Final report
Consultancy Project – Lab Vlieland 2014
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Final Report

Vlieland Energy Independent by 2020

How can Vlieland become energy independent by 2020 using renewables?

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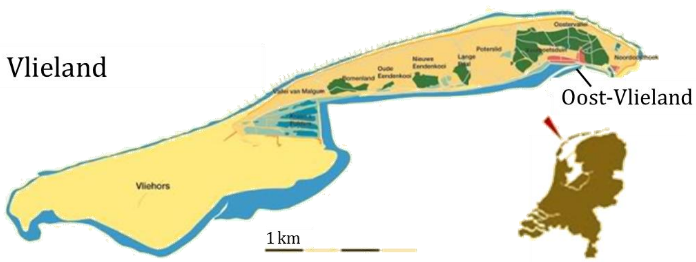
Nederlandse Samenvatting (Dutch executive summary)

Introductie
De Europese Unie heeft doelen gezet om in 2020 20% minder broeikasgassen uit te stoten en 20% minder energie te gebruiken ten opzichte van 1990. Daarbij is het doel voor Nederland om in 2020 14% duurzame energie te produceren (EU, 2014a). Geïnspireerd door het succes van het Deense eiland Samsø op het gebied van duurzame lokale energievoorziening (Andersen et al., 2013) hebben de Waddeneilanden in 2007 gezamenlijk besloten dat de eilanden in 2020 energieonafhankelijk[1] willen zijn. Dit doel wil men behalen door middel van duurzame energiebronnen, energie-efficiënte maatregelen en opties voor energiebesparing (Ambitiemanifest Waddeneilanden, 2007).

Op Vlieland (afbeelding 1), de focus van deze studie, zijn tot nu toe slechts kleinschalige duurzame initiatieven tot stand gekomen (Boorsma, 2010). De opdrachtgever van dit onderzoek, Lab Vlieland, is bezorgd over de huidige voortgang van het eiland richting het doel van energieonafhankelijkheid in 2020. Lab Vlieland wil daarom een advies over wat de beste manier is om dit doel te bereiken.



Afbeelding 1. *Kaart van Vlieland*

Onderzoeksvraag en onderzoeksdomein
De hoofdvraag in dit onderzoek is als volgt geformuleerd: "Hoe kan Vlieland energieonafhankelijk worden in 2020 door middel van hernieuwbare energiebronnen?".

Deze studie richt zich op de gemeente Vlieland en de bijbehorende fysieke grenzen van het eiland met uitzondering van rederij Doeksen. Deze veerdienst is meegenomen omdat de verbinding met het vasteland als cruciaal gezien wordt voor Vlieland. In dit onderzoek is alleen in detail gekeken naar hernieuwbare energiebronnen. Energie-efficiënte maatregelen worden alleen in hun geheel meegenomen in de energie-efficiënte trendlijn voor 2020. Energiebesparende maatregelen zijn niet behandeld in dit onderzoek.

Methode
Om te bepalen hoe Vlieland energieonafhankelijk kan worden in 2020 is het nodig om te weten wat het energiegebruik zal zijn in 2020. Er moest daarvoor een schatting gemaakt worden hoe het energiegebruik zou veranderen ten opzichte van het huidige gebruik. Om een reële vergelijking van energiegebruik en -productie te maken is gewerkt met het primair energiegebruik[2]. Voor het huidige energiegebruik van Vlieland zijn verschillende gegevens

[1] Energieonafhankelijkheid is hier gedefinieerd als de situatie waarbij er nul of positieve net export van primaire energie op het eiland plaatsvindt. Dit betekent dat er nog steeds uitwisseling met het vaste land mag plaatsvinden.

[2] Primaire energie is de totale benodigde hoeveelheid energie om een bepaalde hoeveelheid energie in een energiedrager (zoals elektriciteit) te produceren. De primaire energie is groter dan de

verzameld. Waarden voor gasverbruik en elektriciteitsgebruik zijn afgeleid uit Energie in Beeld (Energie in beeld, 2014). De afschattingen van het energiegebruik voor vervoer zijn aangereikt door rederij Doeksen en het lokale tankstation. Het energiegebruik voor 2020 is afgeschat door middel van twee trendlijnen: één waarbij Vlieland de historische energietrend doorzet en een tweede waarbij maatregelen ten behoeve van energie-efficiëntie toegepast worden. Dit laatste is in overeenstemming met het beoogde nationale en EU-beleid (DNEEP, 2014).

Om te bepalen welke hernieuwbare energiebronnen van toepassing zijn voor Vlieland is een lijst gemaakt die gebaseerd is op Twidell & Weir (2007). Deze lijst is daarna verkort door gebruik te maken van drie criteria: commerciële beschikbaarheid voor 2020, energiepotentieel en economische haalbaarheid. Na toetsing van deze criteria bleef een lijst van drie haalbare technologieën over. Deze opties zijn: windenergie, zonnepanelen en zonnecollectoren. Deze technologieën zijn vervolgens uitgesplitst en verder onderzocht in vijf opties: grote windturbines, kleine windturbines, zonnepanelen op daken, een zonneweide en zonnecollectoren op daken. Voor elke optie zijn het potentieel, de kosten en de winstgevendheid berekend.

Het potentieel [3] geeft aan in hoeverre de optie kan bijdragen aan de energieonafhankelijkheid van Vlieland en is bepaald door middel van gegevens uit literatuur en van commerciële leveranciers. De specifieke kosten[4] van het produceren van energie per optie zijn bepaald door literatuuronderzoeken dienen als indicator om te bepalen welke optie het goedkoopst energie kan leveren. Subsidies zijn meegenomen in de kostenberekening. Behalve de kosten van het produceren van energie zijn er ook opbrengsten van het verkopen of besparen van energie. Hiermee is de interne-opbrengstvoet[5] berekend. Deze is als indicator voor de winstgevendheid gebruikt (Blok, 2007).

Om de mogelijke weerstand[6] van zowel belanghebbenden als bewoners tegen de opties in kaart te brengen is een vragenlijst opgesteld. Deze lijst is ingevuld door lokale bewoners en afgevaardigden van de Gemeente Vlieland, Provincie Friesland, kampeerterrein Stortemelk, Energie Coöperatie Vlieland, havenmeesters, de middelbare school en Defensie.

Als ondersteuning voor het rangschikken van de verschillende technologie-opties is een multi-criteria analyse (MCA)[7] gebruikt. Voor de MCA zijn vier criteria gekozen: de kosten en het potentieel die voortvloeien uit de techno-economische analyse en de mogelijke weerstand van zowel belanghebbenden als bewoners tegen opties vanuit de vragenlijst. De MCA is uitgevoerd vanuit drie perspectieven: door middel van een techno-economische weging, een weging van Lab Vlieland en een weging van de gemeente.

Met behulp van de rangschikking van de technologische opties per perspectief is een energievisie voor 2020 opgesteld. Als uitgangspunt voor het formuleren van de energievisie zijn verschillende combinaties van opties gemaakt. Hierbij is het potentieel van de

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uiteindelijke hoeveelheid energie in de dragen, want bij de productie van energiedragers treden namelijk energieverliezen op.

[3] Potentieel is hier uitgedrukt in primair energie.

[4] Specifieke kosten zijn de kosten voor het produceren van energie uitgedrukt per eenheid primaire energie.

[5] De interne-opbrengstvoet staat voor het jaarlijkse rentepercentage dat investeerders kunnen verwachten als opbrengst van hun investering.

[6] Met weerstand wordt in deze studie alleen de forse weerstand tegen een technologische optie bedoeld.

[7] Multi-criteria analyse is een middel om opties te vergelijken met gebruik van verschillende criteria.

technologische opties opgeteld tot het bereiken van de energievraag voor 2020. Optelling vond plaats aan de hand van de rangschikking die uit de MCA voortvloeide. Voor elke combinatie werden de specifieke kosten, de interne-opbrengstvoet en de totale investeringen berekend.

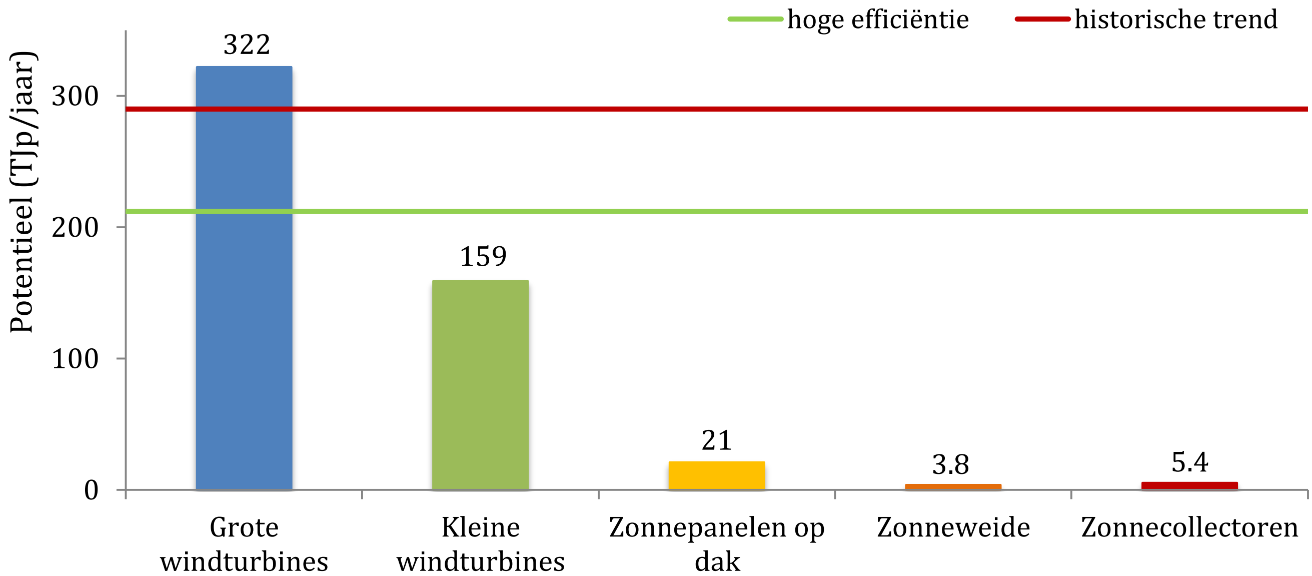
Resultaten

Energiegebruik en -trends

Het huidige energiegebruik van Vlieland is vastgesteld op 271 TJ_p. Deze hoeveelheid zal toenemen tot 290 TJ_p wanneer de historische trend op Vlieland doorzet. Echter, wanneer de energie-efficiënte trend doorzet zal het primaire energiegebruik afnemen naar 212 TJ_p in 2020.

Potentieel

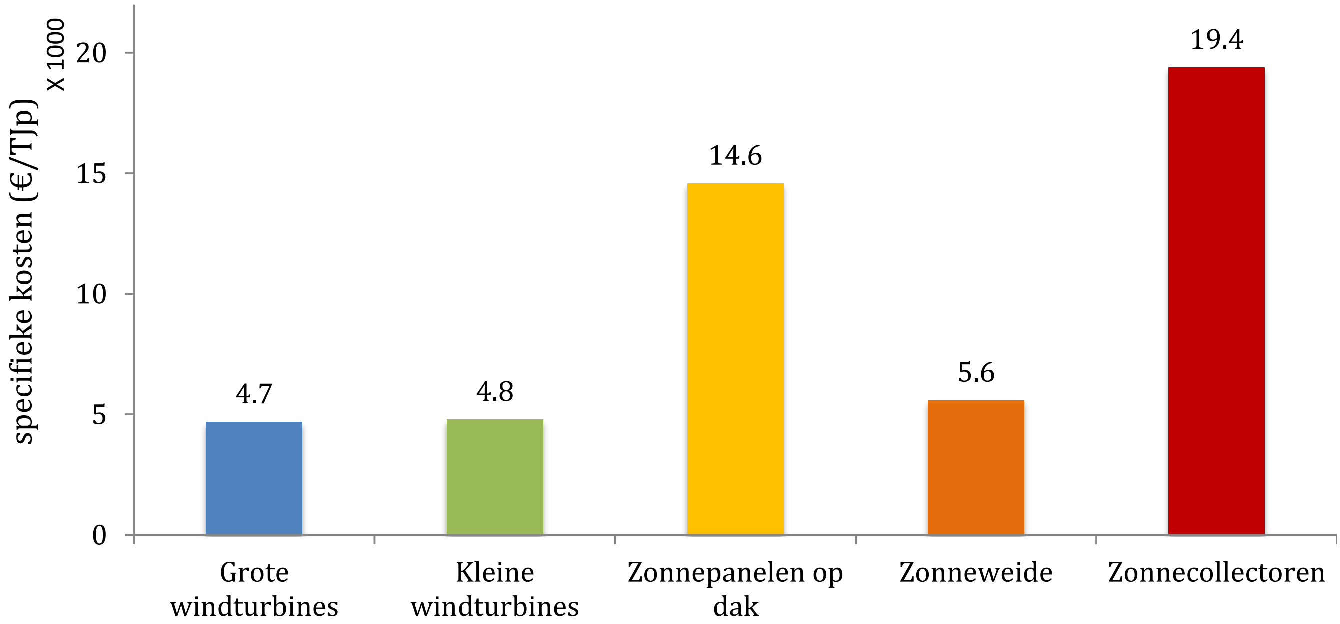
Het potentieel per technologische optie is weergegeven in afbeelding 2. Hieruit volgt dat grote windturbines de gehele energievraag in 2020 kunnen dekken onder beide trends, gevolgd door een mogelijke bescheidenere bijdrage van kleine windturbines. De technologische opties op het gebied van zonne-energie hebben een minder opvallend maar mogelijk aandeel in een hernieuwbare energiemix op Vlieland richting 2020.



***Afbeelding 2** Potentieel uitgezet voor de verschillende technologische opties.*

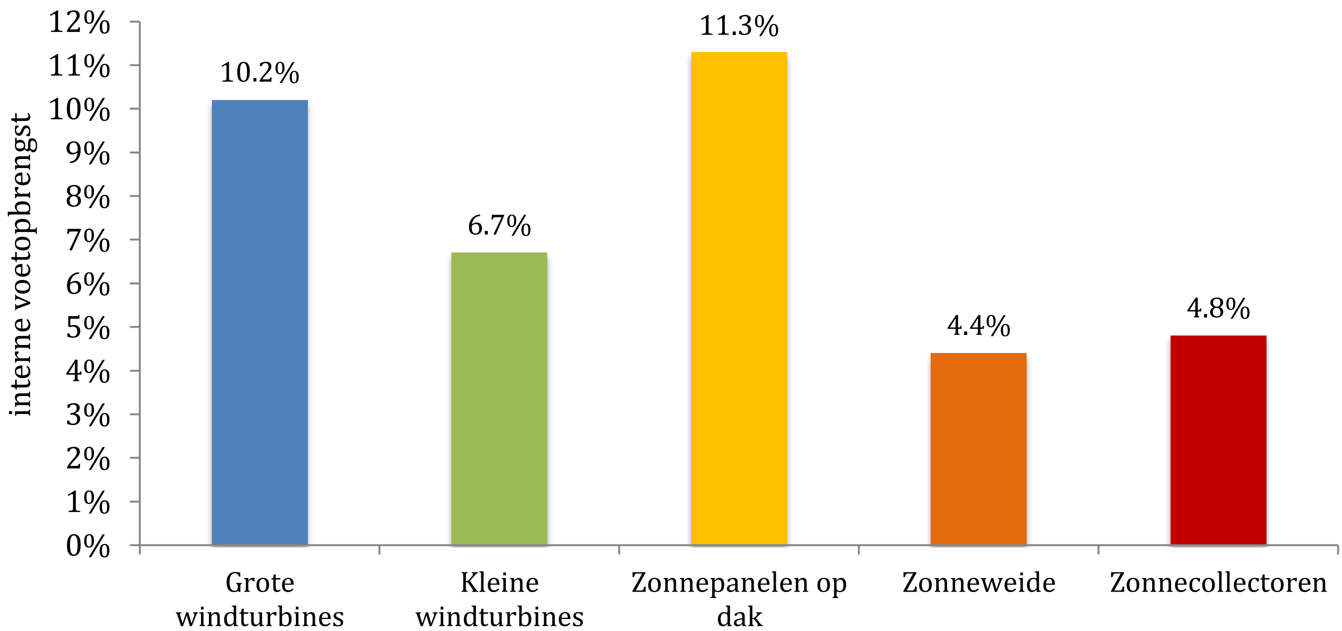
Kosten

In ***Afbeelding*** zijn de specifieke kosten per technologie-optie uitgezet. Grote en kleine windturbines zijn het voordeligst, gevolgd door de zonneweide. Zonnepanelen op daken en zonnecollectoren vallen duurder uit vergeleken met de zonneweide, omdat ze op vele plaatsen kleinschalig geïnstalleerd worden en niet optimaal naar de zon georiënteerd zijn.



Afbeelding 3 *Specifieke kosten uitgezet voor de verschillende technologische opties.*

Winstgevendheid
De technologische opties betalen zich uit over hun levensduur met interne-opbrengstvoeten tussen ongeveer 4% en 11% (zie afbeelding 4). Zonnepanelen op daken hebben de hoogste interne-opbrengstvoet, met name door de hoge prijs van elektriciteit die vermeden wordt. Grote windturbines scoren als tweede en kleine windturbines als derde. De zonneweide heeft een relatief lage interne-opbrengstvoet. Deze is het gevolg van de lage elektriciteitsproductievergoeding vergeleken met de vermeden elektriciteitsprijs die is aangenomen voor zonnepanelen op daken. Vanwege de relatief lage energieproductie tegen gemiddelde investeringskosten hebben zonnecollectoren een lage interne-opbrengstvoet.



Afbeelding 4 *Interne-opbrengstvoet voor de verschillende technologische opties.*

Mogelijke weerstand van bewoners en belanghebbenden

Uit de enquête onder bewoners van Vlieland blijkt dat technologische optie van meerdere kleine windturbines de meeste weerstand hebben. Daarna komt de optie van enkele grote windturbines. Minder weerstand hebben zonnepanelen en zonnecollectoren op daken. De zonneweide heeft de minste weerstand.

Vanuit de enquête onder belanghebbenden blijkt dat grote windturbines gepaard gaan met de meeste weerstand. Kleine windturbines hebben iets minder weerstand. Zonnepanelen en zonnecollectoren op daken en de zonneweide hebben geen weerstand (zie voetnoot 6) vanuit belanghebbenden.

Multi-criteria analyse

Vanuit techno-economisch perspectief is de ranglijst van hoger scorende naar lager scorende opties als volgt: grote windturbines, kleine windturbines, zonneweide, zonnepanelen op daken en zonnecollectoren. Hier ligt de nadruk sterk op kosten en potentie, waardoor opties die daar hoog op scoren hoog in de lijst staan.

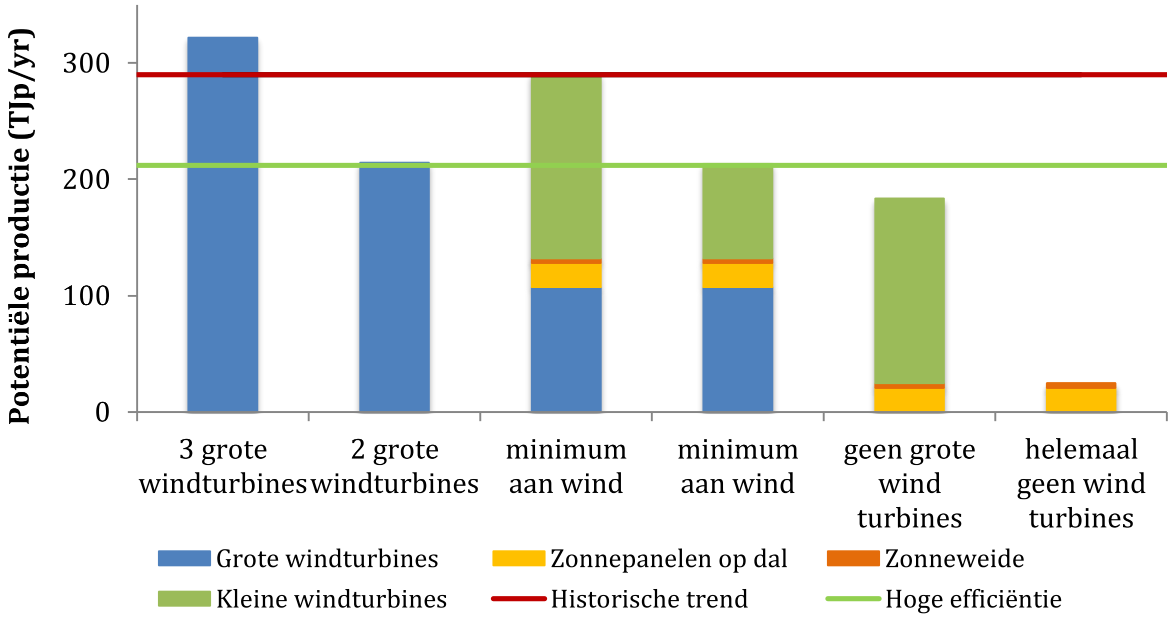
Met de weging van Lab Vlieland wordt de volgorde: zonneweide, zonnepanelen op daken, zonnecollectoren, grote windturbines en kleine windturbines. Aangezien hier de focus sterk op mogelijke weerstand van bewoners en belanghebbenden ligt, zijn de opties met het minste weerstand hoog in de lijst vertegenwoordigd.

