option scores a 0 respectively. The other options are scored linearly between the best and worst scoring options.



Appendix V Vlieland's energy use

The potential energy production per surface area is calculated in Appendix III. To put this into perspective and compare the technologies on land or water area use, the energy use of Vlieland is also determined in tonnes of oil equivalent. As determined by the system operator on Vlieland, Vlieland's total energy use in 2015 was 8.7 GWh electricity and 2.5 million m^3 natural gas (Lab Vlieland, 2016). It is not specified what part of the natural gas use is used for heating and what part for cooking.

The IEA conversion method for electricity (IEA, 2015) uses a conversion of 1 MWh = 0.086 toe. For natural gas use, the net caloric value of gas is used and this gives 1 GJ = 0.024 toe (IEA, 2012). The average gross specific caloric value of natural gas in the Netherlands is 33.34 MJ/m^3 (IEA, 2012). The energy consumption on Vlieland, based on 2015, is therefore:

Energy consumption (toe) = Electricity use (MWh) * 0.086 (toe/MWh)
+ Natural gas use (m^3) * 33.34 (MJ/m^3) * 2.39 * 10^{-5} (toe/MJ)
+ petrol fuel use (l) * 8.6 * 10^{-4} (toe/l)
+ diesel fuel use (l) * 9.8 * 10^{-4} (toe/l)

Filling in this formula gives:

Energy consumption (toe) = 8.7*103 (MWh) * 0.086 (toe/MWh)
+ 2.5*106 (m^3) * 33.34 (MJ/m^3) * 2.39*10^{-5} (toe/MJ)
+ 181,900 (l) * 8.6 * 10^{-4} (toe/l)
+ 117,750 (l) * 9.8 * 10^{-4} (toe/l)
= 748 toe + 1990 toe + 156 toe + 115 toe **= 3009 toe**

Appendix VI Stakeholder group division

Stakeholder group	Name	Relevancy
Lab Vlieland	Tijl Couzij	Client
	Govert Reeskamp	Client
	Kees Terwisscha van Scheltinga	Client
Policy Makers	Henk Visser	Alderman municipality of Vlieland
	Robert Lanting	Policy officer municipality of Vlieland
	Jan Roelof Witting	Councilor municipality of Vlieland
Vlieland 2020 group	Marco Bakker	Member Vlieland 2020 group
	Henk Veerdig	Member Vlieland 2020 group
Relevant experts	Antoine Maartens	Expert on renewable energy implementation at Wadden Islands (Urgenda)
	Jan den Ouden	“Energie Cooperatie Vlieland”
	Ard Tijsterman	Vlieland energy challenge[19]

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[19] Vlieland energy challenge is an initiative that strives to explore economically feasible alternatives to wind turbines (Tijl Couzij, personal communication May 11th, 2016)

Appendix VII Individual weight allocation stakeholders

Policy makers				
Criterion	**Henk Visser**	**Robert Lanting**	**Jan Roelof Witting**	**Group average**
Predictability	10	0	15	**8.33**
Intermittency	15	25	20	**20**
In-house knowledge	10	0	0	**3.33**
Time to commercial realisation	5	0	15	**6.67**
Land area use	10	5	0	**5**
Water area use	0	15	0	**5**
Noise	10	15	20	**15**
Social perception	15	20	20	**18.33**
Job Creation	10	10	5	**8.33**
Social benefits	15	10	5	**10**

Experts				
Criterion	**Jan den Ouden**	**Antoine Maartens**	**Ard Tijsterman**	**Group average**
Predictability	22	3.8	15	**13.62**
Intermittency	22	23.1	15	**20.03**
In-house knowledge	8	3.8	10	**7.28**
Time to commercial realisation	2	15.4	15	**10.79**
Land area use	5	15.4	15	**11.79**
Water area use	5	3.8	5	**4.62**
Noise	10	7.7	5	**7.56**
Social perception	20	11.5	7	**12.85**
Job Creation	1	3.8	5	**3.28**
Social benefits	5	11.5	8	**8.18**

Lab Vlieland				
Criteria	**Tijl Couzij**	**Kees Terwisscha van Scheltinga**	**Govert Reeskamp**	**Group average**
Predictability	10	5	11.8	**8.92**
Intermittency	10	5	10.6	**8.53**
In-house knowledge	5	10	8.2	**7.75**
Time to commercial realisation	10	10	5.9	**8.63**
Land area use	10	20	11.8	**13.92**
Water area use	3	15	2.4	**6.78**
Noise	10	5	11.8	**8.92**
Social perception	14	5	8.2	**9.08**
Job Creation	14	20	11.8	**15.25**
Social benefits	14	5	17.6	**12.22**

Vlieland 2020 group			
Criteria	**Marco Bakker**	**Henk Veerdig**	**Group average**
Predictability	10	10	**10**
Intermittency	10	20	**15**
In-house knowledge	5	0	**2.5**
Time to commercial realisation	10	0	**5**
Land area use	10	10	**10**
Water area use	5	0	**2.5**
Noise	5	10	**7.5**
Social perception	30	30	**30**
Job Creation	10	20	**15**
Social benefits	5	0	**2.5**

Appendix VIII Summary of MCA inputs

A) Relevant criteria (including scale, standardisation method and averaged weighting)

Type of criterion	Criterion	Scale	Standardisation	Weighting
Technical	Predictability	--/-/0/+/++	Maximum	10.2
	Intermittency	--/-/0/+/++	Maximum	15.9
	In-house knowledge	0/+/++/+++	Maximum	5.2
Economic	Expected time to realisation	1-9	Maximum	7.8
Environmental	Land area use	ha	Maximum	10.2
	Water area use	ha	Maximum	4.7
	Noise	---/--/-/0	Maximum	9.8
Social	Social perception	Score	Goal	17.6
	Job creation	0/+/++/+++	Maximum	10.5
	Social benefits	0/+/++/+++	Maximum	8.2

B) Standardised scores

	Solar PV	Wave OWC	Wave OB	Wave overtopping	Tidal Range	Tidal current	Macroalgae	Microalgae	Geothermal heating	GHP	Unconventional wind
Predictability	0.25	0.25	0.25	0.25	1	1	1	1	1	1	0.25
Intermittency	0	0	0.25	0	0.25	0.25	1	1	1	1	0
NL knowledge	0.67	0	0.33	0	0.33	1	0.33	0.33	0.67	0.33	0.33
Expected time to commercial realisation	1	0.75	0.75	0.625	1	0.875	0.625	0.625	1	1	0.75
Land area use	0.74	1	1	1	1	1	1	0	0.8	0.46	0.8
Water area use	1	0.99	1	0.98	0.04	0.97	0	1	1	1	1
Noise	1	0.33	0.33	0.33	0	1	0.67	0.67	0.67	0.67	0.67
Social perception	1	0.25	0.75	0.31	0.21	0.53	0.67	0.56	0.38	0.77	0.29
Job creation	0.67	0.33	0.33	0.33	0.33	0.33	1	1	0.67	0.33	0.67
Social benefits	0	0	0	0.67	1	0	0.67	0	0	0	0

Appendix IX Uncertainty allocation

Criteria	Score uncertainty	Weighting uncertainty
Predictability	10%	33%
Intermittency	10%	46%
In-house knowledge	10%	52%
Expected time to realisation	30%	39%
Land area use	30%	51%
Water area use	30%	47%
Noise	10%	54%
Social perception	30%	71%
Job creation	10%	69%
Social benefits	10%	70%

The weighting uncertainty is the largest deviation from the average weighting (in %), that either of the four stakeholder groups assigned. E.g. if the average weighting was 10 for a criterion, but one of the groups assigned a weighting factor of 15, the uncertainty is 50%.

Appendix X Social perception survey

A) Survey set-up: front page and scoring form

Enquête duurzame energietechnologieën Vlieland

Wat fijn dat u meedoet aan deze enquête, bedankt!

Wij zijn studenten van de universiteit Utrecht en wij doen onderzoek naar potentiele duurzame energie technologieën voor Vlieland.

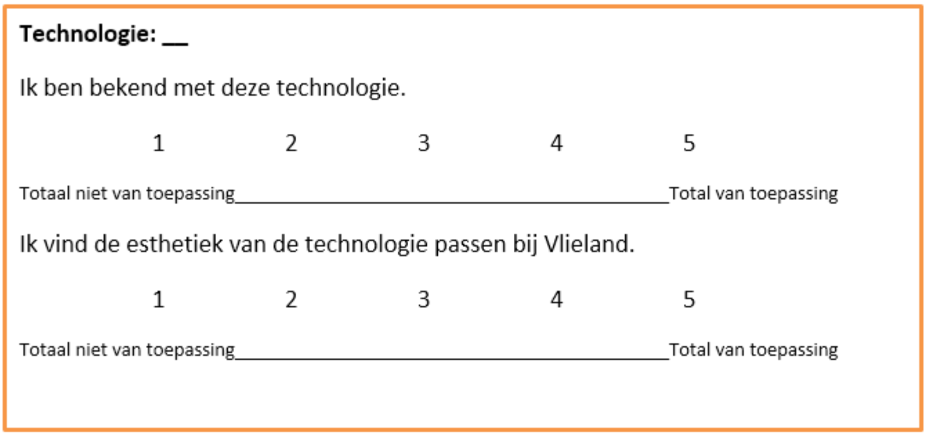
Er zijn misschien wel meer dan duizend en één verschillende manieren om Vlieland in de toekomst nog duurzamer en uiteindelijk energie neutraal te maken. Vlieland heeft veel potentie voor duurzame technologieën, omdat Vlieland over veel duurzame energiebronnen beschikt, wind, zon, de zee en aardwarmte. Daarnaast is er een enorme ontwikkeling gaande als het gaat om duurzame energie systemen en technologieën. De mogelijkheden zijn daar, maar wat is de meest geschikte? Naast de technische en economische 'geschiktheid' is het ook belangrijk of een techniek geschikt is in de betreffende omgeving. Het is belangrijk dat een techniek past in de omgeving en dat de gemeenschap een positieve houding heeft tegenover de technologie. Om deze reden willen wij u een aantal vragen stellen.

In deze enquête zijn wij benieuwd naar zowel de kennis rondom bepaalde technieken als esthetische geschiktheid van een techniek voor Vlieland.

U zult steeds twee foto's zien van een potentiële technologie voor Vlieland. Er zij twee stellingen:

1. *Ik ben bekend met deze technologie*
2. *Ik vind de esthetiek van de technologie passen bij Vlieland.*

Wij zijn benieuwd naar de mate waarin deze stellingen van toepassing zijn voor u. U kunt antwoorden op een schaal van 1 tot 5. Waar 1 staat voor totaal niet van toepassing en 5 voor totaal van toepassing.



Technologie: __

Ik ben bekend met deze technologie.

1 2 3 4 5

Totaal niet van toepassing____Total van toepassing

Ik vind de esthetiek van de technologie passen bij Vlieland.

1 2 3 4 5

Totaal niet van toepassing____Total van toepassing

B) Visual representations used (2 per technology to give an indication of multiple possibilities)

Technology #1: Tidal current energy

Technology #2: Tidal Range power

Technology #3: Oscillating bodies wave power

Technology #4: Oscillating water column

Technology #5: Overtopping wave power

Technology #6: Unconventional wind power

Technology #7: Conventional wind power (used as a reference, not included in the MCA)

Technology #8: Land based biomass production: micro algae

Technology #9: Photovoltaic solar cells

Technology #10: Sea based biomass production: macro algae

Technology #11: Geothermal heat pump

Technology #12: Geothermal direct heating

Appendix XI Account of conducting surveys on Vlieland

Approach

In total 34 surveys were conducted among the local community between the 25th and 27th of May (2016). The surveys were prepared by printing and laminating all the questionnaires. Prior to conducting the surveys, we discussed our approach. People were approached in pairs of two, where one person conducted the conversation and the other person filled out the scores given by the participant. Since the local community was the target group of the survey, a strategy was found to find the right participant. This was not always straight-forward since Vlieland receives a lot of visitors. So the surveys were conducted in the main street. One pair went inside the local stores while the other pair remained on the street to conduct the surveys. The participants were approached with the question; 'Would you like to participate in a survey concerning sustainability technologies on Vlieland?'. If they agreed, it would be checked if they were residents and if this was the case, the survey was conducted. A survey on average took about ten to fifteen minutes. Yet, often people were interested in the research and the technologies, which resulted in a conversation about the research and sustainability on Vlieland in general. The gross of the participants liked the research we were conducting and indicated to be interested in the results.