Uit de weging van de gemeente komt de volgende ranglijst: zonneweide, grote windturbines, kleine windturbines, zonnepanelen op daken en zonnecollectoren. Vanuit dit perspectief scoren de opties met weinig potentieel en hoge kosten laag. Hierdoor komen zonnecollectoren laag in de rangschikking terecht. Aan de andere kant zorgt lagere weerstand van bewoners en belanghebbenden op de zonneweide voor een hoge score van die optie en voor een relatief klein scoreverschil tussen alle opties.

Energievisie Vlieland 2020

Zonder windenergie is er geen combinatie van technologische opties mogelijk waarbij energie-onafhankelijkheid wordt behaald in 2020. Afhankelijk van de trendlijnen zijn twee of drie grote windturbines nodig (afbeelding 5). Ondanks dat een zonneweide de beste optie is vanuit het perspectief van de gemeente, heeft het een beperkt potentieel waardoor grote windturbines ook nu vereist zijn. Echter, grote windturbines maken de extra energieproductie van een zonneweide overbodig. Vanuit het perspectief van Lab Vlieland zijn de technologieën op zonne-energie geprefereerd. Om aan de energievraag te voldoen zijn echter ook in dit geval windturbines nodig. Om deze redenen is voor het perspectief van Lab Vlieland een combinatie gemaakt van zowel zonnepanelen op daken, één zonneweide, één grote windturbine en kleine windturbines. In geval van de energie-efficiënte trend zijn er 22 kleine windturbines nodig en in geval van de historische trend zijn dit er 43. Wanneer geen grote windturbines en de maximale hoeveelheid kleine windturbines geïnstalleerd worden, zijn er in geval van de energie-efficiënte trend acht extra zonneweides nodig om het energiegebruik te omvatten. In geval van energiegebruik volgens de historische trend zijn 28 extra zonneweides vereist. Wanneer geen enkel type windturbine geïnstalleerd wordt, zijn er respectievelijk 50 en 70 zonneweides nodig.

De combinatie waarbij alleen grote windturbines geïnstalleerd worden is de meeste aantrekkelijke combinatie voor investeerders, aangezien deze optie de hoogste interne-opbrengstvoet en relatief lage specifieke kosten en investeringen heeft.



Afbeelding 5 *Voorgestelde combinaties van technologie-opties om energie-onafhankelijkheid te behalen in 2020.*

Discussie

Bij aanvang van deze studie is een definitie voor energieonafhankelijkheid opgesteld (zie voetnoot 1). Deze definitie is betwistbaar om twee redenen. Ten eerste, vier van de vijf opties die wij hebben onderzocht besparen of vervangen alleen elektriciteit; zonnecollectoren besparen een fractie op het gasverbruik. Echter, het gros van het gas- en brandstofverbruik wordt in realiteit niet vervangen, waardoor er geen sprake is van energie-autarkie[8]. Ten tweede is de energieproductie van hernieuwbare bronnen variabel over het jaar. Hierdoor kunnen vraag en aanbod op bepaalde momenten verschillen. Aangezien dit type aanpak het doel van dit onderzoek voorbijschiet, is de definitie van energie-onafhankelijkheid gebruikt op een gemiddelde jaarbasis, evenals in een eerder soortgelijk onderzoek (Van de Weerdhof, 2011).

Binnen de grenzen van dit onderzoek is het energiegebruik van rederij Doeksen volledig meegenomen. Echter, Doeksen opereert buiten de fysieke grenzen van deze studie. Het gedeeltelijk of volledig uitsluiten van Doeksen zou op basis hiervan ook gerechtvaardigd zijn.

Het leeuwendeel van de gebruikte gegevens in deze studie is verkregen uit literatuur. Dit houdt in dat het aandeel van eigen metingen klein is. Omdat de selectie van waarden uit bronnen per onderzoek kan verschillen, kunnen soortgelijke studies vergelijkbare maar verschillende resultaatwaarden verkrijgen.

De uitgevoerde multi-criteria analyse (MCA) is gebaseerd op vier criteria. Hiervan zijn de twee techno-economische (potentieel en kosten) volgens een meer gedegen analyse bepaald dan de twee criteria die voortvloeiden uit de enquête (de mogelijke weerstand van bewoners en belanghebbenden). In andere woorden, de sociale context is minder uitgebreid

[8] Energie-autarkie houdt in dit geval in dat Vlieland voor de energievoorziening volledig onafhankelijk zou zijn van het vasteland. Dit zou dan gelden voor zowel het elektriciteits- en gasverbruik als voor alle brandstoffen die op het eiland verbruikt worden.

onderzocht. Als gevolg hiervan geeft de MCA de betrouwbaarste resultaten voor wegingen die de nadruk leggen op kosten en potentieel.

Belangrijke barrières voor de implementatie van hernieuwbare energietechnologieën op Vlieland zijn sociale acceptatie, beleid, regelgeving en het aantrekken van investeerders.

Aanbevelingen voor verder onderzoek
De mogelijke weerstand van zowel belanghebbenden, bewoners als toeristen kan uitgebreider onderzocht worden om mogelijke problemen omtrent implementatie concreter in kaart te brengen. Ook is het aan te raden om de rol die alle betrokken partijen kunnen vervullen nader te onderzoeken. Energie-efficiëntie is in deze studie niet per optie behandeld. Ook energiebesparende maatregelen zijn niet onderzocht. Kortom, een studie op deze onderwerpen verdient onze aanbeveling. Verder dient er gezocht te worden naar potentiële investeerders naast de Energie Coöperatie Vlieland. Ook kan een concrete planning van implementatie (locatie en tijdsspanne) een toekomstige onderzoeksvraag inleiden. Als laatste aanbeveling is het belangrijk om beleid en regelgeving voor het plaatsen van windturbines nader te bestuderen, aangezien deze een belemmerende rol kunnen spelen bij het verkrijgen van vergunningen.

Conclusie

Er zijn twee manieren om energie-onafhankelijkheid te bereiken met behulp van hernieuwbare energiebronnen in 2020: 1) door het installeren van twee of drie grote (2MW) windturbines; of 2) door het installeren van één grote windturbine gecombineerd met een zonneweide, verscheidene kleine (100kW) windturbines en zonnepanelen op alle geschikte daken. In alle gevallen zijn windturbines onvermijdelijk. Beide opties hebben onder beide trendlijnen het potentieel om de energievraag van 2020 te bereiken. Van deze twee opties is de eerste de gunstigste investeringsoptie vanwege lage specifieke kosten en een hoge interne-opbrengstvoet. Vanuit techno-economisch oogpunt is daarom het installeren van alleen grote windturbines de beste manier om energie-onafhankelijk te worden. Echter, uit onze bevindingen op het eiland blijkt dat zowel bewoners als belanghebbenden op Vlieland van mening zijn dat windturbines (zowel groot als klein) de minst gewenste technologie is.

Samenvattend zijn er twee keuzes voor de toekomst: 1) de weerstand tegen windturbines wordt verminderd, één van de twee opties wordt geïmplementeerd en de ambitie wordt behaald; of 2) de ambitie wordt niet behaald of aangepast. De eerste keuze vereist verder onderzoek 1) naar het lokale draagvlak voor windturbines en hoe dit vergroot kan worden en 2) naar de concrete implementatie van de voorgestelde hernieuwbare energie-technologieën.

1. Introduction

Urged by compelling evidence of the severe consequences and anthropogenic causes of global warming (for latest overview see: IPCC, 2013), the European Union set targets to achieve 20% less greenhouse gas emissions (compared to 1990), to reduce its energy use by 20%, and to increase renewable energy production to 20% of total production by 2020 (EU, 2014a). The renewable energy target for the Netherlands specifically is 14% (EU, 2014a), a percentage that is still far away from the current 4% (IEA, 2013) as the Netherlands struggles to adopt renewable technologies at a sufficient rate (Dutch MEAAI, 2011). Sometimes more can be achieved on a local level: The Danish island of Samsø became fully energy independent in 2005 by reducing energy use and installing renewable capacity (Andersen et al., 2013). Inspired by this success the Dutch Wadden Sea islands declared in 2007 that they too want to become energy independent[9] by reducing energy use and installing renewables, they set 2020 as their target year (Ambitiemanifest Waddeneilanden, 2007).

Making islands energy independent has several advantages. Firstly, implementing renewables and energy efficiency measures to reach energy independency will reduce the environmental impact of the islands' inhabitants and businesses and set an example (Praene et al., 2012) to the Netherlands as a whole. Secondly, the islands' inhabitants can benefit financially (by sharing an island energy cooperation) and at the same time have the societal benefit of an increased sense of independence (Ambitiemanifest Waddeneilanden, 2007). Thirdly, creating energy independent islands is scientifically interesting, as the islands can serve as small-scale testing grounds to study high share renewable energy penetration and some of the associated difficulties (Praene et al., 2012; Ambitiemanifest Waddeneilanden, 2007).

Achieving an energy independent island requires large changes; Samsø provides an excellent example of what those changes could entail. Samsø reached energy independence only eight years after having stated the ambition to achieve it. On- and offshore wind parks provide (more than) the electricity requirement and heat pumps, solar heating and biomass plants (for district heating) provide heating (Saastemoinen, 2009). Transport is still largely non-renewable using imported fuels, but is compensated for by electricity surpluses (Saastemoinen, 2009). It is likely that the Dutch islands will require a similar approach to reach their target. In the Netherlands the island of Texel is currently leading in achieving the energy independence ambition by increasing local energy production using renewables to 8.1% of supply (Elswijk, 2010). Several measures have been implemented here, including the introduction of 26 electric cars, 25 urban wind turbines, and a scheme for households to rent their roofs to the island's energy cooperation, which then has PV installed (for a complete overview see Suurmeijer et al., 2010; Texelenergie 2014a). However, on Texel, as well as on the other Dutch Wadden Sea islands, larger scale projects similar to those on Samsø will probably be needed. The driving force behind all of the aforementioned projects, both on Samsø and on Texel, has been a local energy cooperation that is run by and involved with the community (Saastemoinen, 2009 and Suurmeijer et al., 2010, respectively).

On Vlieland, another Dutch Wadden Sea island (see box 1) and object of the current study, only few and energy efficiency measures and small-scale renewables have been

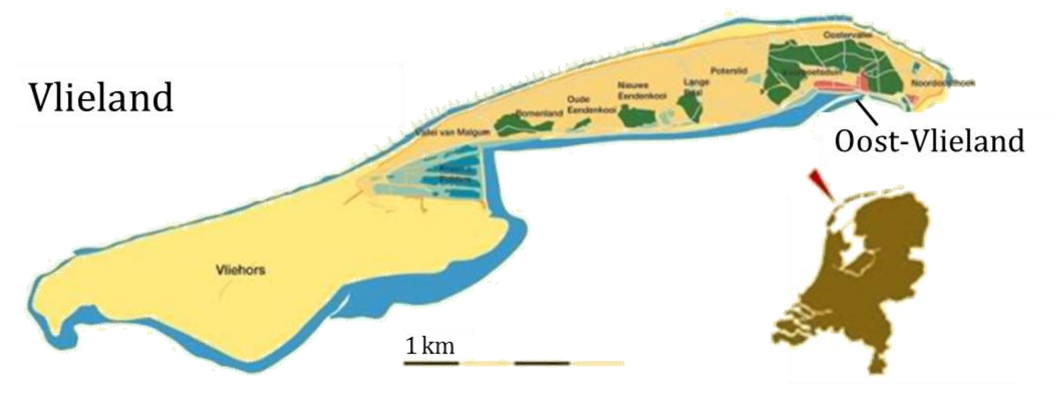
[9] Throughout this report energy independence by definition refers to a situation with zero or positive net export of primary energy from the island, where different energy carriers are interchangeable and are compared based on their primary energy value. Energy independence, according to this definition, does therefore not imply energy autarky. So when more primary energy is produced than is used, the island is considered energy independent; the island will never be detached from the mainland grids though.

implemented since signing the manifesto in 2007; measures include the introduction of LED lights in the yacht-basin, installation of PV panels on a campsite, and solar boilers in 27 homes (Boorsma, 2010). All the changes combined accounted for a reduction of Vlieland's energy import of about 0.6 TJ in 2010 (based on Boorsma, 2010), which is less than one percent of Vlieland's primary energy use in 2011 that was estimated at 258 TJ/year (Van de Weerdhof, 2011). According to Van de Weerdhof (2011), primary energy use will increase to 268 TJ/year by 2020 when current trends continue (in a simplified "business as usual" trend). Van de Weerdhof (2011) then states that if however targets of 30% energy savings in buildings and 15% energy savings in transport fuels are realised, primary energy would be reduced by 26% to 197 TJ/year. Small-scale wind, bio-energy (anaerobic digestion), tidal energy and solar energy (PV and solar heating) could *produce* 205 TJ/year by 2020 (Van de Weerdhof, 2011), making Vlieland energy independent (the island would have a net primary energy export of 8 TJ/year and would therefore by definition be independent). This outlook for 2020 was made in 2011, however trends have not changed since: energy use has not reduced and no substantial new renewable capacity has been installed.

The commissioner of this study, *Lab Vlieland* is concerned about Vlieland's low rate of progress towards energy independence in 2020. *Lab Vlieland* is a platform that aims to get Vlieland energy independent by 2020 and more generally promotes the sustainable use of energy, water and resources on the island. The platform originated from the *Into the Great Wide Open* festival that is held on Vlieland annually. *Lab Vlieland* facilitates contact between various stakeholders on the island and provides opportunities for students and entrepreneurs to solve sustainability issues encountered on the festival and the island in general (Lab Vlieland, 2014; for more information see appendix I). *Lab Vlieland* wants to know the best way forward anno 2014 to still achieve energy independence by 2020 and wants to have a series of concrete (technological) steps that can be taken to reach this goal.

Considering Lab Vlieland's demands, this report provides an answer as to how Vlieland can become energy independent by 2020 using renewables. This question is addressed from a techno-economic perspective. Feasible renewables to get Vlieland energy independent are identified and compared based on energy production potential, costs and public and stakeholder acceptance. Using these results and expected energy use trends (including a high energy efficiency trend) it is assessed how the renewables can add up to energy independency by 2020. Based on the Grontmij report (Van de Weerdhof, 2011), we expect a large role for wind power and foresee a smaller role for solar technologies, including PV and solar heating. Other renewables that are considered are biomass, tidal, wave and geothermal energy technologies.

Box 1. Vlieland



This map is based on maps displayed on koetshuisvlieland.nl and vlieland.net

The Dutch Wadden Sea island of Vlieland has 1,105 inhabitants (CBS, 2014a) and a surface area of 36.3 km^2 (CBS, 2014b). Oost-Vlieland is the island's only village. De Vliehors area to the south-west is a military zone. No agricultural or (large-scale) industrial production takes places on the island. About 155.000 tourists visit Vlieland each year, making tourism one of the most important sources of income. (Van de Weerdhof, 2011).

2. Method

2.1 Research outline

To answer the research question of how Vlieland can become energy independent by 2020 using renewables, the following steps were taken (figure 2.1). First, the scope and the boundaries of the research were defined. Next, Vlieland's current energy use and energy generation were determined; this served as a first indication of the scale of energy production that would be needed to become independent. Based on the current energy use it was then assessed how Vlieland's energy use is likely to change up to 2020; two estimates were made: one in which current energy use trends continue, and a second one in which energy-efficiency is strongly improved. This step provided insight into how much energy must be generated by renewables in 2020, and how much less generation would be required in a high-efficiency scenario.

Subsequently, the most important stakeholders on Vlieland were interviewed to find out what the stakeholders' interests and attitudes are towards renewable energy and energy independence, and to collect additional data.

It was then determined what renewable energy technologies are feasible options to implement on Vlieland towards 2020. This selection was based on three feasibility criteria: commercial availability, energetic potential and economic viability of a renewable energy production technology. Next, the selected renewables were analysed using techno-economic analysis[10] to estimate their potential for generating energy on Vlieland, their specific costs and their profitability. After this, a questionnaire-based survey was held among Vlieland's inhabitants and main stakeholders to get an overview of their perception of the selected renewables. To then determine what renewables are the best options, they were compared in multi-criteria analysis (MCA). The MCA focused on energetic potential, specific costs, public perception and stakeholder perception. Different weightings of these criteria were used to show different points of view on what the optimal option is.

Lastly, an energy vision for Vlieland in 2020 was made based on the MCA results. In this section several combinations of renewables that could add up to energy independence were proposed and analysed.

[10] Techno-economic analysis of renewables aims to determine their energetic and economic potential using an engineering and micro-economic, bottom-up approach, looking at individual technologies (Blok, 2007). Results are based on data like energy flows in the environment, conversion efficiencies of technologies and costs of earlier projects. Here, the energetic potential [in GWh/year and TJp/year], specific costs [in euro/(GWh/year) and euro/(TJp/year)] and profitability [internal rate of return] of the different renewable options were determined.

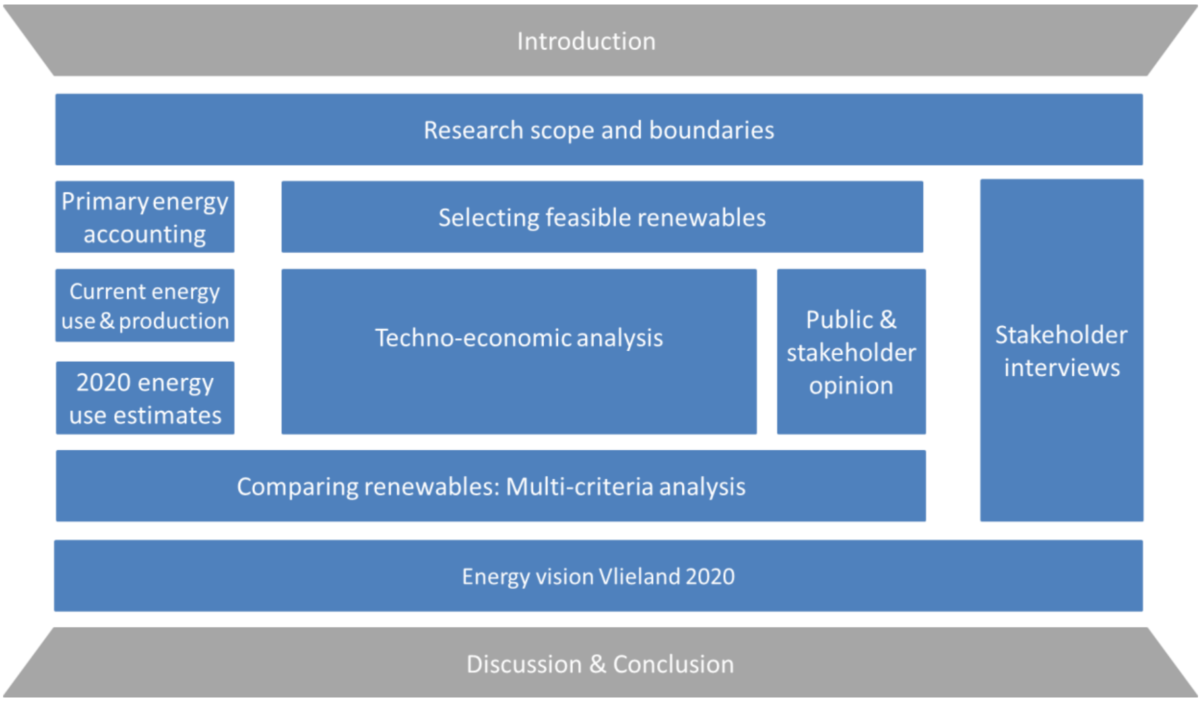


Figure 2.1. *Graphic representation of research outline.*

2.2 Research scope and boundaries

The research was geographically limited to the municipality of Vlieland, which includes 36.3 km^2 of land and a maritime area of 279 km^2 (CBS, 2014b) that consists of predominantly Wadden Sea and a small strip of the North Sea (for an overview see Gemeenteatlas, 2014). Vlieland's energy use includes all registered onshore energy use, all fuel bought on the island by ships, and the fuel use of ferry operator *Rederij Doeksen*[11]. All registered onshore energy use consists of all grid-connected electricity use, all grid-connected gas use and all automotive fuels bought on the island. Non-registered onshore energy use was estimated to be very limited and excluded from this study (for the full argumentation see appendix II).Vlieland's inhabitants can bring their vehicles to the mainland and purchase fuel there, but - applying the same principle as with borders between countries - it is not considered Vlieland's energy use. Vlieland's military base has its own automotive fuel supply and its gas and electricity use are classified and not included in the statistics of the distribution system operator. Energy use by the military was therefore not included in this study.