Some additional results

Pretty much all the participants were familiar with solar energy, and positive about it. Some even had solar PV panels installed on their roof and most at least knew someone with PV panels installed.

People felt involved with renewable implementation and recognised its importance.

In general, all participants were aware of sustainability in a broad sense.

Many people had a preference for either of the two graphical representations of the same technology. E.g. floating devices were generally preferred over shore-based installations.

Appendix XII Summary of the interview with Henk Visser

Interviewee: Henk Visser
Interviewer: Lennard Visser
Date: 26-05-2016, 15:00
Location: conducted over the phone

Henk Visser

Henk Visser has been alderman of the municipality of Vlieland since 2010 and is responsible for energy- and sustainability policies, social affairs and employment, public health, environment, welfare, tourism and culture, sport and recreation and various other projects (Overheid in Friesland, nd). Subsequently, Visser has been dealing with several energy projects including energy efficiency and the zero-emission district at Vlieland, and closely involved in the implementation process of the planned solar PV field.

Solar field Vliehors

Vlieland is planning to construct a 0.8-hectare solar field of around at the Vliehors, terrain of the Dutch National Defence, which will provide electricity for 250 households, equal to 900,000 kWh annually. This plan first came up in 2014, as a direct consequence to enable Vlieland to meet the 2020 energy neutrality targets. Moreover, this specific location was chosen for as the Dutch National Defense was looking to exploit some of its terrain, the field is considered as flat and suitable for solar panels, and one of the few areas available for the construction of a solar field as most of the island is owned by Staatsbosbeheer and the remainder of the island consists of the village Oost-Vlieland and therefore an urban area.

After identifying a possible site for construction, the process towards implementation of the solar field started. Subsequently, the municipality of Vlieland involved several important stakeholders in the project, including the Energy Cooperation Vlieland (ECV), Urgenda and Lab Vlieland. The ECV and Lab Vlieland have been closely involved in planning and policy making. Urgenda has mainly been involved for advice during the implementation process. Leaving the municipality of Vlieland responsible for facilitating the project and spatial planning including jurisdiction and the Dutch National Defence for is facilitating the 0.8 ha field. Over the past two years these parties have been working preparing the construction site and plan the solar field management maintenance and operation. During this period Alliander, the network operator at Vlieland, constructed the necessary electric cables to connect the field to the grid with a total cost of 80,000 euros, which was financed by the municipality of Vlieland. Finally, the municipality of Vlieland granted authorization for the implementation of the solar field earlier this year, on February 9th (Omrop Fryslân, 2016).

Recently, the SDE+ subsidy has been requested and must be awaited before construction can start, as awarding this subsidy will have impact on the project's financial structure. If not granted, the municipality of Vlieland will have to look into additional investors. Moreover, Islanders will be motivated to participate or be part of the project, before and during construction and the project will be marketed towards potential interested parties to finalize selection for parties responsible for operation and maintenance of the solar field.

Finally, due to the common objectives of the parties involved there have been very limited bottlenecks in the process so far.

Energy neutral Vlieland 2020 target

The 2020 targets for Vlieland can still be achieved provided that stakeholders involved are willing to cooperate on the implementation of sustainable resources. This is to be expected as both the province of

Friesland and the municipality of Vlieland have pledged to achieve the 2020 energy neutrality target. According to Henk Visser this is to be achieved by the implementation of 1 or 2 wind turbine(s) and/or an extra solar field. Besides, energy savings measures (in housing) will be taken to reduce the island's energy consumption. Zero net energy usage has already been tested on 50 houses by Urgenda, and may be applied on more houses.

The municipality of Vlieland contemplates that there is sufficient public support to implement 1 or 2 wind turbines at Vlieland to allow for energy neutrality on the short term. However, the province of Friesland is considered to be a major counterpart regarding the implementation of these wind turbines.

If the implementation of the planned solar field turns out to be successful, the municipality of Vlieland will consider to construct a second solar field. There are two potential locations for: (1) the solar field may be placed on a terrain owned by Staatsbosbeheer and (2) the rooftops of the industrial area in the harbour of Vlieland will be used to place the solar panels on.

Future possible methods to generate sustainable energy might be the construction of a geothermal power plant. However, research of Grontmij concluded that this is not considered to become economically feasible within the next 30 to 50 years as one needs to drill 4 km deep.

Appendix XIII Summary of the interview with Ad van Wijk

Interviewee: Ad van Wijk, professor in future energy systems, TU Delft
Interviewer: Laura Mittelmeijer
Date: May 13th, 2016, 11:30
Location: conducted by phone

Research approach

The approach of this research, solely looking at energy producing technologies, is old-fashioned. By looking at the production and consumption separately, a large, innovative part of development of the energy system is missed. A modern, integrated approach should be taken as the future energy system will look very different from what it looks like now.

Future energy system

The future energy system is an integrated system, where producing and consuming technologies are looked up on simultaneously. They have a strong interaction which cannot be ignored. A combination of energy saving measures and energy producing technologies will be the long term solution. It is the wrong approach to look at centralised energy production, since local energy production, integrated in residential buildings, is much more relevant. An example is looking at solar thermal collectors in combination with shower water recycling. These type of innovations will make a real difference.

Vlieland

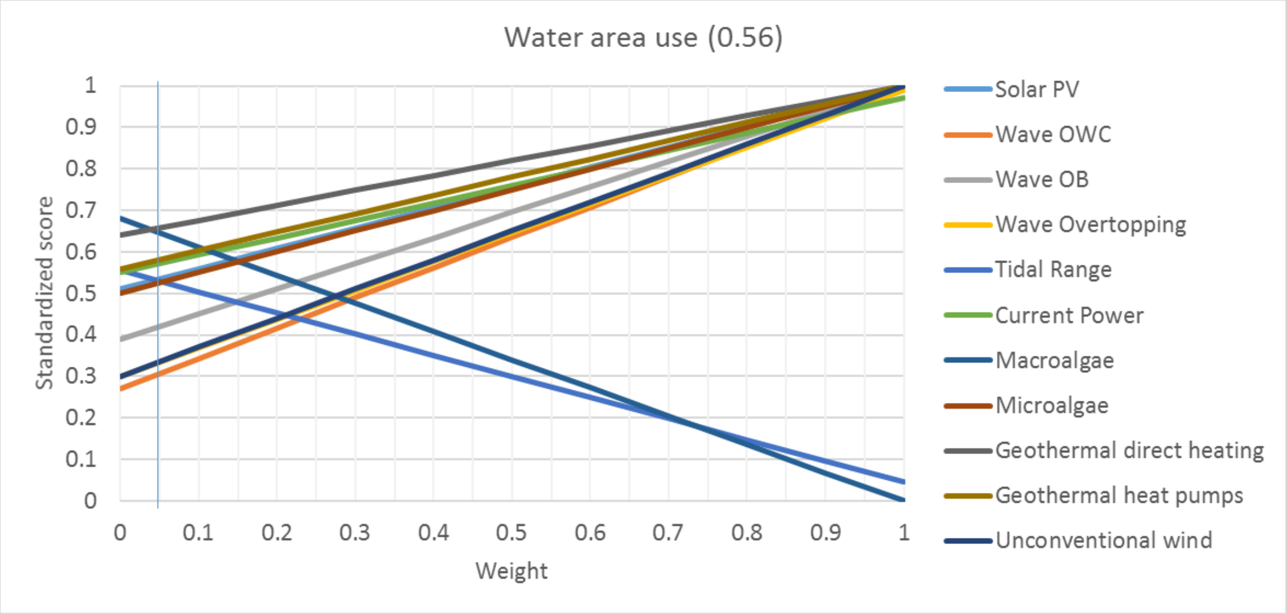
The energy system on Vlieland is very small-scale. On such a scale, only system integrated approaches are interesting. Vlieland is too small and it is also too late now for Vlieland to be an actual testing ground for sustainable energy technologies. Testing and pilot projects are already deployed all over the world, since sustainability is a worldwide movement. It is a popular vision now, to be a testing ground, but it is not realistic for Vlieland.