Only renewable energy technologies were considered in this study to achieve energy independence by 2020 (for the definition of energy independence in this research see footnote 9). Electricity generation from waste incineration is not a (strict) renewable energy source and would not occur on Vlieland itself[12], it was therefore considered outside the scope of this research. Offshore wind energy was not included in this study, because its

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[11] This ferry operator was included because it was considered a crucial part of the island's infrastructure. Vlieland's other ferry operator *De Vriendschap* (which runs lines between Texel and Vlieland) was not considered crucial infrastructure and is based on Texel, its energy use was therefore not included here.

[12] Texel incinerates its waste at HVC in Alkmaar, 50 km to the South of Texel on the mainland (HVC, 2014); waste incineration could be an intermediate solution for Vlieland if transporting the waste to the incineration plant (over a longer distance than from Texel) proves to be cost-effective, however this option lies beyond the scope of this research.

benefits over onshore turbines (lower visual impact and higher wind speeds on sea) would not hold within the Vlieland municipality[13], while still being more expensive than onshore turbines (EWEA, 2009). Energy efficiency measures were accounted for by including them in one of the two energy use trends towards 2020 (the *high energy efficiency* estimate). Energy saving measures that are not efficiency-based (e.g. banning cars from the island) were not considered in this study, as they are not strictly technological options.

2.3 Primary energy and energy accounting

In this report, the current energy use and production, as well as potential energy use and production in 2020 are expressed in their primary energy equivalent (denoted with subscript p, e.g. TJ_p).

Primary energy use represents the total amount of energy that needs to be extracted from the environment (for instance natural gas or crude oil) to consume a certain amount of energy in an energy carrier (like electricity or gasoline). The amount of energy in the carrier itself is called secondary energy. To create a certain amount of secondary energy, an equal or most often larger amount of primary energy is needed. This is because different steps in the energy carrier production chain, like conversion or transport, usually entail energy losses (figure 2.2). These losses are accounted for by energy requirement for energy (ERE) values[14] and conversion efficiencies[15] (figure 2.2).

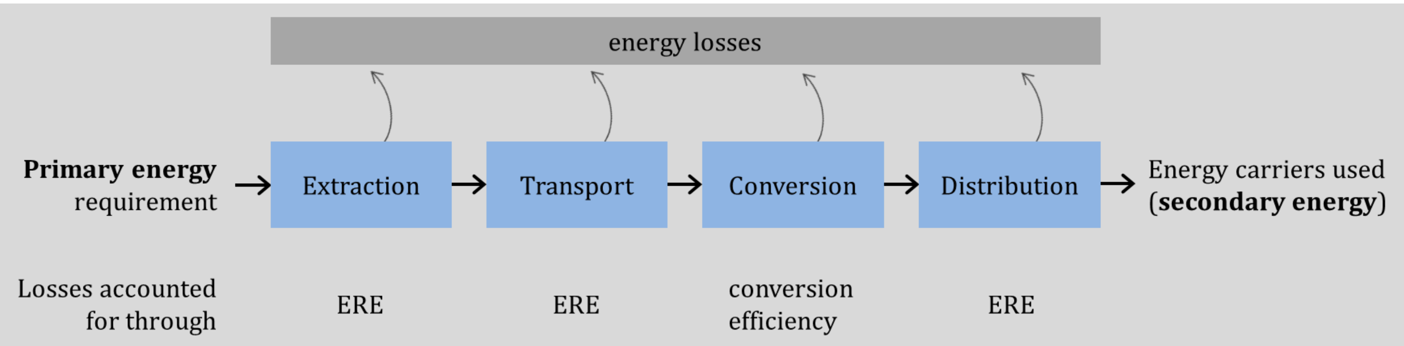


Figure 2.2 *Energy carrier production chain: from primary energy to secondary energy (based on Blok, 2007). Primary energy requirement is calculated using energy requirement for energy (ERE) values and conversion efficiencies of energy carriers.*

Energy production can be expressed in primary energy too. When the original extracted primary energy is difficult to define, like for electricity from nuclear plants or non-thermal renewables (e.g. wind or photovoltaics), international standard conversion efficiencies can be used (IEA, 2013). The produced energy on Vlieland however directly replaces energy import from the mainland. The primary energy equivalent of any energy

[13] The municipality only includes a stretch of North Sea of about 1 km wide and a stretch of Wadden Sea (Gemeenteatlas, 2014). The Wadden Sea is a protected nature area, which precludes building wind turbines (see appendix XIII). For the North Sea it was assumed here that wind speeds would not differ much between a location 1 km offshore or on the coast (where onshore turbines would be planned, see section 3.4). The visual impact is also not reduced when placing turbines just offshore.

[14] An energy requirement for energy (ERE) value is a factor greater than one that compensates for any energy losses or energy inputs required to obtain and transport a certain energy carrier (Blok, 2007).

[15] Conversion efficiency is the (energetic) efficiency with which one energy carrier is converted into another, for instance a typical steam cycle coal plant requires 250 Joules of coal to produce 100 Joules of electricity (Blok, 2007).

produced on Vlieland was therefore defined in this study as the primary energy requirement of the replaced energy carriers. As an example, electricity produced on Vlieland was given a primary energy value equal to that of the average Dutch electricity, which is based on average Dutch conversion efficiency and other losses.

Expressing energy use and production in primary energy allowed for comparison, addition and subtraction of the energy in different carriers. It enabled determining the net island's net export (or currently import).

2.4 Current energy use and production

Vlieland's current primary energy use (TJ_p/year) and primary energy production (TJ_p/year) were determined in two steps. First, data on the consumption and production of different energy carriers was collected. Then, the amount of primary energy required to produce these carriers (secondary energy) was calculated (formula 1; for a graphic representation see figure 2.2). As explained in the previous section, the calculation is the same for energy use and energy production.

$$E_{P\ total} = \sum_{i=1}^{n} \left(\frac{C_i \cdot EC_i \cdot ERE_i}{\eta_i} \right) \qquad (1)$$

Where:

$E_{p\ total}$ = *Total primary energy consumption in 2013 (TJ_P/year)*
i = *Energy carrier i*
n = *Total amount of different energy carriers*
C_i = *Consumption of carrier i in 2013 (unit[16]/year)*
EC_i = *Energy content of carrier i (TJ/unit)*
ERE_i = *Energy Requirement for Energy of energy carrier i[17]*
η_i = *Conversion efficiency of precursor to energy carrier[18]*

2.5 Estimates of Vlieland's energy use in 2020

To investigate how Vlieland can become energy independent in 2020, it is important to know what the energy demand will be in 2020. It could however only be estimated how the current 271 TJ_p per year will change towards 2020, as there is large uncertainty when predicting the future. The expected energy demand was estimated in two ways. The first approach was to assume that historic energy use trends will continue to 2020, yielding a "business-as-usual" estimate of Vlieland's energy demand in 2020. The second approach was to assume that energy efficiency measures will be implemented on Vlieland in accordance with intended national and EU intended policy, yielding a "high energy efficiency" estimate of Vlieland's 2020 energy demand. Both estimates were expressed in the primary energy equivalent of the energy demand.

The business-as-usual estimate of future demand was based on: 1) available data on the use of different energy carriers on Vlieland over the past 20 years (appendix IV); 2) the

[16] Consumption of different carriers is accounted in different units (e.g. m^3 for natural gas and kWh for electricity). This was corrected for via the energy content of each carrier.

[17] note: the unit of $\frac{ERE_i}{\eta_i}$ is TJ_P / TJ

[18] See note 17

projected increase in total primary energy supply (TPES[19]) of 1% per year in the Netherlands in the period of 2010 to 2020 (IEA, 2012b); and 3) the estimated annual increase of Vlieland's primary energy use towards 2020 of 0.34% based on a previous report (Van de Weerdhof, 2011). The latter estimation was made by converting the increase in primary energy demand from 2009 to 2020 as estimated by Van de Weerdhof (2011) to an annual (exponential) growth percentage. The IEA (2012b) estimate of TPES growth was considered leading, as availability of historic data on energy carrier use on Vlieland was limited and the assumptions in the Van de Weerdhof report were not made fully explicit.

The high energy efficiency estimate of the 2020 energy demand was based on the reduction of energy use in the Netherlands towards 2020 that is expected to occur as a result of existing and intended national and EU energy efficiency policy (ECN, 2013; DNEEP 2014). These policies are expected to result in a primary energy consumption of 2541 PJ_P in 2020 (ECN, 2013; DNEEP 2014), which implies a 21.6% reduction from the 3241 PJ_P consumed in 2013 (CBS, 2014e).For the high energy efficiency estimate it was assumed that instead of following historic trends, Vlieland will break trends and reduce use according to the expected national average and therefore reduce primary energy demand in 2020 by 21.6% from the 2013 value (see section 3.1).

2.6 Stakeholder interviews

Stakeholder interviews were performed to obtain data and get a detailed description of the current situation concerning energy on Vlieland. Next to this, valuable information was gained on the viewpoints and expectations of different stakeholders regarding the energy future of Vlieland. Lastly some limitations on the implementation of renewables were identified through these interviews.

Stakeholders were identified via our commissioner and via referrals by our interviewees. In table 2.1 an overview is given of name, function and relevance of the different stakeholders approached. The procedure of interviews was a Dutch one-hour, semi-structured interview[20] (based on Deken, 2013); the general list of questions in Dutch can be found in appendix V.

[19] Total primary energy supply (TPES) is the total primary energy requirement of all consumed energy carriers in a certain year and region, in this case the Netherlands.

[20] Interview is structured but the interviewer is allowed to spontaneously continue on other relevant subjects that come up in conversation (Deken, 2013).

Table 2.1. *An overview of the name, function and relevance of each interviewed stakeholder.*

name	function	relevance
Joke Weeda	'regieambtenaar' municipality Vlieland	Responsible employee in the field of sustainability and energy
Leo Hans Sterenberg	Employee municipality Vlieland	Responsible for infrastructural affairs
Broer Visser	Director Energie Coöperatie Vlieland (ECV)	ECV stimulates the use of renewable energy
Bram Commandeur	Intern at municipality Vlieland	Assists in setting up ECV
Jan van der Veen	Director campsite Stortemelk	Major campsite on the island with a lot of renewable facilities
Jan Lever and Simon Visser	Harbour master Vlieland	Supplies tourists with energy and facilities, caretaker of gas station
Pieter Bruinink	Royal Dutch Air Force	Large part of Vlieland is owned by the Royal Dutch Air Force
Herman Brink	Employee Staatsbosbeheer	Staatsbosbeheer owns large areas on Vlieland
Ben Matoren	Principal VMBO Krijtenburg	Central player in community
Wilco Spoelman	Employee WoonFriesland	WoonFriesland is the public housing foundation on Vlieland
Gerwin Venema	Province of Friesland	Vlieland is part of province of Friesland

2.7 Selection of feasible renewable energy production technologies

In this section it was determined what renewable energy technologies are feasible options to implement on Vlieland towards 2020. The selection process was carried out in two steps: first a longlist of potential renewable energy production technologies on Vlieland was created, which was then shortened down to a shortlist of *feasible* renewable energy technologies.

As a last step the selected technologies were translated to concrete technological options (e.g. covering all available south-facing roofs with photovoltaic panels). These options were further investigated in subsequent sections.

The longlist

As a starting point for the longlist, the overview of renewable energy production technologies as presented in Twidell and Weir (2006) was used. From this overview, four technologies were discarded due to Vlieland's geography or lack of maturity of the technology. Firstly, ocean thermal energy conversion (OTEC) was not included in the longlist, as the surface ocean temperature near Vlieland is too low and no access to cold deep ocean water is present (OTEC International, 2013). Secondly, concentrated solar power (CSP) was discarded, because this technology is not expected to be rolled out beyond the sunniest countries on Earth before 2020 (IEA, 2010d). Thirdly, hydro power was not included in the longlist, as height differences, which would be required for this technology (Twidell & Weir, 2006), are negligible on Vlieland. Lastly, (third generation) biofuels from algae were also discarded, as they still harbour many technical challenges (Lee and Lavoie, 2013) and are still in a research stage (Nigam & Singh, 2011). The resulting longlist of remaining possible renewable energy technologies on Vlieland consisted of:

- Wind energy
- Solar energy - photovoltaic panels (PV)
- Solar thermal energy
- Energy from biomass (first/second generation)
- Geothermal energy (deep aquifer[21])
- Tidal energy
- Wave energy

The shortlist

In the second step, the longlist of possible technologies was further shortened down. It was critically assessed which of the renewable energy production technologies are actual technologically and economically feasible options to be implemented on Vlieland by 2020. Feasibility was determined based on three criteria. The technologies:

- must be currently commercially available
- can have a significant impact on the reduction of annual energy imports (the renewable's total maximum potential is at least one percent of total current energy use)
- must be economically viable based on literature or related case studies (examples of economic operation in similar conditions to Vlieland must exist)

Only the renewables on the longlist that satisfied all three criteria were considered feasible options and made the shortlist. Potential and commercial availability were investigated first, and if their corresponding criteria were met, economic viability of the technology was assessed as well.

Electricity production using wind turbines, electricity production from photovoltaic panels and warm water production from solar heaters are all commercially available. According to Van de Weerdhof (2011) wind power could almost cover the entire primary energy equivalent of Vlieland's energy demand in 2020 and PV panels could cover about 10%. Based on Boorsma (2010) it was estimated that solar thermal heating also has a sufficient energetic potential to meet the criterion[22]. Results of the techno-economic analysis (see section 3.4) confirm that wind energy, photovoltaic panels and solar heating

[21] Geothermal energy has two main forms in The Netherlands: extracting energy from deep aquifers (high-temperature water reservoirs in the subsurface) or extracting heat from the ground near the surface via heat pumps. The feasibility of the former is assessed here. The latter option was considered an energy efficiency measure, as heat pumps are part of the labelling system for buildings (Mitsubishi Electric, 2012).

[22] Boorsma estimated that the solar heating installed on 27 homes on Vlieland covers about half of these houses' heat demand. This implies that if the technology were up-scaled to cover the majority of houses on Vlieland, solar heating would certainly meet the criterion of having the potential to more than one percent of total energy demand, as heat accounts for about a third of the total energy use (see the current energy use and production section).

have significant potential[23]. Furthermore, the technologies are already cost-effectively implemented on Vlieland on a small-scale (Boorsma, 2010) and are implemented on the islands of Samsø and Texel on a larger scale (Saastemoinen, 2009 and Suurmeijer et al., 2010, respectively). The criterion of economic viability is therefore also met. In conclusion, wind energy, photovoltaic panels and solar heating were considered feasible technologies to help Vlieland become energy independent by 2020 and made the shortlist.

Biomass, geothermal, tidal and wave energy were not considered feasible options for Vlieland in this study, as they did not meet the three feasibility criteria outlined above. Energy from biomass was not cost-effective and could not produce a significant amount of energy on Vlieland[23] (for a detailed argumentation see appendix VII). Geothermal energy showed promising energetic potential on Vlieland, but there is great uncertainty regarding this potential. Moreover it would take too long to implement the geothermal technology to make a difference by 2020 (for a detailed argumentation see VIII). Tidal energy had (too) high investment costs and again plant construction would take too long to contribute to supply in 2020 (for a detailed argumentation see appendix IX). Lastly, it was found for wave energy that the wave energy density around Vlieland is relatively low and the technology to harvest the energy is not commercial yet (for a detailed argumentation see appendix X).

The remaining shortlist of renewable energy production technologies that were investigated in subsequent sections consisted of:

- Wind energy
- Solar energy - photovoltaic panels (PV)
- Solar thermal energy

Concrete technological options

Based on the shortlist of wind energy, photovoltaic panels and solar heating, five options were further investigated to assess to what extent they contribute to Vlieland's energy independency by 2020. For wind energy there is a trade-off between the hub height and hence visual impact on one hand, and the amount of turbines required to reach a certain energetic potential on the other. It was therefore decided to investigate two sizes of wind turbines to compare their techno-economic performance on Vlieland. Firstly, large wind turbines (69-80 metre hub height[24]) were investigated. The main advantage of these turbines is the large amount power they produce; their main drawback is their visual impact. Secondly, the option of installing small wind turbines (18 metre hub height[25]) was researched. They have a lower visual impact, but more of these turbines are required to meet the same demand. Photovoltaic panels could be used on Vlieland in two ways: photovoltaic panels could be installed on all south-facing roofs, or more in more centralised way in a so-called "solar farm"[26]. Installing solar heating panels on all south-facing roofs (*instead of photovoltaic panels*) was investigated as the fifth option. Centralised heat generation was not investigated as it would require district heating (see section 2.8 solar thermal heating and appendix XII).

[23]Significant potential means that a renewable energy production technology could contribute more than 1% of the current primary energy equivalent of energy demand

[24] The reasons for selecting this exact size are outlined in the large wind turbines part of section 2.8

[25] The reasons for selecting this exact size are outlined in the small wind turbines section part of section 2.8

[26] The solar farm is an existing plan opted by the military (solar farm part of section 2.8). The Energy Cooperation Vlieland is currently trying to realise this plan.

2.8 Techno-economic analysis

For each of the five renewable energy options the energetic potential (in GWh/year and in TJ_P / year) was calculated. Furthermore the specific costs (in euro/kWh and euro/TJ_P) were calculated to assess the cost-effectiveness of each option. Also, the internal rate of return (IRR) was determined as a measure of attractiveness of investing in each option. The IRR was included on top of the specific costs to look at the technologies from an investor's perspective and include external factors like the energy price, which varies between different options.

The energetic potential was determined using data from literature and commercial suppliers. The primary energy equivalent of the potential was calculated according to formula 2, using the values given in appendix III.

$$E_P = E_S \cdot \frac{ERE}{\eta} \qquad (2)$$

Where:
E_P = *Primary energy equivalent of produced energy*
E_S = *Produced energy in carrier (secondary energy), e.g. electricity*
ERE = *Energy requirement for energy*
η = *conversion efficiency of production process of energy carrier*

As explained in the primary energy and energy accounting section the primary energy equivalent of any produced energy is basically the primary energy equivalent of the energy from the mainland that it replaces. ERE and η values are therefore the values of energy carriers that would be replaced by production on Vlieland (for instance electricity form the mainland).

Costs per unit energy, for example the costs of producing a kWh of electricity, are called specific costs. The specific costs of producing energy were determined for each option as an indicator to compare different options and find out which option can deliver energy at lowest costs. Specific costs were calculated in euro/GWh (one million kWh) for comparison with literature in the discussion section. Specific costs were also converted to euro/TJ_p values to determine the costs of producing an amount of primary energy on Vlieland and reduce the equivalent energy import.

Specific costs were calculated according to international convention using the concept of levelised costs of electricity (LCOE; IRENA, 2012; IEA, 2010a), as defined in formula 3 (based on IEA, 2010a). The concept of LCOE was used here in a wider sense as levelised costs of energy (either in euro/kWh or euro / TJ_P).

$$LCOE = \frac{\sum_{t=0}^{L}((I_t + O\&M_t) * (1+r)^{-t})}{\sum_{t=0}^{L}(E_t * (1+r)^{-t})} \qquad (3)$$

Where:
$LCOE$ = *levelised cost of energy*
t = *time step in years*
L = *lifetime of the technology*
I_t = *investment costs in year t (only occur in year 0)*
$O\&M_t$ = *annual operation & maintenance costs in year t*

r = *discount rate*
E_t = *energy production in year t*

Investment costs (or capital costs) are all costs made to get from nothing to an operational project. Operation and maintenance (O&M) costs are annual costs to keep the project operational. All the costs (investment and O&M[27]) of all years are summed up and are divided by the total energy production during all the years of the project, yielding the costs per unit energy. The investment costs only occur in year 0 and the annual O&M costs occur from year 1 to the end of the lifetime. The costs and energy yields are also discounted over time to account for the time value of money. In short, the same amount of money is worth less in the future than in the present; the discount rate determines how much less (as an annual percentage of value reduction). Energy is also discounted (even though it is not a monetary quantity) to enable dividing by it.

To calculate the levelised costs of energy, the investment costs, annual costs (O&M and other) and lifetime were determined for each option separately using data from literature and commercial suppliers (see individual sections below). The discount rate used in the levelised cost calculations was set at 5% for all options (IEA, 2010a). Energy production in each year was the potential (in GWh/year and in TJ_P/year) of the options. The same conversion from kWh to TJ_p was used as for the potential calculations (see the five options' individual sections).