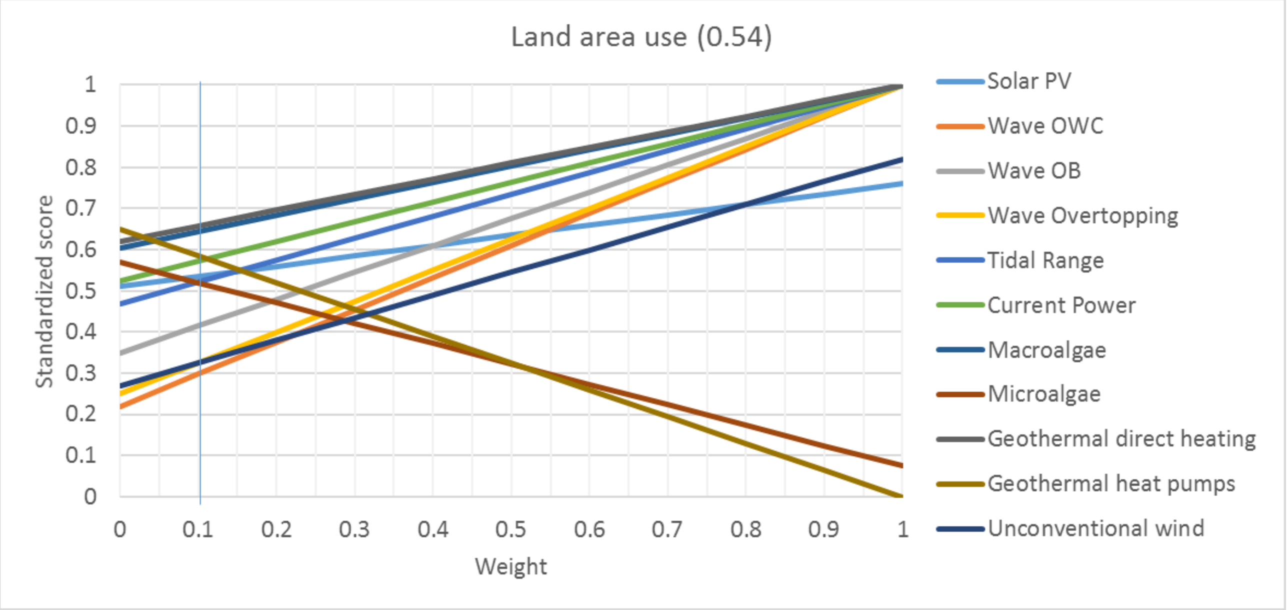
Possibilities

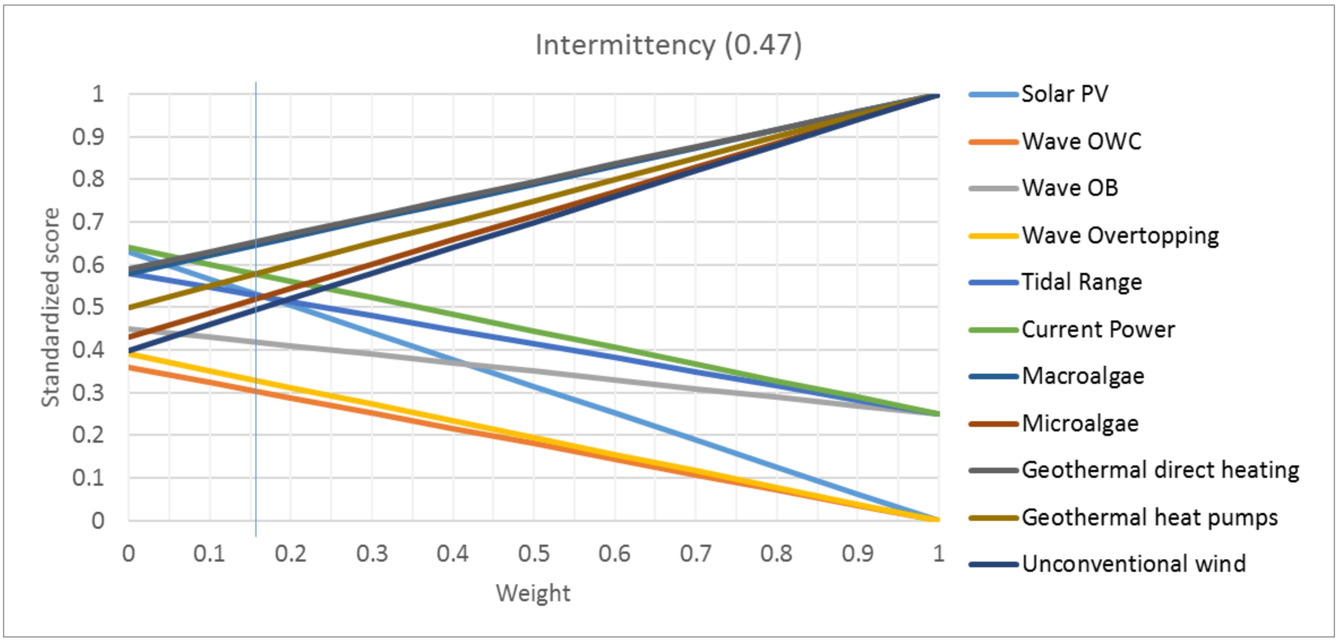
The possibilities for a sustainable energy system on Vlieland are integrated system solutions. For instance, off-grid street lighting using solar energy and storage and local small-scale systems for heating using solar thermal collectors or heat pumps could be interesting. Also, smart grid solutions, smart EV-charging and electric bicycle charging should be looked at. It might seem futuristic, but it is an interesting innovation in which Vlieland could be a frontrunner: package delivery using drones on PV power. These type of innovations would be suitable for Vlieland.

Appendix XIV Sensitivity analysis results, including average slope

In paragraph 6.4, it was explained how sensitivity analysis graphs are to be read. The absolute average sensitivity of each criterion (the value behind each graph title) was determined by taking the average of the absolute difference between the final score of each technology when the criterion was weight at 0 and 100% respectively. To put this into perspective, a low value of this measure for a certain criterion indicates that the score of each technology is relatively insensitive to the weight of the criterion, while a high value implies the opposite. As can be seen, the criteria are sensitive to different extents. The criteria that are most sensitive are in decreasing order water area use (0.56), land area use (0.54), intermittency (0.47), social benefits (0.47) and social perception (0.42). The rest is less sensitive, in order expected time to commercial realisation (0.33), predictability (0.32), job creation (0.28), level of in-house knowledge (0.23) and noise (0.21).






Intermittency (0.47)
Standardized score
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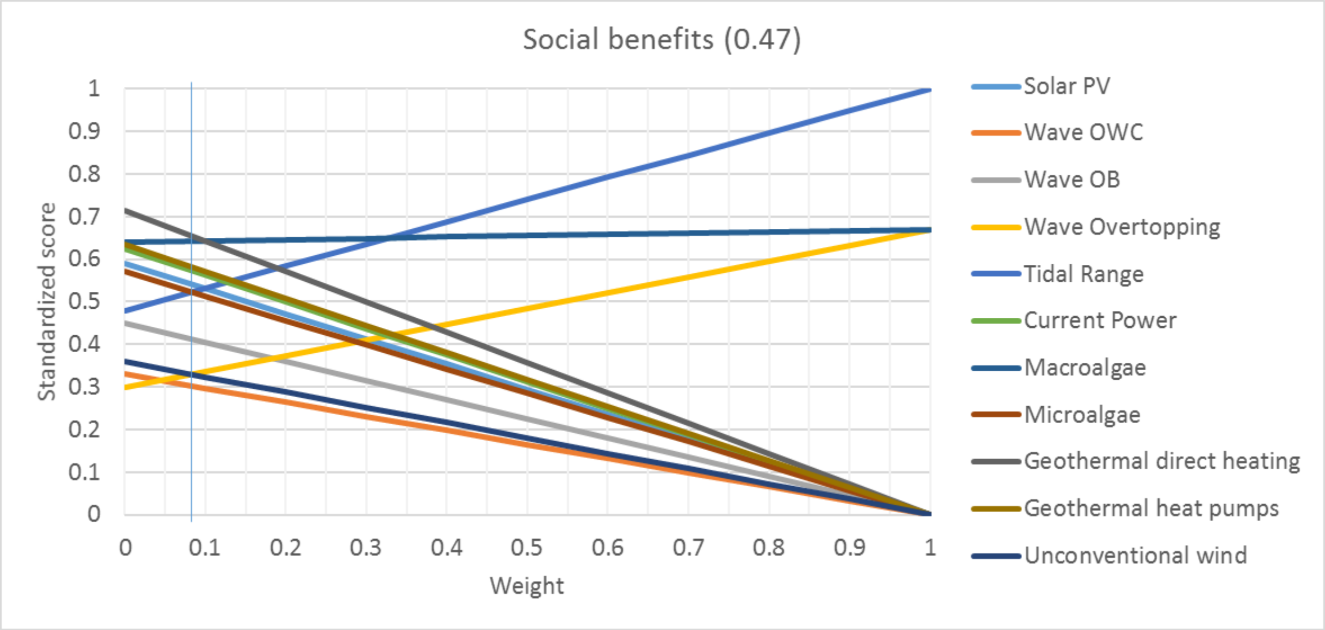
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Weight
Solar PV
Wave OWC
Wave OB
Wave Overtopping
Tidal Range
Current Power
Macroalgae
Microalgae
Geothermal direct heating
Geothermal heat pumps
Unconventional wind


Social benefits (0.47)
Standardized score
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Weight
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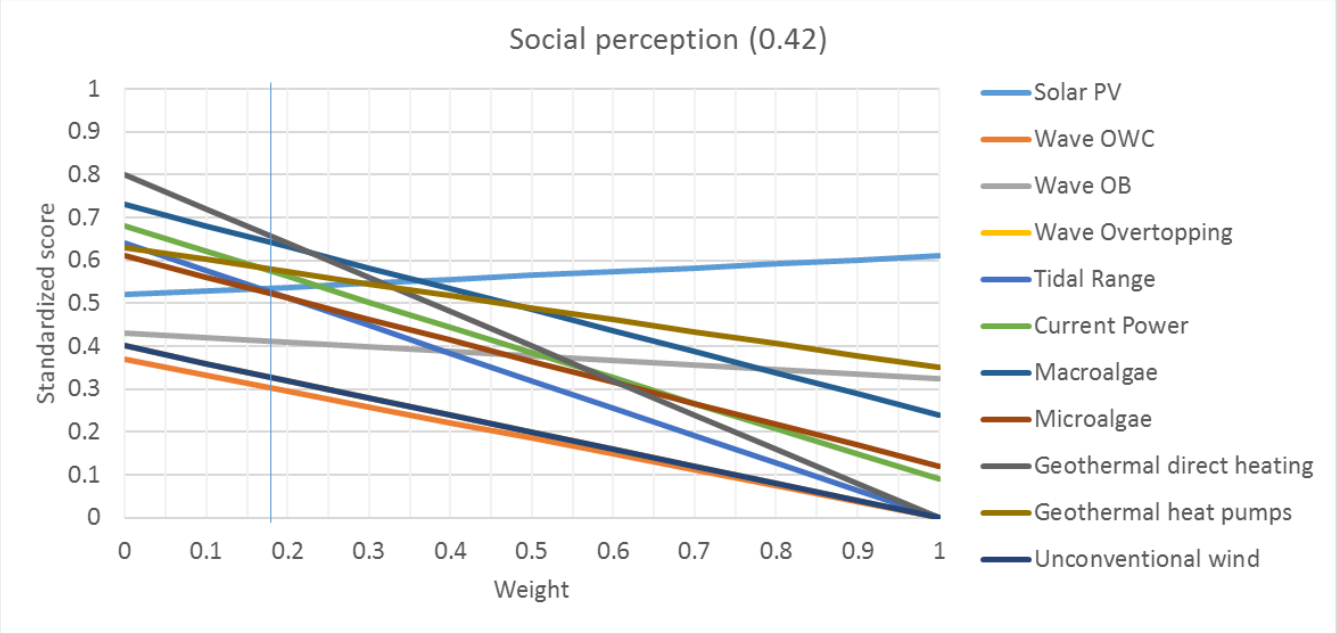
Wave OB
Wave Overtopping
Tidal Range
Current Power
Macroalgae
Microalgae
Geothermal direct heating
Geothermal heat pumps
Unconventional wind


Social perception (0.42)
Standardized score
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0.7
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0.4
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0
0.1
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1
Weight
Solar PV
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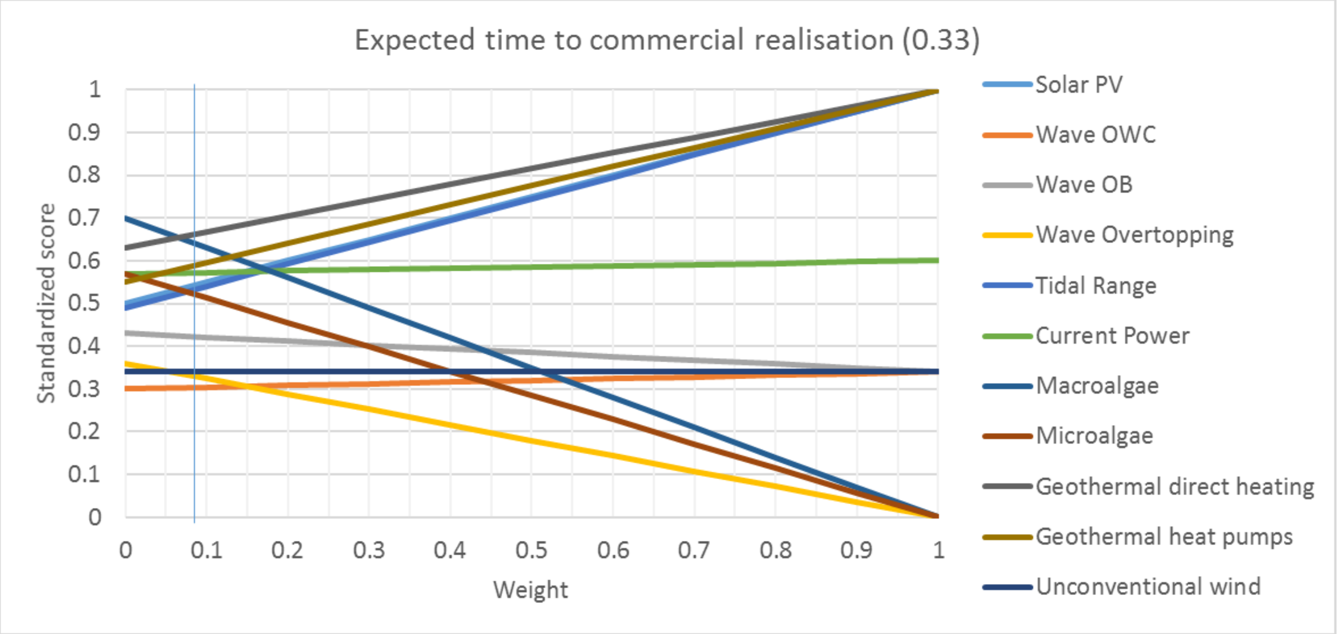
Wave Overtopping
Tidal Range
Current Power
Macroalgae
Microalgae
Geothermal direct heating
Geothermal heat pumps
Unconventional wind