Two national subsidy schemes exist that are directly relevant for the investments in renewable energy on Vlieland (RVO, 2014a; RVO 2014b). For large-scale renewables, like the solar farm and both types of wind turbines, the *SDE+* (Stimulation Renewable Energy*)* is applicable; this scheme provides a premium on top of the electricity price (RVO, 2014a; see appendix XI). For the small-scale options, i.e. the photovoltaic panels and solar heating on roofs, the *EIA* (*Energie-Investeringsaftrek*, Energy Investment Discount) is applicable: a fiscal discount where the financial benefit is around 10% of the investment costs (RVO, 2014b). The exact amount of subsidy received differed among the different options investigated and was calculated in the individual sections below.

The subsidy received on each option was converted to a "levelised subsidy": an amount of money per unit of energy produced (euro/kWh and euro/ TJ_P). Levelised SDE+ and levelised EIA subsidies were calculated according to formulae 4 and 5 respectively.

$$S_{levelised} = \frac{\sum_{t=0}^{L}((s_t) * (1+r)^{-t})}{\sum_{t=0}^{L}(E_t * (1+r)^{-t})} \qquad (4)$$

Where:
$S_{levelised}$ = *levelised subsidy (euro/TJ_P or euro/kWh[28])*
t = *time step in years*
L = *lifetime of the technology (years)*
s_t = *subsidy received in year t[29]*
r = *discount rate*

[27] It was assumed that there are no annual costs other than O&M (in line with Blanco, 2009); fuel costs or carbon taxes (as used in IEA, 2010a) are not relevant for the renewables investigated here.
[28] The levelised costs can be expressed as euro per TJ_P or per kWh, this is because the energy production can be expressed as primary or secondary energy.
[29] In some cases the duration of the subsidy is shorter than lifetime, this in indicated in the sections on the individual options below. If this happens, the subsidy is 0 euro in the remaining years of the lifetime.

E_t = *energy production in year t*

$$S_{levelised} = \frac{s_{investment}}{E_{lifetime}} \qquad (5)$$

Where:
$S_{levelised}$ = *levelised subsidy (euro/TJ$_P$ or euro/kWh)*
$s_{investment}$ = *subsidy on investment cost (euro)*
$E_{lifetime}$ = *lifetime energy production (TJ$_P$ or kWh)*

The costs of producing primary energy (and thus reduce energy import) of each option formed one of the criteria in the multi-criteria analysis (MCA; 2.10) To achieve the fairest comparison and have an overview of what options reduce energy import to Vlieland most cost-effectively. The cost values used in the MCA were the specific costs (in euro/TJ$_P$) minus the levelised subsidy (in euro/TJ$_P$). This net amount is further referred to as the net specific costs (in euro/TJ$_P$).

Besides the costs of producing energy, there are also the benefits of selling it. To assess the economic opportunity and attractiveness of the technological options, it is therefore important to investigate the returns on capital invested in these five options. This was determined using the internal rate of return – the annual interest on money that is paid back to the investor.

The internal rate of return is based on the net present value (Blok, 2007), so this concept is explained first. The net present value of a project represents all the (net) profit that will be made during a project expressed in today's money (i.e. corrected for the time-value of money). The net present value can be calculated according to formula 6 (based on Blok, 2007).

$$NPV = \sum_{t=0}^{L} \left(\frac{B_t - O\&M_t - I_t}{(1+r)^t} \right) \qquad (6)$$

Where:
NPV = *net present value*
t = *time step in years*
L = *lifetime of the project*
B_t = *benefits in year t*
$O\&M_t$ = *annual operation and maintenance costs in year t*
I_t = *investment costs in year t (only occur in year 0)*
r = *discount rate*

Again, investment only occurs in year 0 and annual benefits and annual costs occur from year 1 to the end of the lifetime. As mentioned before, investment, annual costs (O&M) and the lifetime of the project were determined for each option separately using data from literature and commercial suppliers. Annual benefits depend on the determined potential (in GWh/year), the energy price and any renewable energy subsidies (euro/GWh). The energy price is either the electricity price or in the case of heat the price of natural gas – corrected for conversion to heat. The exact energy prices and benefits from subsidies differed among the five different options and were determined in the individual option sections below.

A discount rate has to be assumed in order to calculate the net present value. As mentioned before, the discount rate sets the time value of money. The initial investment in the project is usually financed by external investors who are slowly paid back their money during the project – with interest. The discount rate is basically the interest rate the investor sets; it represents how much return an investor wants to receive on investment.

When determining the internal rate of return, the NPV principle is reversed. Instead of assuming a discount rate and determining the NPV, the NPV is set at exactly zero (zero profit over the whole project) and it is determined what the accompanying discount rate is. This discount rate is called the internal rate of return; it can be considered the annual interest rate that investors *could* set on the capital they loaned, while (just) keeping the project executable. It is not a percentage of the investment that can be expected as an annual return on the investment though, because the returns can vary over the years. Calculating the internal rate of return of all options allowed comparison of their profitability, the interest investors could receive on their capital. Besides the IRR, the total investment cost of each option was calculated.

Large wind turbines

To calculate the potential of large wind turbines on Vlieland wind speed data and wind turbine characteristics were required. Hourly wind speed data from the period 1998-2013 were used in this research. These data were originally collected at a KNMI (Royal Netherlands Meteorological Institute) weather station on Vlieland at 10 metres above the land surface (KNMI, 2014a; KNMI 2014b). In further calculations the wind speed data were adjusted for the hub height of the turbine, as wind speeds are higher at greater distance from the surface (Twidell & Weir, 2006). Each individual hourly wind speed measurement was adjusted according to formula 7 (Twidell & Weir, 2006).

$$v_h = v_{10}\left(\frac{h}{10}\right)^b \qquad (7)$$

Where:

v_h = *estimated wind speed at height h (m)*
v_{10} = *wind speed in original measurement at 10 metres above surface (m/s)*
h = *height for which wind speed is to be estimated (m)*
b = *a hilliness coefficient, for non-hilly country (like Vlieland), it is estimated at 0.14 (Twidell & Weir, 2006)*
10 = *height at which the original measurement was taken (m)*

Turbine characteristics depend on the wind turbine model. Selection of wind turbines was based on the required wind class and the desired rated electricity output. Turbines are classified according to international IEC standards (International Electrotechnical Commission) depending on the wind conditions they can tolerate (IEC, 2005). The average of all hourly wind data measurements corrected at different possible hub heights (according to formula 7) was calculated. Anywhere between 40 metre and 100 metre hub height (9.63 m/s and 11 m/s average wind speed respectively) Vlieland's wind conditions require an IEC class I wind turbine (based on[30]: wwindea, 2014; windwire, 2014; Vestas, 2013). The IEC also distinguishes subclasses a (high turbulence) and b (low turbulence; based on[9]: wwindea, 2014; windwire, 2014; Vestas, 2013). No turbulence data

[30] We did not have access to the official IEC documents and therefore based the classification on average wind speed and secondary sources only. If wind power implementation is further investigated, officially classifying Vlieland's wind regime should be one of the first steps.

are available for Vlieland, but all considered turbines are class Ia and can handle high turbulence, so even if Vlieland has high turbulence, it would not matter for the analysis.

The desired rated output per turbine was set at 2 MW. In literature, 2 MW wind turbines are often the standard "large" turbines (EWEA, 2009). Moreover, turbines larger than 2 MW in class I (this class is required for Vlieland's wind conditions above 40 metres) usually require a hub height of over 100 metres, which would be disproportionally large for a relatively small island. Out of the major European wind turbines manufacturers, three deliver IEC class-I turbines with a rated capacity of 2MW (see table 2.2)[31]. Potential energy production on Vlieland of each of these three turbine models was calculated separately, their results were then averaged to represent a typical 2MW turbine.

Table 2.2 *2 MW IEC class I wind turbine models from European manufacturers*

Manufacturer	Turbine model	Rated capacity (MW)
Vestas	V80 2.0 MW	2.00
Gamesa	G80	2.00
Senvion	MM82	2.05*

*at extra 2.5% rated power, the Senvion MM82 was assumed to still be representative of a regular 2 MW turbine.

The potential annual electricity production on Vlieland of each of the three selected turbine models was calculated using their power curves and hub heights (see appendix XIV) and Vlieland's wind speed data (KNMI, 2014a). A turbine's power curve gives the electricity output at a given wind speed[32]. It accounts for the efficiency of the conversion of energy in the wind to kinetic energy of the turbine, and for the conversion of this kinetic energy to electricity. Wind speed measurements were corrected for each wind turbine's hub height (formula 7; fur hub heights see appendix XIV). Then for each height the wind speed distribution was determined over the 1998-2013 period (KNMI, 2014a): it was determined what fraction of time the wind blows at a certain speed, this was done in steps of one metre per second. The weighted average power output was then calculated according to formula 8

$$P_{avg} = \sum_{i=0}^{40} f_i \cdot P_i \qquad (8)$$

Where:
P_{avg} = *weighted average power output (kW)*
f_i = *fraction of time that winds blow at speed i m/s*
P_i = *power output at wind speed i m/s (kW)*

The average power output is the actual output that can be expected based on the location's (in this case Vlieland's) wind regime and is often lower than rated output. Multiplying this

[31] Two other major European manufacturers were investigated: Enercon and Siemens. However they do not produce 2 MW models. The Enercon E-82 E5 (2.35 MW) and Siemens SWT 3.0-108 (3MW) models came closest to 2 MW, but their output and size were considered too different from the other models to properly represent a 2 MW turbine in terms of potential and costs.
[32] *Vestas*, *Gamesa* and *Senvion* did not provide the exact numbers behind the power curves in their catalogues, so numbers were read from the power curve graph.

average power output by 8760 hours/year yielded the amount electricity produced in kWh per year, which was converted to GWh/year. The electricity output of each turbine was also converted to its primary energy equivalent as described in the general techno-economic method, using the ERE and conversion efficiency of mainland electricity (see appendix III).

The results of the three turbine models were then compiled into "a typical 2MW wind turbine" in the following way: The rated power was assumed to be exactly 2 MW and the actual power output was averaged over the three models. The annual electricity production and its primary energy equivalent were therefore also the average values of the three models.

As a final step the overall potential of large wind turbines on Vlieland was calculated. To do so, it was determined how many of these typical 2 MW turbines could be installed on Vlieland and this number was multiplied by the potential of the typical 2MW turbine. As an estimate it was assumed that turbines could be installed in a row covering Vlieland's windswept North-Western shore. The military base could not be used, because of flight routes[33]. Furthermore, no turbines could be planned in the dunes right North of the village of Oost-Vlieland to limit public opposition that would be caused by the turbines' visual impact. This left an 8.3 km stretch of land available for wind turbines (geodistance, 2014). This stretch of land runs through a protected nature area (Natura 2000), but this does not imply *a priori* prohibition of wind turbines (see appendix XIII).The next step in calculating the amount turbines that could be installed was to determine the required space between two consecutive wind turbines. Meyers & Meneveau (2011) indicate that wind turbines are conventionally spaced seven rotor diameters apart, but suggest a spacing of fifteen diameters, as it is more cost optimal. Since both cost optimisation and overall potential were both considered important in this study, an average turbine spacing value of 11 rotor diameters was used here. Dividing the 8.3 km stretch of land by 11 rotor diameters and adding one turbine at the end of the stretch, gave the total amount of turbines that could be installed on Vlieland. As a final rule for determining the amount of large wind turbines, it was assumed that if the primary energy equivalent of the entire expected 2020 energy demand could be met by a certain amount of wind turbines (determined for both energy trends), no additional turbines would be planned.

To calculate the specific costs of energy produced with large wind turbines via the levelised costs of energy concept (LCOE; see formula 3) the investment costs, O&M costs, lifetime, discount rate and lifetime energy production were required. These quantities were determined for 2 MW turbines using literature (values and their determination are given in XIV; the energy infrastructure on Vlieland was also used to determine the investment costs, see appendix XII). No scaling laws[34] were used to calculate the investment costs, so the LCOE was constant regardless of the amount of turbines installed.

Large wind turbines on Vlieland would be eligible for an SDE+ subsidy (RVO, 2014a). The SDE+ subsidy for wind consists of a premium of 2.95 eurocent per kWh (RVO, 2014a). A premium is given on top of the market price for electricity. For wind, the subsidy is provided

[33] The aviation approach routes run directly from the North Sea to the Vliehors and never cross the village Oost-Vlieland or the Eastern part of Vlieland in general. The installation of wind turbines outside of the Vliehors military base is therefore not restricted by military aviation (see also appendix VI)

[34] Scaling laws can be applied to correct for economies of scale (see for example Blok, 2007). Specific investment costs can go down when a project is realised on a larger scale. Scaling laws were not applied here as it was expected that only few large turbines could already cover the entire primary energy equivalent of the 2020 demand and with few turbines economies of scale are limited.

annually during the first 15 years of the project (RVO, 2014a). The subsidy only applies to electricity generated during the first 2800 full load hours[35] each year, for projects at or under 6MW rated (RVO, 2014a). The International Energy Agency (IEA) estimated that onshore wind turbines in the Netherlands achieve 1600 to 2800 full load hours and offshore turbines achieve 3300-4000 full load hours (IEA, 2010b). Vlieland is one of the windiest places in the Netherlands (KNMI, 2014c). Furthermore, wind blows predominantly from the South-West and West (KNMI, 2014a), so from the North Sea without land masses or obstacles in its path, similar to offshore wind turbines. It was therefore estimated that the full 2800 full load hours could be realised each year. The annual subsidy was calculated according to formula 9.

$$S_{annual} = P_{rated} \cdot h_{ful\ load} \cdot p_{kWh} \qquad (9)$$

Where:

S_{annual}	*= annual Subsidy per turbine (euro/year)*
P_{rated}	*= rated capacity of the turbine (kW)*
$h_{full\ load}$	*= annual full load hours (hour/year)the maximum value of 2800 was used*
p_{kWh}	*= premium per kWh (euro/kWh)*

The annual subsidy during the first 15 years was converted to a levelised subsidy value of large turbines as described in the general techno-economic methodology (beginning of this section). Lastly, the levelised subsidy was subtracted from the levelised cost of energy to yield the *net* specific costs of large wind turbines on Vlieland.

The internal rate of return (IRR) was calculated as explained in the general techno-economic method section. Again no scaling laws were applied, so the IRR was constant regardless of the amount of turbines. Investment costs, annual O&M costs and lifetime were the same as in the specific costs calculations (see appendix XIV). Annual benefits consisted of the SDE+ subsidy and the selling of electricity. The annual subsidy was already calculated before and added as a benefit during first 15 years of production. The annual benefits from selling electricity were the annual electricity production (calculated under potential, see also appendix XIV) times the electricity price (see appendix XIV). It is difficult to predict future electricity prices; it was therefore assumed that this price would not change over time. This is likely to be a conservative estimate, as inflation alone would increase prices.

Small wind turbines

The potential annual electricity production of small wind turbines was determined in the same way as was done for large turbines.

First the turbine model was selected. The smaller turbine should have a substantially lower hub height to limit visual impact (around 10-20 metres), but at the same time still have a substantial rated power output. Vlieland's wind regime below 25 metres (<9 m/s average wind speed, calculated using formula 7) required an IEC class II wind turbine (based on[36]: wwindea, 2014; windwire, 2014; Vestas, 2013). The market for wind turbines with hub

[35] The (theoretical) amount of hours that a turbine would have to run at rated capacity to achieve the electricity output of a certain year.

[36] We did not have access to the official IEC documents and therefore based the classification on average wind speed and secondary sources only. If wind power implementation is further investigated, officially classifying Vlieland's wind regime should be one of the first steps.

heights of between 10 and 20 metres is not dominated by a few big companies that build similar models (as is the case for the larger wind turbines), but rather by various smaller manufacturers with very different models. Small wind turbine models within right hub height range and with a relatively large rated output (as compared to other manufacturers) from two Dutch and one German company were shortlisted (table 2.3).

Table 2.3 *Small wind turbine models*

Manufacturer	Model	Rated power (kW)	Hub height (m)	IEC class	source
WES	WES100	100	18	II	1
Lely	Lely Aircon 10	10	10	II	2
UniWind	UniWind 9	9.0	12	-	3

[1]WES, 2014; [2]Lely, 2014; [3]UniWind, 2014

Because the characteristics of these turbines are so different, it was decided to select one model instead of averaging out results. The WES100 was chosen to further investigate and represent a small wind turbine. It was selected because it has an IEC-II classification and the highest rated output (thanks to its large rotor diameter of 17.9 metre).

Secondly, the electricity output and its primary energy equivalent were determined in the exact same way as for large turbines. All individual hourly wind measurements on Vlieland in the period 1998-2013 (KNMI, 2014a) were adjusted for the 18 metre hub height of the WES100 (WES, 2014) using formula 7. It was then determined what fraction of time the wind blows at what speed; this was done in steps of one metre per second. Using this wind speed distribution and the electric output at each wind speed of the WES100 (see power curve in appendix XV). The weighted average power output (in kW) was calculated according to formula 8. Multiplying this average power output by 8760 hours/year yielded the amount electricity produced in kWh per year, which was converted to GWh/year. The electricity output of each turbine was also converted to its primary energy equivalent according to formula 2 using electricity's ERE of 1.09 and its average conversion efficiency of 0.38 (see appendix III).

Lastly the amount of turbines that could be installed on Vlieland was calculated. This was done using the same assumptions as for large wind turbines.

The levelised costs of energy generated with small wind turbines were calculated according to formula 3. Lifetime and discount rate were obtained from literature (see appendix XV). Lifetime energy production was determined by multiplying annual production (calculated as described in previous paragraphs) and lifetime. *Wind Energy Systems,* the company that produces and installs the WES100, was contacted to obtain information on investment costs and annual O&M costs (see appendix XV). For consistency with others renewable options no scaling was applied.

The levelised subsidy was calculated in the exact same way as was done for large turbines. It was estimated that small wind turbines, like large turbines, realise the all 2800 SDE+ subsidised full load hours each year. The amount of subsidy per kWh is the same as for large turbines (0.0295 euro/kWh), as is the duration of the subsidy, which is 15 years. The annual subsidy is therefore again calculated according to formula 9. The annual subsidy was converted to a levelised subsidy as explained in the general techno-economic methodology (formula 4). Lastly the levelised subsidy was subtracted from the levelised cost of energy to yield the *net* specific costs of small wind turbines on Vlieland.

The internal rate of return of small wind turbines was calculated as described in the general techno-economic methodology (using formula 6) Lifetime, investment costs and O&M costs were already calculated. Annual benefits were the annual subsidy during the first 15 years plus sales of electricity during the entire 20 years of the project. Electricity would be sold at the same price as for large wind turbines (see appendix XIV). Again, it was conservatively estimated that this price would not change through time. For consistency with other renewable options investigated here, no scaling laws were applied.

Photovoltaic panels on roofs
For calculations on photovoltaic panels, prices and conversion efficiencies from the Dutch market analysis (Van Sark et al., 2013a) were taken for three reported utility categories of tilted roof systems: small-scale, <1 kW_p; medium-scale, 1 – 5 kW_p, and large-scale, >5 kW_p. As a first step, the primary energy equivalent which could be achieved by the PV-on-roofs option was determined.

Firstly, the system efficiency, the potential total roof capacity and the full load-hours equivalent were required to calculate the potential energy production of PV on roofs. Secondly, energy accounting as in the energy use section gave the transition from potential energy production to the primary energy equivalent.

After determining the primary energy equivalent, the levelised costs of energy (LCOE) and the net specific costs based on levelised subsidies were calculated. This was followed by the determination of the profitability, which was expressed as the internal rate of return of the project.

In order to give a preliminary assessment on sensitivity, calculations were performed for two cases: an average case (with average panel characteristics) and a "high performance" case (with characteristics of high performing panels). A list of all input values is provided in Appendix XVI).

In the average case, the average market module efficiency was taken (Van Sark et al., 2013a)[37]. Also, the average European converter efficiency[38] was chosen (Van Sark et al., 2013a). Other system losses were assumed to be a "typical" 10% of the total (Van Sark et al., 2013a). In this way, the total system efficiency became:

$$\eta_{system} = \eta_{module} \cdot \eta_{conv} \cdot \eta_{other}$$

Where:
η_{system} = *system efficiency* (kW_p/m^2)
η_{module} = *module efficiency* (kW_p/m^2)
η_{conv} = *converter efficiency*
η_{other} = *combined efficiency of other system components (1-"typical losses")*

[37] This means a PV module efficiency under standard spectral irradiance conditions (STC): 1.5 times atmospheric mass (AM), a fixed spectral irradiance of 1000 W/m^2 and an ambient temperature of 25 °C amongst others (IEC 60904-3).
[38] For the definition of the European converter efficiency, please consult Harberlin et al. (1995).

The latter two efficiency terms are usually called the "performance ratio" (PR) of a PV system[39,40].

Based on the available roof space (which was determined as shown in Appendix XVII), multiplication with the module efficiency (η_{module}) gives the potential cumulative roof capacity for solar energy options on Vlieland:

$$C_{roof} = \eta_{module} \cdot A_{roof}$$

Where:
C_{roof} = *potential cumulative roof capacity* (W_p)
η_{module} = *module efficiency* (W_p/m^2)
A_{roof} = *available roof space* (m^2)

The annual solar irradiance required for determining the full load-hours equivalent of PV on roofs followed from potential energy density calculations (see Appendix XVIII). As mentioned in the corresponding section, measured roofs oriented southward have average irradiance values nearly equal to those on horizontal planes. Therefore, the annual irradiance for PV on roofs was used here without the requirement of an orientation correction factor.

Multiplication of the aforementioned solar irradiance with the performance ratio (PR) and division relative to the standard insolation gave the full load hours equivalent[41,42]:

$$FLE = \frac{PR \cdot G_{ann}}{G_{STC}}$$

Where:
FLE = *full load hours equivalent* ($kWh/kW_p/yr = h/yr$)
G_{ann} = *annual local insolation* ($kWh/m^2/yr$)
G_{STC} = *standard reference solar irradiance* ($1\ kW_p/m^2$)
PR = *performance ratio of the system* (-)

Subsequently, the potential roof capacity was multiplied with the full load hours equivalent to determine the electricity production potential:

$$E_{pot} = FLE \cdot C_{roof} \cdot 3.6 \cdot 10^6$$

Where:
E_{pot} = *electricity production potential* (J_e/yr)
FLE = *full load hours equivalent* ($kWh/kW_p/yr = h/yr$)
C_{roof} = *potential cumulative roof capacity* (W_p)

[39] Multiplying the "outside-the-module" system efficiency with the converter efficiency gives us the performance ratio (PR), which is defined as the actual energy output divided by the rated output of the module (Marlon et al., 2005). As the rated output of a PV system itself already includes module efficiency losses, the PR can also be defined as the outside-the-module system efficiency: $PR = \eta_{conv} * \eta_{other}$.

[40] The PR in the average PV-on-roofs case turned out to be 86%, which is more or less in line with the IEA (2011) utility-scale PR estimate of 82%.

[41] A full load of 1 kW_p over a year would lead to a total energy production of 8760 kWh. Therefore, the unit $kWh/kW_p/yr$ is equal to the annual full load hours equivalent of a PV system (h/yr).

[42] This value was based on the "yield" formula from Siderea (2013) and intermediate steps in PV exercises in Van Sark et al. (2013b).

Analogously to the performed electricity energy accounting in section, the potential just mentioned was translated to the primary energy equivalent:

$$E_{P,av} = 10^{-12} \cdot E_{pot} \cdot \frac{ERE_{grid}}{\eta_{grid}}$$

Where:
$E_{P,av}$ = *primary energy equivalent* (TJ_p/yr)
E_{pot} = *electricity production potential* (J_e/yr)
ERE_{grid} = *energy requirement for energy on grid* (J_p/J)
η_{grid} = *electricity grid efficiency* (J_e/J)

After determination of the potential, the PV costs were calculated. To obtain the levelised cost of energy for PV on roofs, the investment and O&M costs had to be determined first. Also the lifetime of PV on roofs had to be specified. In this section, a subdivision was made between installation investment costs and system investment costs. Total investments were thus expressed as follows:

$$I_0 = I_{sys} + I_{inst}$$

Where:
I_0 = *total investment costs (€)*
I_{sys} = *system investment costs (€)*
I_{inst} = *installation investment costs (€)*

Specific PV system prices do not vary with capacity (Van Sark et al., 2013a). Therefore, specific system investment costs were taken independent of capacity. The system investment costs thus followed from the cumulative roof capacity potential (which was determined in the potential calculations) multiplied with the specific investment costs:

$$I_{sys} = SIC \cdot C_{roof}$$

Where:
I_{sys} = *system investment costs (€)*
SIC = *specific investment costs* ($€/W_p$)
C_{roof} = *potential cumulative roof capacity* (W_p)

Based on tabulated results for average installation costs at varying system capacities (Van Sark et al., 2013a), a best-fit regression power curve for the installation investment costs was constructed. This best-fit was expressed as follows (manipulated from Blok, 2007, p. 202):

$$SI_{inst} = \gamma \cdot C^{R-1}$$

Where:
SI_{inst} = *specific investment costs for system installation* ($€/W_p$)
C = *system capacity* (W_p)
R = *scale factor with* $1\text{-}2^{R-1}$ *as price reduction factor per doubling of to-be-installed capacity*
γ = *a constant*

Subsequently, the average PV capacity per dwelling was determined to define the correct scaling to apply for the installation investment costs. The value of this average capacity also defined which capacity category-specific prices were used for the economic calculations (those for <1 kW_p, 1 – 5 kW_p or >5 kW_p, as mentioned at the start of the PV-on-roofs methodology section):

$$C_{avg} = \frac{C_{roof}}{N_{dwell}}$$

Where:
C_{avg} = *average potential residential system capacity* (W_p)
C_{roof} = *potential cumulative roof capacity* (W_p)
N_{dwell} = *number of dwellings*

In this equation, CBS (2010) provided the number of residential and company dwellings.

From the table relating average specific installation costs and system capacities (Van Sark et al., 2013a), reference specific installation costs at a reference module capacity were obtained. These values were used as the arbitrary[43] standard scale. Subsequently, the installation investment costs scaled to the average capacity (shown just above) were calculated. This expression was deduced from the aforementioned formula describing the scale law power curve:

$$I_{inst} = SI_{ref} \cdot \left[\frac{C_{avg}}{C_{ref}}\right]^{R-1}$$

Where:
I_{inst} = *installation investment costs (€)*
SI_{ref} = *reference specific installation investment costs* ($€/W_{p,\,ref}$)
C_{avg} = *average potential residential system capacity* (W_p)
C_{ref} = *reference system capacity* ($W_{p,\,ref}$)
R = *scale factor with* $1\text{-}2^{R\text{-}1}$ *as price reduction factor per doubling of to-be-installed capacity*

Undiscounted annual operation and maintenance costs ($O\&M_0$) were expressed as a fraction of the total investment costs (as in Enbar, 2010; Ossenbrink et al., 2013). The economic lifetime chosen was as in Ossenbrink et al., 2013.

Ultimately, the levelised cost of energy (LCOE) was calculated analogously to the description in the general techno-economic outline section.

Conclusively, the same calculations were done again, but now including a 10% EIA subsidy on initial PV system investments for small installations (RVO, 2014a). Recalculation using this investment cost reduction led to the net specific cost (€/kWh), which is the levelised cost of energy minus the net levelised subsidy:

$$NSC = LCOE - sub_{net}$$

Where:
NSC = *net specific costs* ($€/kWh_e$)
$LCOE$ = *levelised cost of energy* ($€/kWh_e$)
sub_{net} = *net levelised subsidy* ($€/kWh_e$)

[43] The standard scale is arbitrary because only ratios are involved in the intermediary scaling calculations. However, a standard scale has to be chosen somewhere to allow for a scaling-up towards the desired capacity as described later in this section. In this way, a difficult calculation for determining the "constant" is avoided.

For PV on roofs, the net levelised subsidy followed from the net specific costs instead of vice versa. Transition of net specific costs from kWh^{-1} to TJ_p^{-1} was based on energy accounting as in energy use section (see appendix III):

$$NSC_P = NSC \cdot \frac{\eta_{grid}}{ERE_{grid}} \cdot \frac{10^{12}}{3.6 \cdot 10^6}$$

Where:
NSC_P = *net specific costs (€/TJ_p)*
NSC = *net specific costs (€/kWh_e)*
η_{grid} = *grid efficiency (J_e/J)*
ERE_{grid} = *energy requirement for energy on grid (J_p/J)*

Once the potential and costs for PV on roofs were known, the profitability was determined using the IRR. For these calculations, subsidies were always included. The project benefits were still required in order to determine the profitability.

The price of electricity saved which was obtained from Milieucentraal (2014) was assumed to be constant over the project lifetime. Undiscounted electricity savings were therefore expressed by means of the following expression:

$$B_0 = p_e \cdot \frac{E_{pot}}{3.6 \cdot 10^6}$$

Where:
B_0 = *undiscounted electricity savings (€)*
p_e = *price of electricity (€/kWh)*
E_{pot} = *electricity production potential (J_e/yr)*

Subsequently, the IRR followed as described in the general techno-economic methodology section.

The "high performance" PV system case proceeded in exactly the same manner as the "average" system case, except that some input values were changed (also see Appendix XVI):

1) As converter efficiencies above the European average are numerously available for small DC input power values (Van Sark et al., 2013a), a higher converter efficiency was used.
2) The averages of all below-average PV system prices in three module size categories (<1 kW_p, 1 – 5 kW_p, >5 kW_p) were determined from a PV system cost database (Van Sark et al., 2013a) and used as the new specific investment costs.
3) The average of all above-average module efficiencies was calculated and determined as in 2).
4) Annual O&M accounted for a smaller fraction of the total investment sum here, as in Van Sark et al. (2013a).

Photovoltaic panels on a solar farm

The solar farm will consist of 1200 PV panels oriented in an optimal direction and is planned at a site on the army basis "De Vliehorst" (B. Visser, director of Energy Cooperation Vlieland, personal communication, June 6, 2014). Using this information, the total surface area of the farm was determined using a standard PV module size[44].

The average and high performance cases considered for PV on roofs were used for the solar farm as well. For an overview of input value variation between the two cases, please refer to appendix XVI.

A high capacity converter efficiency (Van Sark et al., 2013a) was used in both average and high performance cases, as the solar farm is large compared to a typical household PV system. For the determination of the full load hours equivalent for the solar farm, the equation used in the PV-on-roofs option was used as a basis. However, since the solar farm panels were oriented optimally with a 35° dip south (Agentschap NL 2010, p. 29), the optimal irradiance value was used for the solar farm, contrary to the 85%-of-the-maximum value for PV on roofs (also see appendix XVIII). Therefore the following orientation gain factor was used as a correction:

$$G_{ann,sf} = f_{gain} \cdot G_{ann} = \frac{1}{0.85} \cdot G_{ann}$$

Where:
f_{gain} = *orientation gain factor of solar farm relative to PV on roofs (-)*
$G_{ann,\,sf}$ = *annual local insolation on an optimally oriented plane for the solar farm (kWh/m²/yr)*
G_{ann} = *annual local insolation on a horizontal / roughly southward oriented plane (kWh/m²/yr)*

The installable solar farm capacity was then calculated analogously to the potential cumulative roof capacity for PV on roofs. This subsequently led to the determination of the energy potential and the primary energy equivalent in the same way as for PV on roofs.

Specific PV system prices only differ marginally above 5 kW_p (Van Sark et al., 2013a). Therefore, average and “high potential” system prices were assumed to fall in line with the > 5 kW_p class as determined for the PV-on-roofs option. This led to a similar equation for system investment costs as for PV on roofs, only now with typical “large order” price reductions as shown in recent similar Dutch projects (SMZ, 2013):

$$I_{sys} = (1 - d_{LO}) \cdot SIC \cdot C_{inst}$$

Where:
I_{sys} = *system investment costs (€)*
d_{LO} = *“large order” discount (as fraction of system investment costs)*
SIC = *specific investment costs (€/W_p)*
C_{inst} = *installable solar farm capacity (W_p)*

The installation investment costs were based on the same power law expression as for PV on roofs. Again, the economic project lifetime was as in Ossenbrink et al. (2013).

Subsequently, the levelised cost of energy (LCOE) was determined analogously to the PV-on-roofs option.

[44] Baltussen (2013) mentions a typical PV module size of 1.1 m x 1.6 m, which holds a typical surface area of 1.76 m^2. This value times 1200 panels yields a solar farm surface area of 2112 m^2.

Given the LCOE for both solar farm cases, SDE+ will provide a fixed selling price close to the LCOE (RVO, 2014a). However, this subsidy only lasts 15 years and holds only for the first 1000 full load hours equivalent. Assuming a reference grey electricity cost as in the SDE+ description (RVO, 2014a), the annual breakdown of costs and benefits with and without subsidies allowed for the determination of discounted SDE+ subsidies over the lifetime. Division by the total (undiscounted) energy production over the lifetime then gave the net levelised subsidy as shown in the results section.

After determination of the net levelised subsidy for the two solar farm cases, the net specific costs were calculated with the same expressions as for PV on roofs.

The IRR was ultimately defined using the expression as shown in the general techno-economic part.

Please note that all costs and prices here were expressed in $€_{2013}$. As the inflation between 2013 and 2014 was -0.3%, (Statbureau, 2014), no correction to 2014 money-of-the-day terms was applied.

Solar thermal heating

Solar thermal energy technology harvests energy from the sun through heating up water that flows through solar thermal collectors on sun-facing roofs. Warm water is used directly and for space heating. In the Netherlands warm water is normally produced by burning natural gas and solar thermal energy can partially replace natural gas use. Solar thermal collectors can contribute a maximum of 45% of the total heat demand of warm water in a household (Zegers, 2013). This is due to mismatches between variable solar influx and heat demand: solar influx is lowest in winter and night, when heat demand is highest and vice versa (Zegers, 2013).

The total potential heat production using solar thermal energy on Vlieland was determined by calculating the total amount of heat that would no longer have to be produced using natural gas when solar thermal collectors are installed (formula 10).

$$H = C_g * a * b * \eta \qquad (10)$$

Where:

H = *heat potential of solar thermal energy (TJ/yr)*
C_g = *total gas consumption on Vlieland (TJ/yr)*
a = *fraction of natural gas used for heating water*
b = *fraction of warm water produced by solar thermal energy*
η = *conversion efficiency of natural gas to heat*

Total gas consumption on Vlieland was obtained from the current energy use section and the fraction of warm water that could be produced was set at the maximum 0.45 (Zegers, 2013), assuming that roof space would not be a limitation (which was proven in the solar thermal heating part of section 3.4). Typical conversion efficiencies from natural gas to heat in a household scale boiler range from 80 to 97% (Blok, 2007); it was conservatively assumed here that average the boiler efficiency is 85%. The fraction of natural gas used for heating water was determined in two steps. Firstly, this fraction was calculated for households by dividing the average (Dutch) household's gas consumption for heating water (van Dril, 2012; see appendix XIX) by the average (Frisian) household's natural gas consumption (ING, 2013; see appendix XIX). Natural gas use by households represents one third of total natural gas use on Vlieland (Energie In Beeld, 2014). The largest other users are hotels, restaurants & bars, holiday homes, stores and public buildings (Energie In Beeld, 2014). The fraction of natural gas used for water heating is likely to be similar to households, as these service buildings get similar energy end-uses from natural gas (predominantly space heating, direct warm water use and cooking). Other sectors that would have different gas use patterns, like agriculture and large-scale or heavy industry are not present on Vlieland. As a second step it was therefore assumed that for all sectors the fraction of natural gas used for water heating is the same as for households.

Apart from the total heat production potential (in TJ/year), the primary energy equivalent of this heat production (in TJ_P / year) was calculated as well, to later compare the potential of solar thermal to other options. The heat collected in solar thermal collectors replaces heat produced by burning of natural gas. The primary energy equivalent of the total heat production potential was therefore calculated using the conversion efficiency (to heat) and ERE of natural gas according to formua 11.

$$H_P = \frac{H * ERE_{ng}}{\eta} \quad (11)$$

Where:
H_p = *primary energy equivalent of total production potential of solar thermal collectors* (TJ_p/yr)
H = *heat production potential (TJ/yr) (see formula 10)*
ERE_{ng} = *energy requirement for energy of natural gas*
η = *conversion efficiency of natural gas to heat*

As mentioned earlier, it was assumed that the maximum 0.45 fraction of heat demand for warm water was met by solar thermal collectors. This assumption required that enough roof area is available. The last step in assessing the potential was to verify that enough roof area was available. The required roof area to cover the maximum 0.45 fraction of warm water heat demand was calculated according to formula 12.

$$RRA = \frac{H}{LH * TO} * \frac{1 * 10^6}{3.6}{}^{45} \quad (12)$$

Where:
RRA = *total required roof area to cover warm water heat demand* (m^2)
H = *heat potential of solar thermal energy (TJ/yr)*
LH = *load hours per year (h/yr)*
TO = *thermal output of a solar collector* (kW/m^2)

The total heat that could be supplied by solar thermal collectors (H) was calculated using formula 10. The typical thermal output (kW/m^2) and the amount of annual load hours of a solar thermal collector in the Netherlands were obtained from a study on techno-economic parameters of renewable energy generation by ECN (Lensink, 2012) and can be found in appendix XIX. The resulting required roof area for solar thermal collectors was compared to the total roof area suitable for solar thermal energy on Vlieland (which was calculated in the same way as for PV panels, see appendix XVII) according to formula 13

$$f = \frac{RRA}{SRA} \quad (13)$$

[45] This correction factor was used to correct for the units of H (TJ/yr) and TO in (kW/m^2)

Where:
f = fraction of suitable roof area covered with solar thermal collectors
RRA = total required roof area to cover the maximum 45% of warm water heat demand (m^2)
SRA = total suitable roof area available on Vlieland (m^2)

In the cost calculations a distinction was made between small- and large-scale solar thermal installations. The distinction was made at 100 m^2 as different subsidy schemes exist for solar installations smaller and larger than 100 m^2. Despite the fact that specific investment costs are lower for large-scale solar thermal installations, it is not practical to fully cover large buildings with large-scale solar thermal installations, as a heat grid infrastructure is absent on Vlieland (see appendix XII), which makes it impossible to transport surpluses of heat production. Therefore, the assumption was made that all buildings suitable for large-scale solar thermal installations would be covered by a fraction f (see formula 13), and that the remaining solar thermal heat potential was covered by the installation small-scale solar thermal installations.

Large-scale solar thermal installations would only be placed on buildings with a minimum south-facing roof area of 100m^2 divided by fraction f. As explained in the previous paragraph, only the fraction f of the south-facing roofs on these larger buildings would be covered by solar thermal collectors (see formula 14).

$$RRA_L = f * SRA_L \quad (14)$$

Where:
RRA_L = total roof area covered with large-scale solar thermal installations (m^2)
f = roof area fraction covered with solar thermal collectors to cover demand
SRA_L = suitable (i.e. south-facing) roof area of buildings considered suitable for large-scale solar thermal installations (m^2)

The total area needed for small-scale solar thermal installations (RRA_S) was calculated by subtracting the total roof area suitable for large-scale solar thermal installations (RRA_L, see formula..) from the total required roof area needed to cover the maximum 45% of heat demand for water heating (RRA; see formula..) .

In order to calculate the levelised costs of energy (LCOE) of solar thermal energy, a weighted average (based on the fraction of heat produced by small- and large scale installations respectively) of the LCOE of the two types of installations was made. To calculate the LCOE (formula 3), the investment costs (or capital costs), O&M costs, discount rate and lifetime of both small- and large scale installations were needed. Investment and O&M costs for roofs larger than 100 m^2 were obtained from ECN (Lensink, 2012) and assumed to be dependent on thermal output, see appendix XIX. For roofs smaller than 100 m^2 investment cost data from a report on solar thermal systems by E4S Consult was used (Zegers, 2013), which can be found in appendix XIX as well. This report was used, because it provides costs data of the standard solar thermal collector. Standard solar thermal collectors have the greatest potential and market position in the short run. It is the most mature solar thermal collector technology with the best price/potential ratio (Zegers, 2013). O&M costs for small roofs were obtained from NREL (2014) and assumed to be percentage of investment costs, see appendix XIX. Both for small- and large-scale solar thermal collectors, the lifetime of solar thermal collectors was assumed to be 20 years (Twidell & Weir, 2006). A discount rate of 5% (IEA, 2010a) was assumed.

In order to take subsidies on solar thermal installations and their resulting cost reduction into account when calculating the net specific costs and the internal rate of return, research on subsidies for the two different types was conducted. Investment costs of large-scale solar thermal collectors decreased as a result of the Frisian Energy Premium that provides €350 per household for the installation of solar thermal collectors (Province of Friesland, 2014a). The number of households was determined by the number of buildings suitable for large-scale installations[46] and hereafter the total subsidy. Investment costs of small-scale solar thermal installations decreased as a result of both the Energie Investeringsaftrek (EIA) and the Frisian Energy Premium. The EIA subsidy reduces total investment costs by 10% (RVO, 2014b). The assumption is made that all households place a small-scale solar thermal collector on their roof. Therefore, the amount of subsidy for small-scale solar thermal collectors as a result of the Frisian Energy Premium is calculated by the amount of subsidy multiplied by Vlieand's 550 households (CBS, 2010). As our calculations do not allow for heat exchange between residences, no SDE+ subsidy for small users was taken into account. Using the adjusted investment costs, the net specific costs of energy and the internal rate of return (profitability) were determined. The net specific costs of solar thermal energy were, as like the LCOE, calculated by taking a weighted average (based on the fraction of heat produced by small- and large scale installations respectively).