Expected time to commercial realisation (0.33)
Standardized score
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0.8
0.7
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0.5
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0
0.1
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0.4
0.5
0.6
0.7
0.8
0.9
1
Weight
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Current Power
Macroalgae
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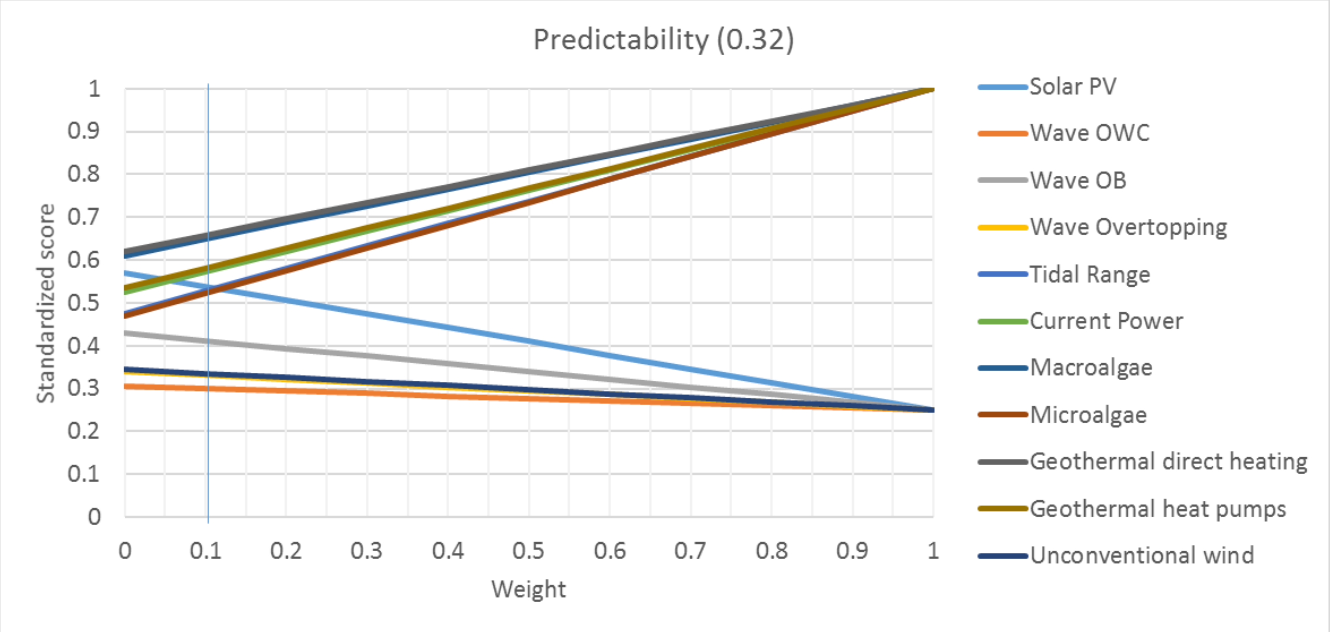
Geothermal direct heating
Geothermal heat pumps
Unconventional wind


Predictability (0.32)
Standardized score
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0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Weight
Solar PV
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Wave OB
Wave Overtopping
Tidal Range
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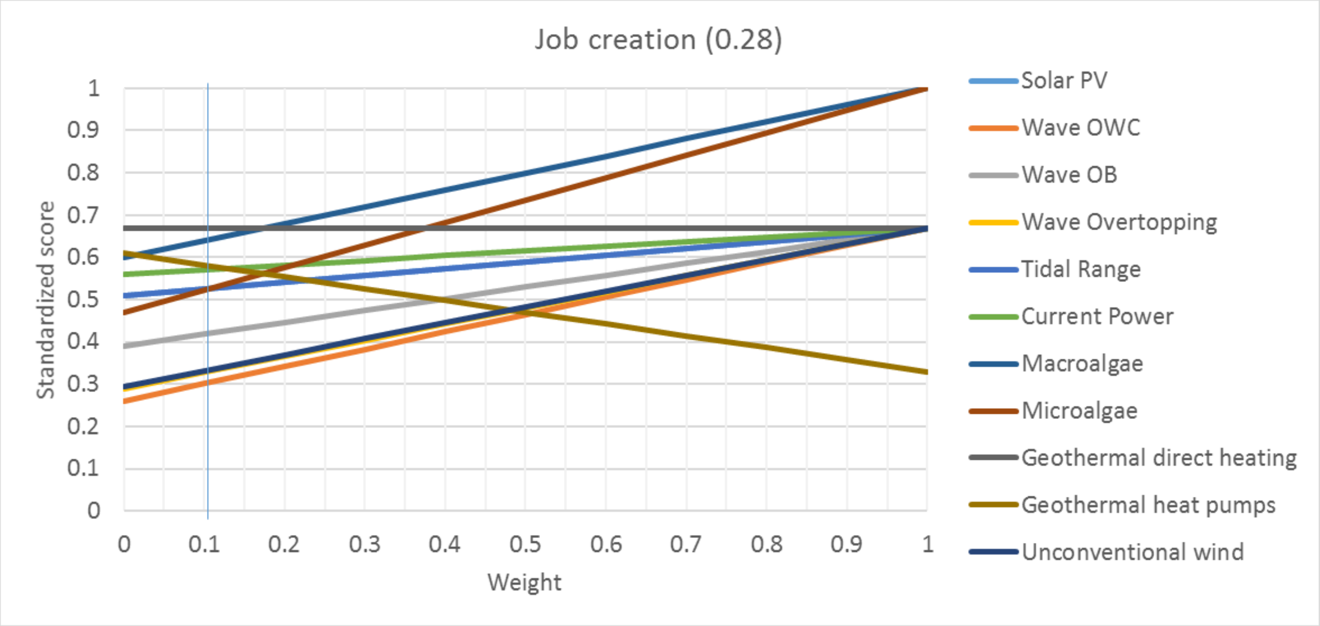
Macroalgae
Microalgae
Geothermal direct heating
Geothermal heat pumps
Unconventional wind