To calculate the internal rate of return the total (adjusted) investment costs, total O&M costs, and annual benefits were required. In order to calculate the annual benefits the price of heat was needed. The price of heat was calculated by converting the gas price (see appendix XIX; van Dril, 2012) to a €/MJ price, and then dividing this gas price by the conversion efficiency from natural gas to heat (based on Blok, 2007; see appendix III).

2.9 Public & Stakeholder perception

To obtain an overview of the opinion of Vlieland's community on the considered renewable energy technologies which could be fed into the MCA, we asked representatives of inhabitants and influential stakeholders to fill in a questionnaire (see Appendix XX).

For the overview of public perception, 32 inhabitants were interviewed. Sampling of results for public perception was conducted by approaching: 1) inhabitants encountered on the island during the day at the 5th of June; 2) inhabitants in stores in the Dorpsstraat and near the ferry departure area in the morning of the 6th of June. The stakeholders interviewed in the orientation phase of this study (see section 2.6) were also requested to fill in the questionnaire. All stakeholders that responded to this request were included in the results for stakeholder perception.

The questionnaire started with general questions on the important of independence and more specifically energy independence and switching to renewables. Then, three statements were posed for each renewable energy option. These statements include one emotional statement on visual hindrance per technology option and two more rational statements: 1) whether the energy technology mentioned is a good option for achieving energy independence; 2) whether benefits per energy technology outweigh the disadvantages. Answers could range between seven options from --- (totally disagree), 0 (neutral) to +++ (totally agree).

[46] i.e. the number of buildings with a minimum south-facing roof area of 100m^2 divided by fraction f

2.10 Multi-criteria analysis (MCA)

Multi-criteria analysis (MCA) is a tool to compare separate options using different criteria and units to come up with the best option according to the criteria. The MCA in this research served to rank different renewable energy options for Vlieland covered in the techno-economic analysis. These options were: large wind turbines, small wind turbines, the solar farm, photovoltaic panels on roofs and solar heating. For the photovoltaic options, it was assumed that the "high performance" systems would be used (see appendix XVI)

Based on the results from the techno-economic analysis and the questionnaires, the five different renewable energy options were scored on the four criteria listed in table 2.4. The described MCA input data can be found in appendix XXII. The potential criterion was scored twice: once for the "business-as-usual" trend and once for the "high efficiency" trend regarding the 2020 primary energy demand.

The four criteria were weighted from three different perspectives, as explained under the weighting section. The MCA was performed using *BOSDA* MCA software; the followed steps in the programme were based on can be found in appendix XXIII.

Thus, a total of six MCA runs were performed using the three weightings and two energy demand trends for 2020.

Table 2.4 *MCA Criteria and units*

Criteria	Unit
Net specific costs	€/TJ_p
Potential	% of expected 2020 primary energy demand Vlieland
Public perception	---/+++
Stakeholder perception	---/+++

Costs

The net specific costs (in euro/TJ_P) indicate how cost-effective each option can replace conventional primary energy equivalents on Vlieland and were included in the MCA to represent the economics of each option. Net specific costs of each option followed from the techno-economic analysis (see section 3.4). The internal rate of return was not included in the MCA, because it is heavily dependent on the energy price. Specifically for PV panels on roofs, the electricity selling price for households is currently very high, but this may well change in the near future (see discussion section). The net specific costs reflect the actual economic performance of the technology itself better[47].

The standardisation used is maximisation in line with Hellendoorn (2001) because of the natural point of zero and the linear character of costs. The criterion is inserted as a cost; this means that a higher value (euro/TJ_P) will yield a lower score.

Potential

The potential of each renewable technology option was expressed as the percentage of the primary energy equivalent of Vlieland's energy demand in 2020 that could be met by

[47] It must be noted that net specific costs do include the external factor of subsidies. However subsidies were assumed to be less volatile than the energy price (specifically the price of electricity sold back to the grid by households).

individual options. The primary energy demand in 2020 was determined in the energy trend section for an energy-efficient trend and a "business-as-usual" trend. The potential was determined for both trends and the MCA was performed for both as well.

In line with guidelines of Hellendoorn (2001) a maximum standardisation was used. This method is used for criteria that have natural point of zero like costs or temperature in Kelvin, a doubling of the criterion means a doubling of the impact (Hellendoorn, 2001). Potential is characterised as a benefit: a higher value of potential will give a higher score in the MCA.

Public and stakeholder perception
Public and stakeholder perception of the five renewable energy options for Vlieland were assessed in section 3.5 and the distribution of scores for all five options as given by stakeholders and inhabitants can be found there. Taking the average score of each option for all questions answered would yield a more or less neutral opinion. In this case, extreme opinions would be levelled out. Extreme opinions can polarise the general opinion (Deffuant et al., 2002). To emphasize the more influential extreme opinions, the input of the MCA consisted of the percentage of extreme negative opinions (---). The percentage of extreme negative opinions was calculated for each of the three considered statements. After averaging the two rational statements, which was done to create a balanced opinion on rational and emotional answers, the rational and emotional percentages were averaged as well. The procedure to average the opinions was as follows: the sign --- corresponded to a value of -3, where a value of +++ corresponded to a value of +3.

To make a clear division between the outcomes of both public and stakeholder perception for the options interval standardisation was used. This means that the option with the least favourable input receives a score of zero, and the one with the most favourable input receives one. The values in between have a linear distribution of the scores. The criteria are inserted as cost, which means a higher input means a lower score.

Criteria weighting
Different parties may view not all criteria to be equally important. The commissioner of this study, Lab Vlieland, and the most influential stakeholder on Vlieland, the municipality, were therefore both asked to assign weights to the four criteria (overview XXII). The techno-economic weighting perspective was based on the focus points of this research.

Procedure
Each criterion received a score based on results and weighting. Adding up the scores of the different criteria gave final result: the higher the number, the more desirable the renewable technology option.

Lastly, the results were subjected to a sensitivity analysis for both weight and scores. This analysis was conducted with the sensitivity analysis tool of *BOSDA*.

Sensitivity analysis
To get insight in the robustness of the MCA results, a sensitivity analysis was performed with an internal function of *BOSDA.* As input data *BOSDA* needed uncertainty percentages of each criterion; these uncertainty percentages can be found in XXII. As an example, 10% uncertainty for a score of 100 means that the real score is likely to be between 90 and 110 (Hellendoorn, 2001).

The sensitivity of both scores and weights can be determined. Sensitivity of weights can also be determined by using different weightings (Hellendoorn, 2001), which was done in this research. So a sensitivity analysis on weights was not performed.

The sensitivity analysis generated MCA results with random combinations of the given uncertainties and noted which option is ranked on what position (Hellendoorn, 2001). As result *BOSDA* produced a table containing probability scores between zero and one for the ranking position of each option. As an example, if the solar farm receives 0.60 for position one this indicates that in 60% of the cases it will receive the first position taking into account the given uncertainty. Due to the random generation of results each sensitivity analysis might give slightly different results.

2.11 Energy vision Vlieland 2020

The purpose of this energy vision section is to explore combinations of the investigated renewable energy options that could add up to meet Vlieland's energy demand in 2020. Each combination of renewables was based on the outcomes of the multi-criteria analysis (MCA). The MCA was performed three times with different weightings (see section 2.10): the techno-economic weighting focused on potential and costs, the more distributed weighting by Vlieland's municipality and the weighting by Lab Vlieland with a stronger emphasis on public and stakeholder support. For each of the three MCA weightings, two combinations of renewables were proposed, one assuming the business as usual energy use trend towards 2020 and one assuming the high energy efficiency trend. Combinations were made by adding up the potential of the different renewable options until the 2020 energy demand was met. Renewable options were added in order of the rank that they were given in the (differently weighted) MCAs. In this way the most preferred option was used first, followed by the second most preferred option, etc., until the entire demand was met. Energy demand and potential were both based on their primary energy equivalent (see section 2.3).

The potential of each combination (in TJ_P/year) was determined by summing the potentials of the different renewable energy options. Besides the potential, the net specific costs (euro/TJ_P), internal rate of return (%) and total investment costs of each combination were also determined. For the net specific costs and internal rate of return this was done by calculating the weighted average over the individual renewable options that the combination consisted of (formulae 15 and 16). For the total investment costs the investment costs of individual technologies were summed up (formula 17)

$$NSC_{wavg} = \sum_{i=1}^{n} (f_i * NSC_i) \qquad (15)$$

$$IRR_{wavg} = \sum_{i=1}^{n} (f_i * IRR_i) \qquad (16)$$

$$IC_{total} = \sum_{i=1}^{n} (a_i * SIC_i) \qquad (17)$$

Where:

NSC_{wavg} = *weighted average net specific costs of a combination of renewables*

List continues on next page

IRR_{wavg}	= *weighted average internal rate of return of a combination of renewables*
IC_{total}	= *total investment costs of a combination of renewables*
n	= *amount of different renewable options that the combination consists of*
f_i	= *fraction renewable i contributes to total potential of the combination*
a_i	= *amount of units (e.g. turbines) of renewable i*
NSC_i	= *net specific costs of renewable i*
IRR_i	= *internal rate of return of renewable i*
SIC_i	= *specific (i.e. per unit) investment costs (e.g. investment costs per turbine)of renewable i*

3. Results

3.1 Current energy use and production

Energy consumption on Vlieland in 2013 was 271 TJ_P. Electricity, natural gas and transport fuels each accounted for about a third of the energy consumption (figure 3.1). Transport fuels were dominated by the fuel use of ferry operator *Rederij Doeksen*.

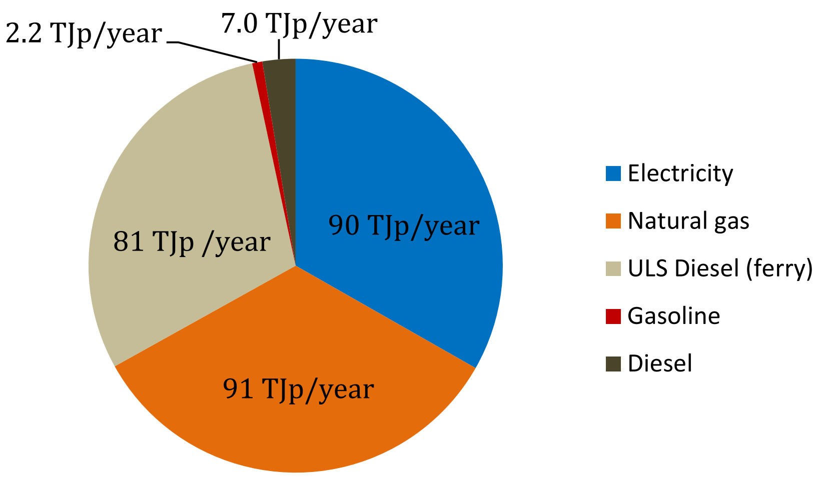


Figure 3.1 *Primary energy equivalent of energy consumption on Vlieland in 2013. ULS Diesel = ultra-low sulphur diesel.*

Energy production on Vlieland in 2013 only occurred in the form electricity and was 0.50 TJ_p in total. The large majority of production can be attributed to photovoltaic panels on houses, the campsite and municipality-owned buildings. The only other energy sources are some small-scale wind installations at the harbour office, municipality and campsite Stortemelk. Since the current production is almost negligible compared to the energy use[48], the current energy production was not taken into account in subsequent sections of this report.

3.2 Estimates of Vlieland's energy use in 2020

The use of different energy carriers on Vlieland over the past 20 years shows that energy use slightly increases over time (appendix IV), this trend is likely to continue towards 2020. More quantitatively, if Vlieland follows the projected national trend of an annual 1% increase in the total primary energy supply (IEA, 2012b), the primary energy use on Vlieland increases from 271 TJ_P in 2013 to 291 TJ_P in 2020. If Vlieland follows the annual increase in energy demand based on Van de Weerdhof (2011), primary energy demand in 2020 would be 278 TJ_P. Based on these numbers, our business-as-usual estimate of Vlieland's primary energy demand in 2020 is *290 TJ_P per year*.

If Vlieland breaks current energy use trends and implements sufficient energy efficiency measures energy use will reduce towards 2020. Based on the expected national average 21.6% reduction of primary energy use between 2013 and 2020 as a result of national and EU policy, the high energy efficiency estimate of Vlieland's 2020 energy demand is *212 TJ_P per year* by 2020.

[48] When current production is subtracted from current use, the rounded figure for current use is still 271 TJ_P.

3.3 Stakeholder interviews

The key outcomes of the interviews are summarised per stakeholder in this section. Some interviewees do not appear in this section, but more elaborate point wise summaries of all interviews can be found in appendix VI.

According to the municipality current share of renewable energy on Vlieland is around the average of the Netherlands, and a lot has to be done to reach the target set in 2020. Solar and wind energy both have approval of the municipality. However wind energy has two major opponents: the *Waddenvereniging* and the province of Friesland, though the latter's opinion is changing slowly. At the moment the 'welstandsafspraak' prohibits installing solar panels on roofs at the Dorpsstraat and Kerkplein. A plan for a solar field exists on the military terrain. For wind there is an option to build wind turbines at the industrial area, but this is still far from realisation. Furthermore the housing of WoonFriesland will be improved from energy label D/E to energy label B in the coming years. Reports commissioned by the municipality argued that geothermal heat and biomass is not suitable for commercial use on Vlieland.

The Energie Coöperatie Vlieland (energy cooperation Vlieland - ECV) is in its start-up phase. It aims to increase the share of renewable energy on Vlieland, profit will be invested in further increasing renewable energy supply. ECV is in favour of all renewable energy techniques available, but as cooperation it is dependent on members as well. As an example, inhabitants said they would not become a member of the cooperation if wind turbines are financed by the ECV. To fulfil the energy needs of Vlieland using PV panels, an area of 30 ha is needed according to director Broer Visser. This area is hard to realise on a small island surrounded by designated Natura 2000 area. For wind the major barrier is the community, and in the past, the province of Friesland, which is slowly changing its viewpoint as reaffirmed by Visser. He also states that installing wind turbines at sea would not be a problem for the community.

Jan van der Veen, director of campsite *Stortemelk* is the driving force behind all renewable innovations present at the campsite. From 2001 onwards almost all available roofs were equipped with PV panels or solar heating andLED lighting is installed everywhere. Geothermal heat is used for the owner's residence at the campsite. Objects or tools that need to be replaced will be replaced by more efficient equivalents. The barrier for implementation of renewable energy on Vlieland is the passive attitude of the municipality according to Van der Veen. He states that the municipality waits for subsidies and other support programmes to act, while a more pro-active attitude will give a better result, like for instance at *Stortemelk*. The campsite is willing to help local sustainable initiatives financially and with experience.

Staatsbosbeheer is a major player on Vlieland and owns a large part of Vlieland. Currently local inhabitants can take a lease of a part of the forest to use the wood for heating of homes. This saves maintenance costs and gas for heating, 80 to 100 inhabitants make use of this. The organisation is in favour of renewable energy as long as it will not negatively effect the environment. According to Herman Brink *Staatsbosbeheer* is willing to contribute to a few wind turbines on the island as long as they are not placed in the dunes or when they form a complete wind park. Major barriers according to Herman Brink are the local community and the province.

As principal of the only secondary school on Vlieland, Ben Matoren is to some extent representative of the local inhabitants on Vlieland. He questions the ambition to be energy independent, and is not really willing to invest in this ambition. He does agree that independence in general is appreciated on the island. In a few years a new school building will be built, nearly energy neutral. The inhabitants do not like change and are extremely sceptic about wind energy, wind energy at sea however would not be a problem.

The Vliehors, southwestern part of Vlieland, is owned by the military. According to major Pieter Bruinink, the ministry of defence has its own energy targets as well. Some tests have been done with biodiesel in helicopters. The lighting at the terrain works with green LED lighting with sensors. The idea to make a solar farm on a currently unused area of the terrain was welcomed by the municipality. Wind turbines are not acceptable on the military base on the Vliehors, due to flying routes.

The Province of Friesland plays a facilitating and directing role in the process towards the energy independence on Vlieland. An energy fund *Fonds Schone Friesche Energie* of €90 millions exists which is available for good business cases regarding renewable energy installation. The Province of Friesland can finance a maximum of 49% of the investment. Gerwin Venema, programme manager Sustainable Innovations at the Province of Friesland, believes that it is not likely that the Province of Friesland will accept large wind turbines on Vlieland[49], but states that it will probably not hamper the installation of small turbines on the island, as the Province leaves this up to the municipality of Vlieland. At the moment the Province of Friesland is working on a programme together with NHL Leeuwarden (a higher vocational education institute) and the Wadden Sea Islands to see if installation of solar panels in the protected rural area is possible. However, this program is still in a start-up phase and the results of this study will need to be further examined.

3.4 Techno-economic analysis

The main results of techno-economic analysis are presented here; detailed results are presented in individual sections below. A large-turbine wind park (based on 2 or 3 large turbines) has the highest energetic potential, followed by a small-turbine wind park (based on 43 small turbines) and lastly the solar based renewables (figure 3.2. A large-turbine wind park also produces energy at the lowest net specific costs of all options considered (figure 3.3). Energy produced with small wind turbines is only slightly more expensive, followed by energy produced on a PV solar farm. The net specific costs of PV on roofs and solar heating panels on roofs are both more than twice as high as the costs of the other options. Note that when combining different options, PV panels on roofs and solar thermal heating (which would require the same roof space) are mutually exclusive.

[49] The province of Friesland has installed many wind turbines in the last decade. In 2012, the policy regarding wind turbines became stricter and 3 areas in the province were appointed to be possible areas for new wind turbines. The Wadden Sea was not one of these areas (RVO, 2014d).

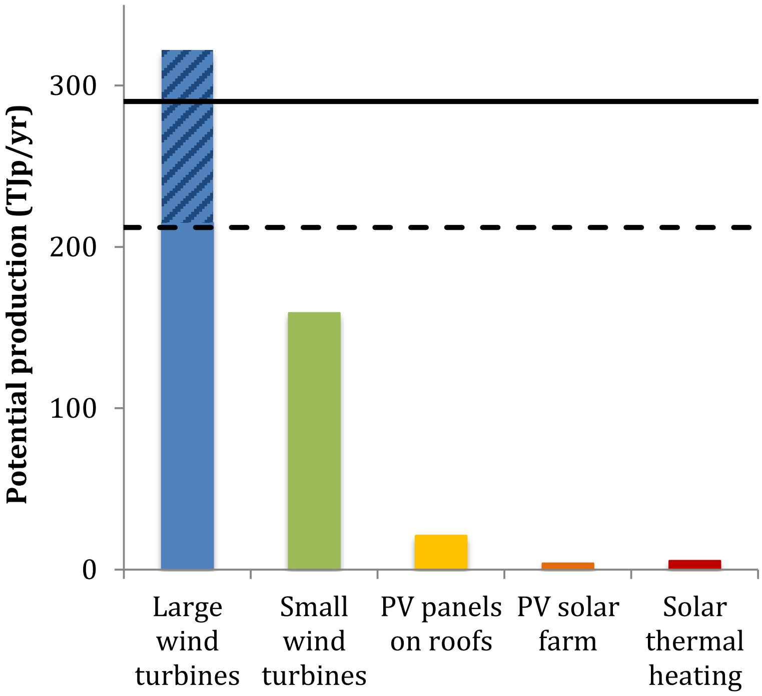


Figure 3.2 *Energetic potential of different renewable options on Vlieland. The solid black line indicates the "business as usual" estimate of Vlieland's energy demand in 2020, the dashed line represents the "high energy efficiency" estimate (see 2020 energy use estimates section). The dashed area of first bar indicates the additional potential of a third large turbine*[50]*.*

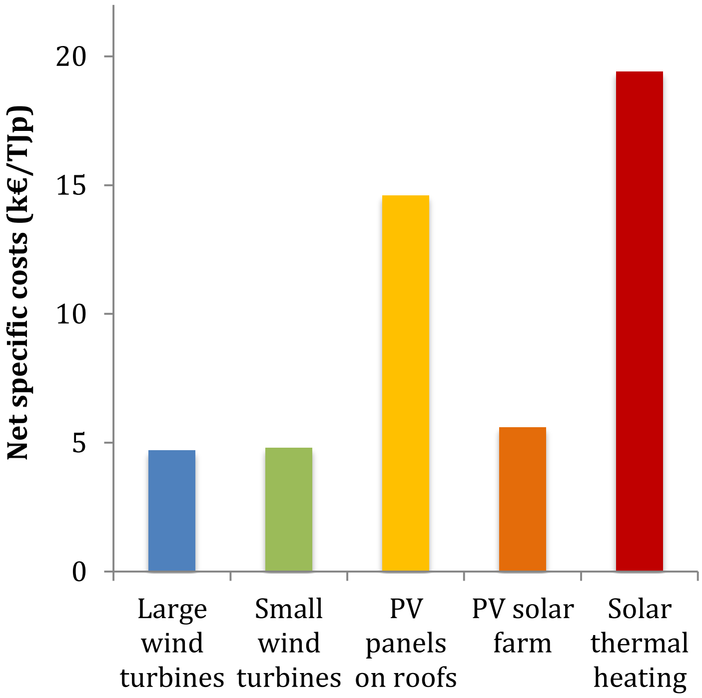


Figure 3.3 *Net specific costs of the different renewable options on Vlieland. A k€ is 1000 euros.*

The internal rate of return (IRR), i.e. the "interest rate" investor can expect on invested capital, is highest photovoltaic (PV) panels on roofs (table 3.1). The costs of producing energy using PV panels on roofs are high (figure 3.3), but the electricity production occurs on household scale, which allows selling electricity to the grid at a high price (this is further explained in the PV part of section 3.4).Together, the high costs and high selling price still result in the highest IRR. Large wind turbines have the second highest IRR, because of their low net specific costs, and despite the lower price paid for electricity from large-scale plants (like a wind park).

[50] Large turbines have such great energetic potential that they could cover the full future energy demand. Under a business as usual estimate of 2020 energy demand, a large-turbine wind park requires three turbines to meet full demand. When using the high energy efficiency estimate of 2020 demand, two turbines suffice.

Table 3.1 *Internal rates of return of different renewable options on Vlieland*

option	internal rate of return
Large wind turbines	10.2%
Small wind turbines	6.7%
PV panels on roofs	11.3%
PV panels on solar farm	4.4%
Solar thermal heating	4.8%

Large wind turbines
The potential of the three investigated 2 MW turbine models on Vlieland is very similar, with an annual electricity production of 10.3 to 10.5 GWh (table 3.2). A typical wind turbine (based on the average of the three investigated models) would yield 10.4 GWh of electricity per year, which has a primary energy equivalent of 107 TJ_P per year (table 3.2).

Table 3.2 *Energetic potential of 2 MW turbines on Vlieland*

	rated capacity (MW)	actual power* (MW)	predicted electricity gen. (GWh/year)	primary equivalent** (TJp / year)
Vestas V80 2.0 MW	2.00	1.18	10.3	107
Gamesa G80	2.00	1.20	10.5	109
Senvion MM82	2.05	1.18	10.3	106
Average	-	1.19	10.4	107
typical 2MW turbine	2.00	1.19	10.4	107

gen. = generation; *actual expected average power based on Vlieland wind data and turbine characteristics (hub height and power curve); **the primary energy equivalent of the predicted electricity generation (see formula 2).

Three typical 2 MW turbines cover more than the expected primary energy demand in 2020, which was estimated at 290 TJ_P per year assuming continuing energy use trends. The three-turbine wind park would produce 31.2 GWh of electricity per year, or 322 TJ_P per year in primary energy (table 3.3). Even when using the largest rotor diameter of 80m (appendix XIV), this wind park could only measure 1.76 km in length (80 metres times a spacing of 11 diameters times two intervals between turbines)[51], so space is not a limitation. If Vlieland

[51] Because of large turbines' high potential, space is not a physical limitation on Vlieland in order to meet the 2020 energy demand. A larger turbine spacing may therefore be preferred as it could turn

follows the higher energy efficiency trend (see section 2.5), primary energy demand in 2020 will only be 213 TJ_P per year. In this case two 2MW turbines would suffice to meet demand, as they would produce 20.8 GWh of electricity per year, or 215 TJ_P per year (table 3.3). Again space would not be a limitation.

Table 3.3 *Energetic potential of a wind park on Vlieland that consists of either two or three 2MW turbines.*

	rated capacity (MW)	actual power* (MW)	predicted electricity gen. (GWh/year)	primary equivalent** (TJp / year)
3 x 2MW wind park	6.00	3.56	31.2	322
2 x 2MW wind park	4.00	2.37	20.8	215

gen. = generation; *actual expected average power based on the average "actual power" values of the three turbine models in table 3.2; **the primary energy equivalent of the predicted electricity generation (calculation: formula 2; values: appendix III).

The net specific costs of producing electricity using 2 MW turbines on Vlieland are 0.049 euro per kWh, or 4700 euros per TJ_P (table 3.4), lowest of all investigated options. These values do not change for different amounts of turbines, because no scaling laws were applied.

Table 3.4 *Specific costs of producing electricity and its primary energy equivalent using large wind turbines*

	cost of electricity (euro / kWh)	cost of primary energy equivalent (euro / TJp)
Levelised costs of energy (LCOE)	0.062	$6.0 \cdot 10^3$
Levelised specifc subsidy	0.013	$1.3 \cdot 10^3$
Net specific costs	0.049	$4.7 \cdot 10^3$

The total initial investment is linearly higher for 3 wind turbines than for 2 (table 3.5), since no scaling laws were applied. The internal rate of return (IRR) is the same for both wind parks, at a considerable 10.2%, highest of all studied options. The IRR is twice as high as the conventional discount rates on electricity plant projects, which are about 5% (IEA, 2010a). Large wind turbines could be an attractive long-term investment, as the annual interest on money that is paid back to the investor could be up to 10.2%.

out to be more cost-efficient (Meyers & Meneveau, 2011). Land availability may also result in a different spacing.

Table 3.5 *Investment costs and internal rate of return of a wind park on Vlieland that consists of large (2MW) wind turbines*

Total initial investment (3 x 3MW wind park)	8.4E+06 $Euro_{2014}$
Total initial investment (2 x 3MW wind park)	5.6E+06 $Euro_{2014}$
Internal Rate of Return (incl. subsidies)	10.2%

Small wind turbines
The potential electricity production of a single 100 kW WES100 wind turbine on Vlieland is 0.356 GWh per year, or 3.69 TJ_P per year in primary energy (table 3.6). With a rotor diameter of 17.9 metre and a turbine spacing of 11 diameters (see small turbine part of section 2.8), 43 turbines would fit on the 8.3 km stretch of land along the North-Western shore between the military base and the borders of the village of Oost-Vlieland. Together these turbines would produce 15.4 GWh of electricity per year, or its primary equivalent of 159 TJ_P per year (table 3.6).

Table 3.6 *Energetic potential of 100 kW turbines on Vlieland*

	rated capacity (MW)	actual power* (MW)	predicted electricity gen. (GWh/year)	primary equivalent** (TJp / year)
WES WES100	0.100	0.0408	0.357	3.69
43 x 100kW wind park	4.30	1.75	15.4	159

gen. = generation; *actual expected average power based on Vlieland wind data and turbine characteristics (hub height and power curve); **the primary energy equivalent of the predicted electricity generation (calculation: formula 2; values: appendix III)

The net specific costs of producing electricity using small wind turbines are 0.050 euro per kWh, or 4800 euro per TJ_P (table 3.7). Again, these cost estimates are independent of the amount of turbines installed.

Table 3.7 *Specific costs of producing electricity and its primary energy equivalent using small (100 kW) wind turbines*

	cost of electricity (euro / kWh)	cost of primary energy equivalent (euro / TJp)
Levelised costs of energy (LCOE)	0.069	$6.7 \cdot 10^3$
Levelised specifc subsidy	0.019	$1.9 \cdot 10^3$
Net specific costs	0.050	$4.8 \cdot 10^3$

The total initial investment of a 43 100kW turbine wind park is 1.12 million $euro_{2014}$. The internal rate of return of this investment is 6.7%, second highest of all investigated options.

This is still a fairly attractive investment opportunity as investors can expect up to 6.7% annual interest on their investment.

Photovoltaic panels on roofs and on a solar farm

The power curve analysis of the installation investment costs resulted in the following. For each doubling of capacity, the costs per W_p drop by nearly 17%. This yields a scale factor R = 0.729, which strongly resembles the typical value of R = 0.7 (Blok, 2007, p. 202). The correlation of the best-fit power curve for the installation investment costs is 99.3%.

All other intermediate and final calculation results are shown in table 3.8.

Table 3.8 *Techno-economic results for PV on Vlieland*

		PV on roofs		Solar farm	
Result	Unit	Average	HP	Average	HP
FLE	$kWh/kW_p/yr$	914	939	1076	1105
C_{roof} / C_{inst}	kW_p	2,030	2,200	310	330
E_{pot}	TJ_e/yr	6.9	7.4	1.2	1.3
$E_{P, av}$	TJ_p/yr	19	21	3.4	3.8
2^{R-1}	-	0.83	0.83	0.83	0.83
C_{avg}	W_p/dwelling	2,000	2,160	-	-
I_{sys}	$M€_{2013}$	3.02	2.98	0.333	0.316
I_{inst}	$M€_{2013}$	0.76	0.80	0.029	0.031
I_0	$M€_{2013}$	3.78	3.79	0.362	0.347
$O\&M_0$	$M€_{2013}/yr$	0.0567	0.0379	0.0054	0.0035
B_0	$M€_{2013}/yr$	0.43	0.48	0.041*; 0.018	0.045*; 0.020
IRR	%/yr	8.9	11.3	3.9	4.4
LCOE	$€_{2013}/kWh$	0.194	0.166	0.105	0.085
sub_{net}[52]	$€_{2013}/kWh$	0.016	0.015	0.044	0.028

[52] Given an SDE+ subsidy of €0.11/kWh for the average solar farm case and €0.09/kWh for the HP solar farm case. Taking a reference grey electricity cost of €0.054/kWh as in the SDE+ description (RVO, 2014a) and 1065 FLE for the average case, this means electricity benefits of the solar farm consists of 1000/1065 part €0.11/kWh, while the other 65/1065 has a price of €0.054/kWh during the first 15 years of economic lifetime. The same holds for the high performance case, but then with 1105 full load hours equivalent and €0.09/kWh. Discounting the lifetime electricity benefits with and without SDE+ subsidies results in 179 k€ and 126 k€ of net discounted SDE+ subsidies for the average and high performance cases respectively.

NSC	$€_{2013}$/kWh	0.178	0.151	0.061	0.058
NSC_P	$k€_{2013}/TJ_p$	17.2	14.6	5.92	5.60

*Benefits with a single asterisk are *including* SDE+ subsidies. Note: values were rounded to 2 - 3 sign. numbers.

Where:
FLE = full load hours equivalent
C_{roof} = potential cumulative roof capacity for PV on roofs
C_{inst} = installable solar farm capacity
E_{pot} = electricity production potential
$E_{P, av}$ = primary energy equivalent
2^{R-1} = installation price doubling factor with scale law R
C_{avg} = average potential residential system capacity
I_{sys} = system investment costs
I_{inst} = installation investment costs
I_0 = total investment costs
$O\&M_0$ = undiscounted O&M costs
B_0 = undiscounted electricity savings (PV on roofs) / benefits (solar farm)
IRR = internal rate of return, a measure for project profitability
LCOE = levelised cost of energy
sub_{net} = net levelised subsidy
NSC = net specific costs
NSC_P = net specific costs (expressed in primary energy terms)

Solar thermal heating

In table 3.9 results of the calculation of the potential of solar thermal energy on Vlieland can be found. The heat potential of solar thermal energy is limited to the total amount of heat that would no longer have to be produced using natural gas when solar thermal collectors are installed. Furthermore, the table shows the roof area required to cover the maximum 45% of heat demand for water heating that can be covered by solar thermal collectors. From these results it can be concluded that less than a fifth of the roofs should be covered with solar thermal installations to achieve this maximum, which shows that roof space is no limitation.

Table 3.9 *Results of heat potential of solar thermal energy and its primary energy equivalent*

Fraction of natural gas used for heating water	0.13
Heat potential of solar thermal energy (TJ/yr)	4.5
Primary energy equivalent of total production potential of solar thermal collectors (TJ_p/yr)	5.4
Roof area needed to cover total gas demand for water heating covered by solar thermal installations (m^2)	2572
Fraction roof area covered by solar thermal installations	0.19

In the case without a subsidy the results of the techno-economic analysis for both types of solar thermal collectors can be found in table 3.10 These results show that 85% of the total roof area covered with solar thermal collectors are covered by small-scale solar thermal installations and the remaining roof area by large-scale installations.

Table 3.10 *Results of techno-economic analysis of solar thermal energy – calculations on potential and costs (subsidy not taken into account)*

	Small-scale solar thermal installations	Large-scale solar thermal installations	Total
Number of buildings suitable for large-scale solar thermal collectors	-	3	-
Roof area needed for solar thermal collectors (m^2)	$2.2 \cdot 10^3$	$0.40 \cdot 10^3$	$2.6 \cdot 10^3$
Heat potential of solar thermal energy (TJ/yr)	3.8	0.70	4.5
Primary energy equivalent of total production potential of solar thermal collectors (TJ_p/yr)	4.6	0.8	5.4
Investment costs ($M€_{2013}$)	1.3	0.19	1.5
O&M costs ($€_{2013}$)	$10 \cdot 10^3$	$2.5 \cdot 10^3$	$12 \cdot 10^3$
Annual benefits ($M€_{2013}$/yr)	0.088	0.016	0.10

In the case of subsidy the investment cost of both large- and small-scale solar thermal installations are lower. O&M costs of small-scale installations depend on investment costs and are therefore lower as well. Results on the new investment costs & O&M costs can be found in table 3.11

Table 3.11 *Results of techno-economic analysis of solar thermal energy – cost calculations (subsidy taken into account)*

	Small-scale solar thermal installations	Large-scale solar thermal installations	Total
Investment costs ($M€_{2013}$)	1.0	0.19	1.2
O&M costs ($€_{2013}$)	$7.5 \cdot 10^3$	$2.5 \cdot 10^3$	$10 \cdot 10^3$

Table 3.12 shows the IRR, LCOE, net specific costs and levelised specific subsidy of solar thermal energy. The internal rate of return is 4.8%, which is the second lowest of all options. The net specific costs of solar thermal energy are 19.4 $\cdot 10^3$ €/TJ_p and thereby the highest of all options.

Table 3.12 *Results of techno-analysis of solar thermal energy – cost calculations*

Internal rate of return (%) (incl. subsidy)	4.8	
	cost of electricity (€/kWh)	cost of primary energy equivalent (€/TJp)
Levelised costs of energy	0.11	24.7 $\cdot 10^3$
Net specific costs	0.084	19.4 $\cdot 10^3$
Levelised specific subsidy	0.023	5.26 $\cdot 10^3$

3.5 Public & Stakeholder perception

The public perception results (table 3.13 and for more detail appendix XXI) indicate that energy independence and increasing the share of renewable energy are considered important by Vlieland's inhabitants. Furthermore, they show that solar energy is more broadly accepted than wind energy. There is a higher degree of positive scores for solar energy options compared to wind energy, while the degree of negative scores is smaller compared to wind for all statements. The solar farm is considered less visually bothersome than panels on roofs. Concerning wind energy, two large turbines are more broadly accepted than fifty small-scale turbines.

For the stakeholder perception, representatives of the municipality (2), province of Friesland, campsite Stortemelk, energy cooperation ECV (2), the harbour masters (2), the secondary school (2) and the military filled in our questionnaire. The results are shown in table 3.14. It can be concluded that energy independence and increasing the share of renewable energy are again considered important. For this purpose solar energy technologies are considered more desirable than wind energy technologies. Again, the opposition to small wind turbines is more pronounced than that to few large wind turbines. The solar farm is seen as less visually bothersome than PV or solar thermal collectors on roofs. In general, the stakeholder perception is less opposed to the technological options they were presented compared to the public perception.

Table 3.13 *An overview of the results for public perception on the analysed energy technologies and options. Absolute and relative answer scores per statement are presented. (Very) positive answers are in (bold) green, while (very) negative answers (in relation to the option) are (bold) red.*

Statement	---	--	-	0	+	++	+++	*Con*	*Neutr*	*Pro*
Wind energy would be a good solution towards Vlieland's energy independence	**3**	0	2	6	6	6	**9**	16%	19%	66%
Solar energy would be a good solution towards Vlieland's energy independence	**0**	1	1	5	6	10	**9**	6%	16%	78%
50 small wind turbines (hub height ~15 m) would be visually bothersome	**2**	5	3	3	8	2	**9**	31%	9%	59%
Two large wind turbines (hub height ~75 m) would be visually bothersome	**6**	4	2	3	10	2	**5**	38%	9%	53%
Solar thermal / PV collectors on roofs would be visually bothersome	**3**	7	3	3	6	4	**6**	41%	9%	50%
A solar farm on the military terrain would be visually bothersome	**15**	8	0	3	0	2	**4**	72%	9%	19%
The advantages of wind energy outweigh the disadvantages	**3**	1	2	7	7	7	**5**	19%	22%	59%
The advantages of solar energy outweigh the disadvantages	**0**	2	1	7	4	10	**8**	9%	22%	69%

Table 3.14. *An overview of the results for stakeholder perception on the analysed energy technologies and options. Absolute and relative answer scores per statement are presented. (Very) positive answers are in (bold) green, while (very) negative answers (in relation to the option) are (bold) red.*

Statement	---	--	-	0	+	++	+++	*Con*	*Neutr.*	*Pro*
Wind energy would be a good solution towards Vlieland's energy independence	**2**	0	0	1	3	3	**2**	18%	9%	73%
Solar energy would be a good solution towards Vlieland's energy independence	**0**	0	0	0	5	3	**3**	0%	0%	100%
Numerous small wind turbines (hub height ~15 m) would be visually bothersome	**2**	1	1	1	1	1	**4**	36%	9%	55%
A few large wind turbines (hub height ~75 m) would be visually bothersome	**4**	3	1	1	0	1	**1**	73%	9%	18%
Solar thermal / PV collectors are visually unattractive	**0**	0	1	4	1	4	**1**	9%	36%	55%
A solar field would be visually unattractive	**0**	0	3	1	0	6	**1**	27%	9%	64%
The advantages of wind energy outweigh the disadvantages	**1**	2	0	3	2	2	**1**	27%	27%	45%
The advantages of solar energy outweigh the disadvantages	**0**	1	0	3	2	3	**2**	9%	27%	64%

3.6 Multi-criteria analysis (MCA)

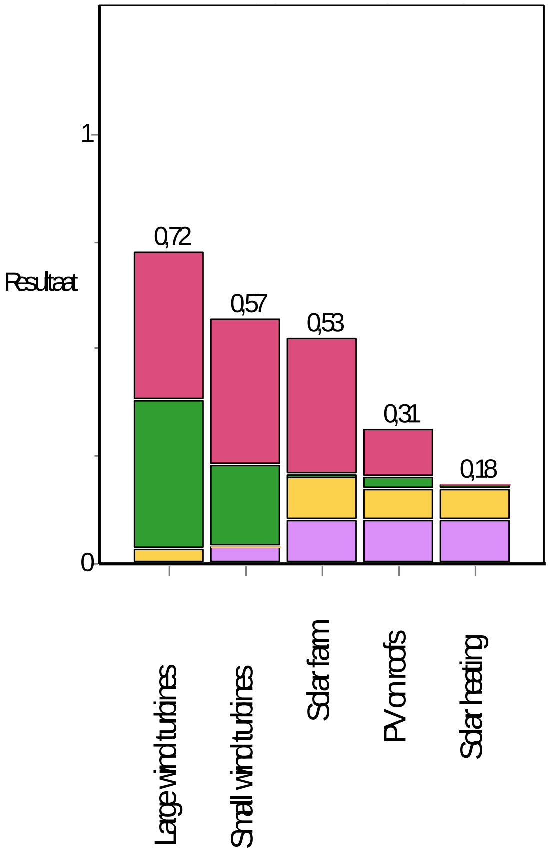
Six MCA runs were performed to determine a ranking of the different renewable energy technology options considered. The results are shown for the different weightings of the techno-economic perspective, *Lab Vlieland* and the municipality. The input data can be found in Appendix XXII.

The scores for both energy trends are nearly identical, no change in ranking can be observed in any MCA run. This can be explained by the fact that only the potential is changed in the high efficiency energy demand trend, in practice this means the total score of all options will increase slightly. Only the score of large wind turbines will not change, as the potential has the maximum score of 100 in both trends. In the explanation below, the MCA run of high-efficiency energy demand trend is not discussed due to the similar results.

In general a high weight for costs or potential is an advantage for the wind energy options and a high weight for public and stakeholder perception is beneficial for the solar energy options.