Job creation (0.28)
Standardized score
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0.7
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0.5
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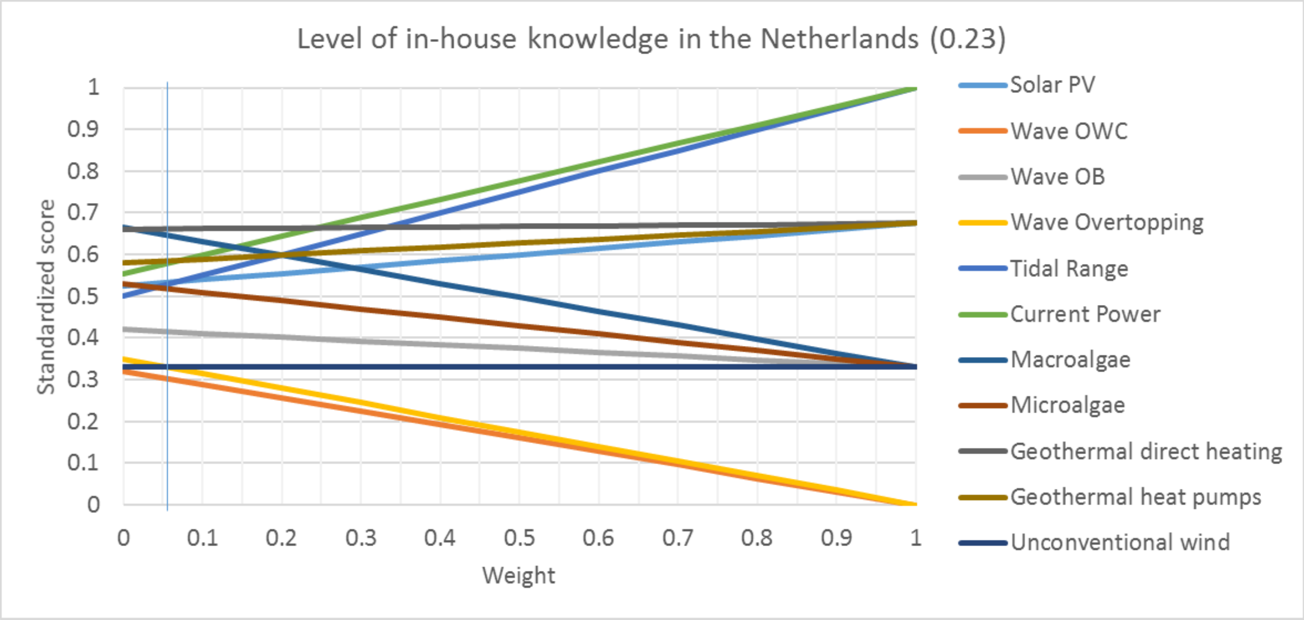
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Weight
Solar PV
Wave OWC
Wave OB
Wave Overtopping
Tidal Range
Current Power
Macroalgae
Microalgae
Geothermal direct heating
Geothermal heat pumps
Unconventional wind


Level of in-house knowledge in the Netherlands (0.23)
Standardized score
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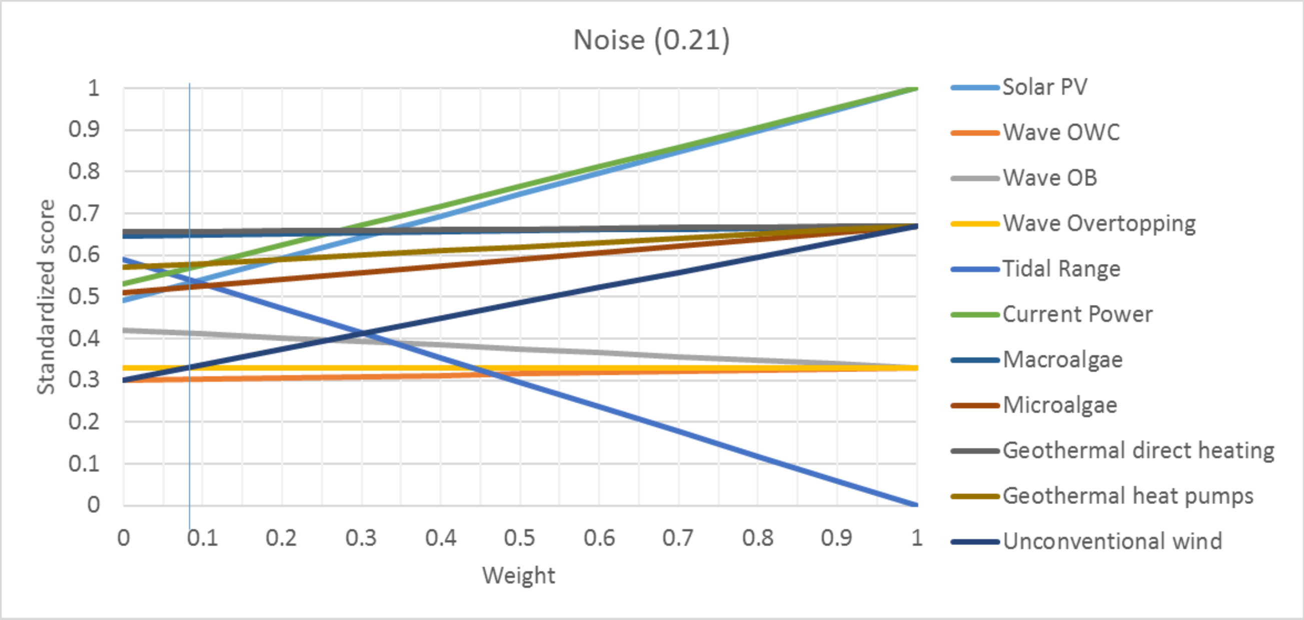
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Weight
Solar PV
Wave OWC
Wave OB
Wave Overtopping
Tidal Range
Current Power
Macroalgae
Microalgae
Geothermal direct heating
Geothermal heat pumps
Unconventional wind


Noise (0.21)
Standardized score
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0.5
0.4
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0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Weight
Solar PV
Wave OWC
Wave OB
Wave Overtopping
Tidal Range
Current Power
Macroalgae
Microalgae
Geothermal direct heating
Geothermal heat pumps
Unconventional wind