Techno-economic weighting

In the techno-economic weighting there is a strong emphasis on costs and potential (appendix XXII). These are the two criteria that were most thoroughly investigated in this study. Table 3.4 shows the results of the MCA with techno-economic weighting.



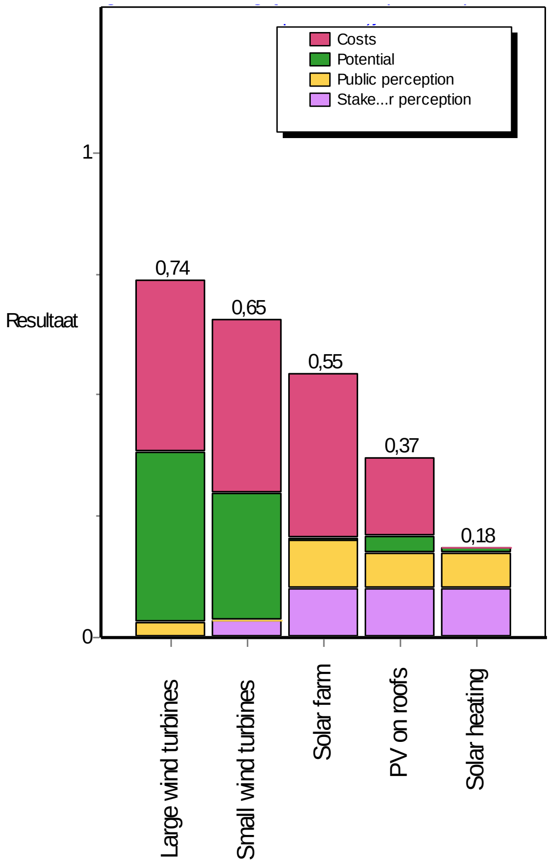


Figure 3.4 *MCA results using techno-economic weighting, business as usual energy demand in 2020 left and efficient energy demand in 2020 right.*

Costs and potential have a larger weight in this weighting, and thus have more influence on the score compared to the other two weightings. This leads to a first position for large wind turbines. Small wind turbines and solar farm have only a small difference in scores (however, in the high efficiency trend the difference increases). While the solar farm profits from public and stakeholder perception, small wind turbines have potential to their advantage. PV on roofs and solar heating lag behind due to their low score on costs and potential.

Weighting by Lab Vlieland

According to *Lab Vlieland* stakeholder perception was the most important criterion (see appendix XXII). Figure 3.5 shows the results that are generated with *BOSDA* for the both energy demand trends.

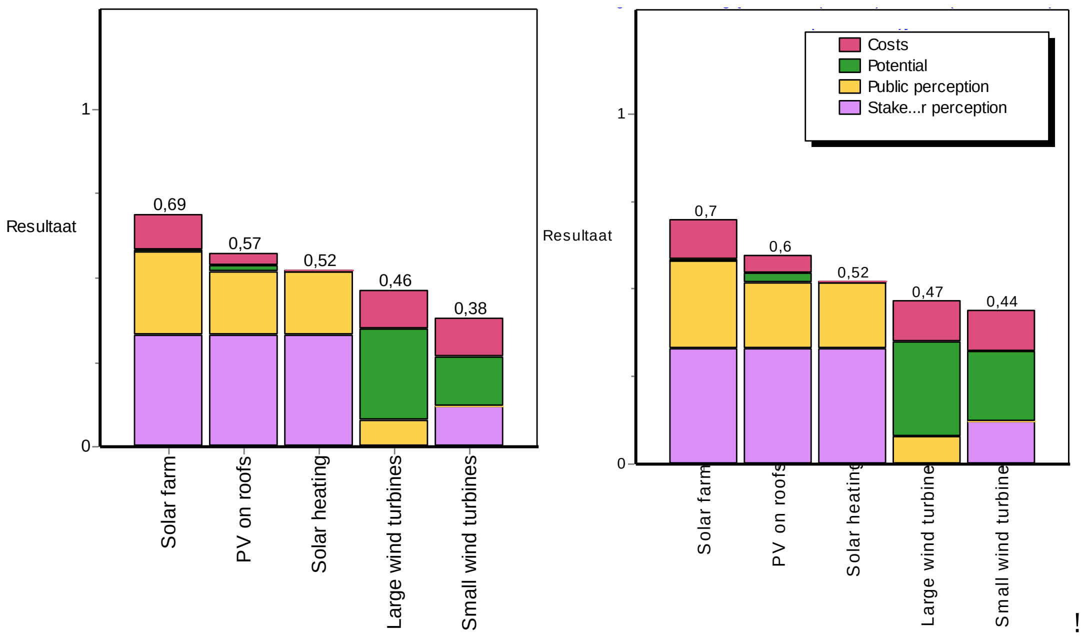


Figure 3.5. *MCA results using Lab Vlieland's weighting, left assuming business as usual energy demand in 2020 and right energy efficient demand in 2020.*

Using the Lab Vlieland's weighting the solar farm is the most desirable option compared to the other options. The solar farm thanks its position to the higher score on public perception and net specific costs. PV on roofs is the second best option, followed by solar heating, large wind turbines and small wind turbines. In the distribution of the results one can see public perception and stakeholder perception are the two most influencing criteria. These criteria determine the difference between the scores of the solar energy and wind energy options. Wind energy options score best on the criteria of potential and costs, but this cannot make up for their lower score on public and stakeholder perception as compared to the solar energy technology options.

Weighting by the municipality of Vlieland

According to the municipality of Vlieland costs and potential are the most important criteria (appendix XXII).

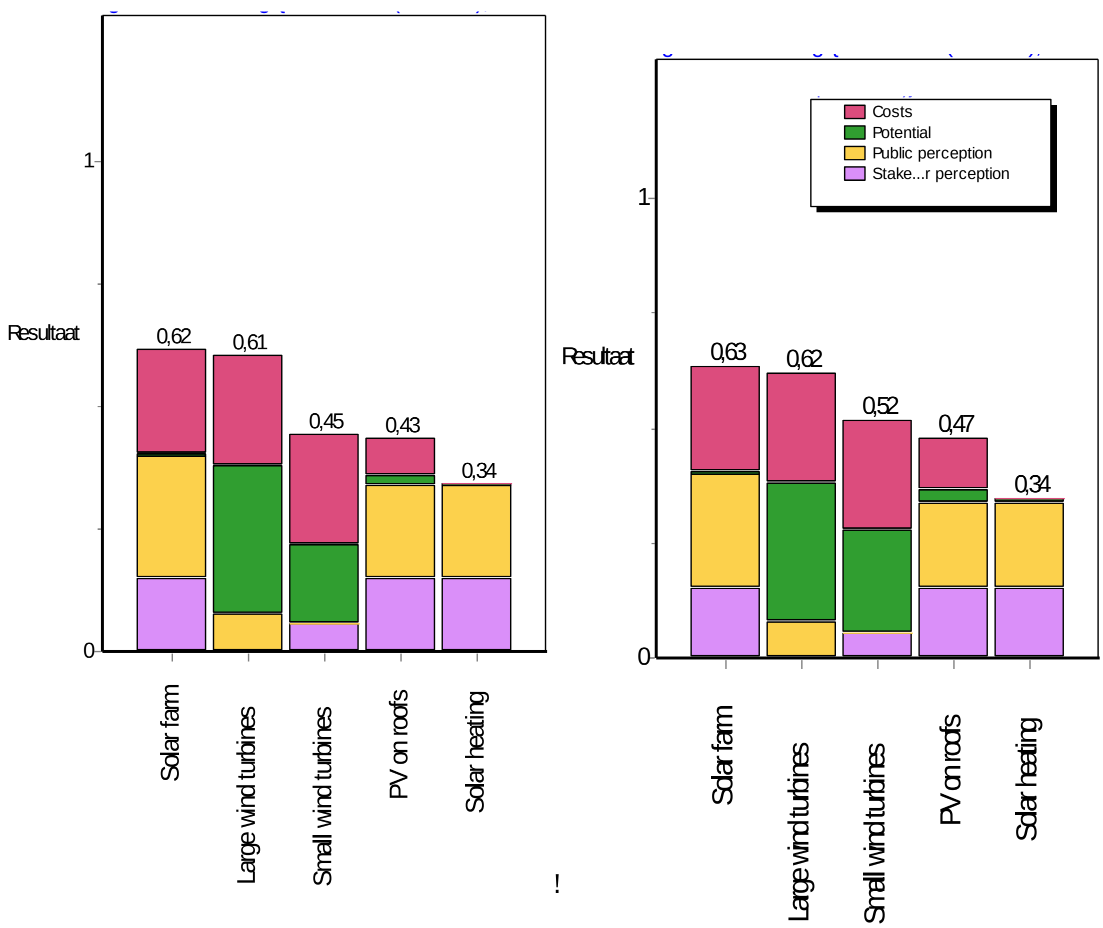


Figure 3.6. *MCA results using the municipality's weighting under a business as usual energy demand in 2020 (left) and under efficient energy demand in 2020 (right).*

Using the municipality's weighting yields a different ranking than two previous weightings (figure 3.6). The solar farm is the best option, closely followed by large wind turbines. Small wind turbines, PV on roofs and solar heating form the latter three options. The main reason for the shift in ranking as compared to Lab Vlieland's weighting is the higher weight for costs.

Sensitivity analysis

The sensitivity analysis outcomes of the weighting of *Lab Vlieland* have little variation in all positions. In almost all cases there is no switch in position, except in the efficient energy demand trend where small and large wind turbines can switch between the fourth and fifth position. For the first position the solar farm always remains the best option (see appendix XXII for exact results).

The municipality weighting gives more variation in positions. Solar farm is just ahead of large wind turbines for the first position. Small wind turbines dominate the third position. With given uncertainties, the solar farm option is still favourable in most cases, but the difference with large wind turbines is small. The third to fifth positions show only minor variations (see appendix XXII).

The business as usual energy demand trend for the techno-economic weighting gives clear-cut results for the first position: for large wind turbines dominate and for small wind turbines a minor share is given. However for the second position small wind turbines are dominant over the solar farm. The other solar options have no variations in position.

3.7 Energy vision Vlieland 2020

In this energy vision section, several combinations of the investigated renewable options were proposed to add up to Vlieland's energy demand in 2020. Combinations were based on MCA results under a techno-economic weighting and the weightings as indicated by the municipality of Vlieland and Lab Vlieland[53].

Based on the MCA with techno-economic weighting (see figure 3.4) large wind turbines are the best option[54] and because of their large potential no other renewables are required to meet demand in 2020. The resulting optimal solution for Vlieland is therefore in fact not a combination of renewables, but rather a single option. If energy demand develops according to the business-as-usual estimate, three turbines would be needed; if demand develops according to the high-energy-efficiency estimate, two suffice (figure 3.7).

Based on the municipality weighted MCA, a PV solar farm is the best option, followed by large wind turbines. Since a solar farm has very limited potential, large wind turbines are still required to achieve a combination of renewables that adds up to energy independence. However, the large wind turbines have sufficient potential by themselves and a solar farm cannot replace one turbine, effectively making the solar farm redundant. This is true for both the business-as-usual (three turbines) and high-energy-efficiency (two turbines) estimate of 2020 energy demand. Based on the municipality-weighted MCA, the large wind turbines are again the best solution if energy independence is to be achieved.

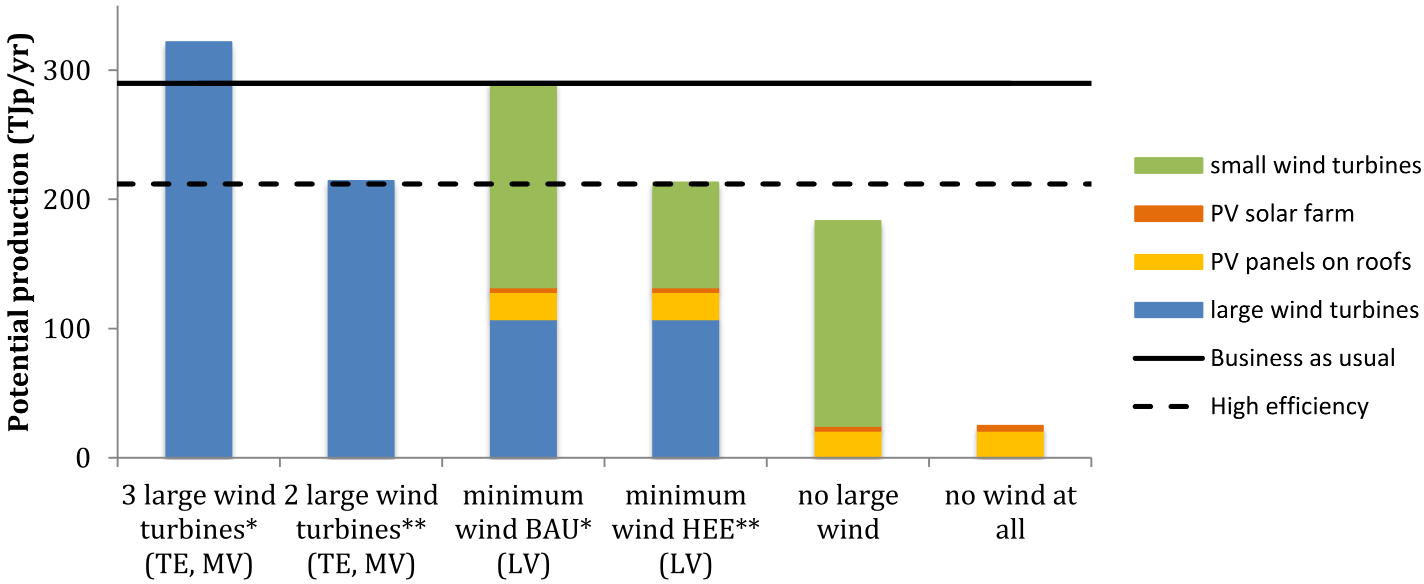
The Lab Vlieland weighted MCA yields a strong preference for solar options, due to public and stakeholder resistance to wind turbines. A PV solar farm is the best option, followed by PV on roofs and solar thermal collectors on roofs. Since PV and thermal panels are mutually exclusive (they require the same roofs), only the preferred PV on roofs would be used. However to meet demand solar options do not suffice, even when assuming a high-energy-efficiency 2020 demand estimate (figure 3.7). What is more, this demand is not met even when using a combination of solar options and the maximum amount of small wind turbines (figurre 3.7), which the Lab Vlieland-weighted MCA outcome prefers over large turbines. One large turbine is therefore always required to meet demand, in either energy demand trend. Our results thus indicate that if energy independence is to be achieved by 2020, one large turbine is a given. Based on the Lab Vlieland-weighted MCA the remaining demand would be filled in with the preferred options of a PV solar farm and PV panels on roofs and lastly small wind turbines (figure 3.7). Assuming business-as-usual energy demand, all 43 small wind turbines would be needed. In case of high energy efficiency, only 22 small turbines are required.

The wind energy options receive strongest public and stakeholder resistance on Vlieland (see sections 3.3 and 3.5). This may move policymakers, such as the municipality, to abandon the option of installing wind turbines. Moreover, the provincial government may overrule the municipality and prevent the implementation of large wind turbines on Vlieland (for the interview with a representative of the provincial government see appendix VI)

[53] A representative of the municipality and of Lab Vlieland both scored the weighting of the MCA criteria. Results presented here are based on these weightings, but may not directly reflect opinions of these institutions. However, the results do show what would be the optimal renewables mix for these institutions according to the criteria posed this study.

[54] Because of their large potential and low costs in general (see general techno-economic analysis results at the beginning of section 3.4) and relatively high public and stakeholder support compared to small wind turbines (see section 3.5).

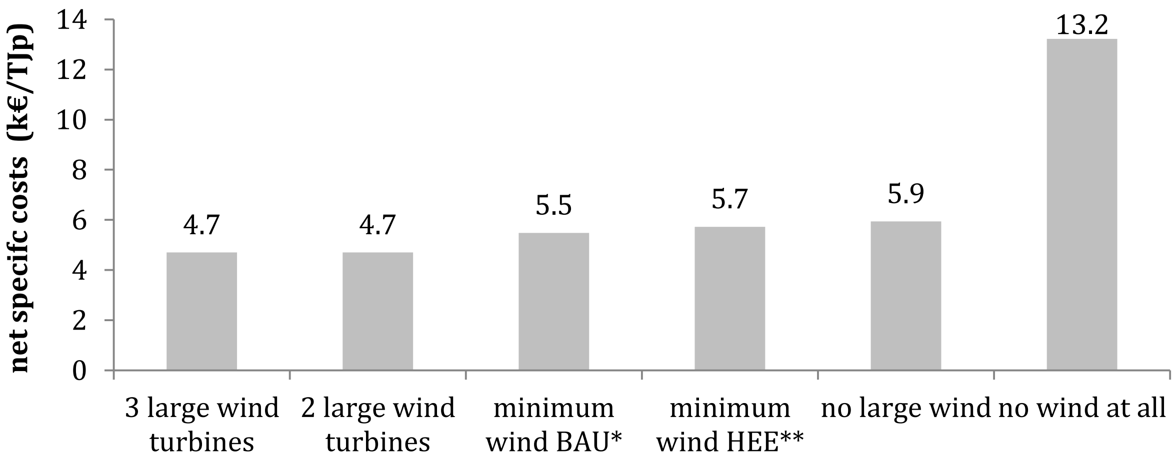
However our results suggest that if large wind turbines are not implemented, the energy independence ambition for 2020 cannot be realised. It was therefore calculated how close Vlieland would get to realising the energy independence without (large) wind turbines. Without these large wind turbines and *with* the maximum amount of *small* wind turbines, only 87% of the high-energy-efficiency demand in 2020 could be met. An energy production equivalent to eight additional solar farms would still be needed (figure 3.7). When assuming the business as usual estimate, 63% of the 2020 demand could be realised and 28 solar farm equivalents would still be needed (figure 3.7). If neither large nor small wind turbines could be implemented, only 12% and 9% could be realised, meaning that 50 or 70 solar farm equivalents would be needed respectively.



*Assuming a business-as-usual (BAU) estimate of energy demand in 2020; ** assuming a high energy efficiency (HEE) estimate of energy demand in 2020; TE: based on techno-economically weighted MCA; MV: municipality of Vlieland-weighted MCA; LV: Lab Vlieland-weighted MCA.

Figure 3.7 *Proposed (combinations of) renewable energy options to meet Vlieland's energy demand in 2020.*

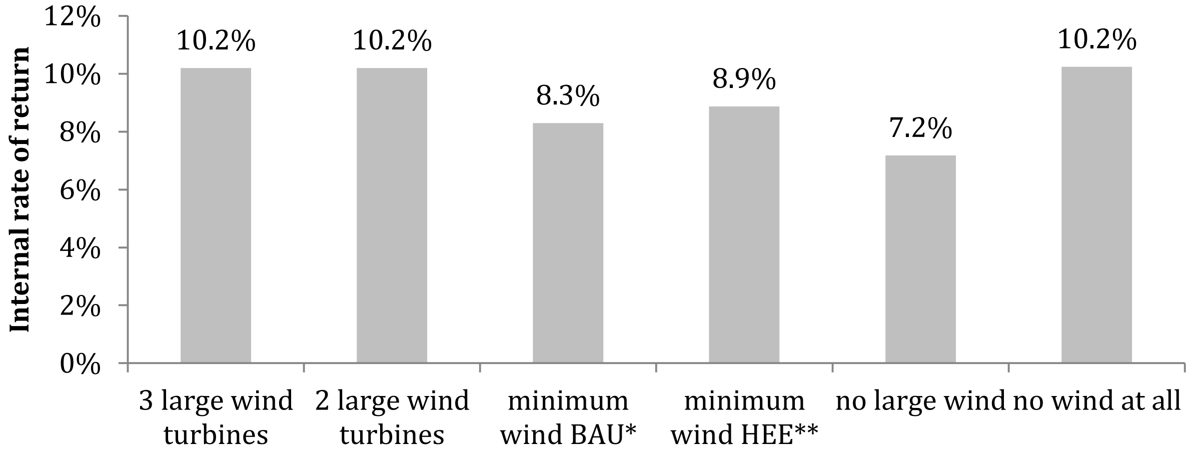
In terms of net specific costs all combinations are similar (varying between 4700 and 5900 euro / TJ_P), except for the combination where no wind is used (figure 3.8) The low net specific costs of the wind options keep the overall net specific costs of the combinations low. The net specific costs, are in essence the subsidy corrected production costs of energy. So production costs do not differ substantially among the first five combinations.



*Assuming a business-as-usual (BAU) estimate of energy demand in 2020; ** assuming a high energy efficiency (HEE) estimate of energy demand in 2020;

Figure 3.8 *Net specific costs of combinations of renewables (as presented in figure 3.7)based on the weighted average of the individual technologies' net specific costs.*

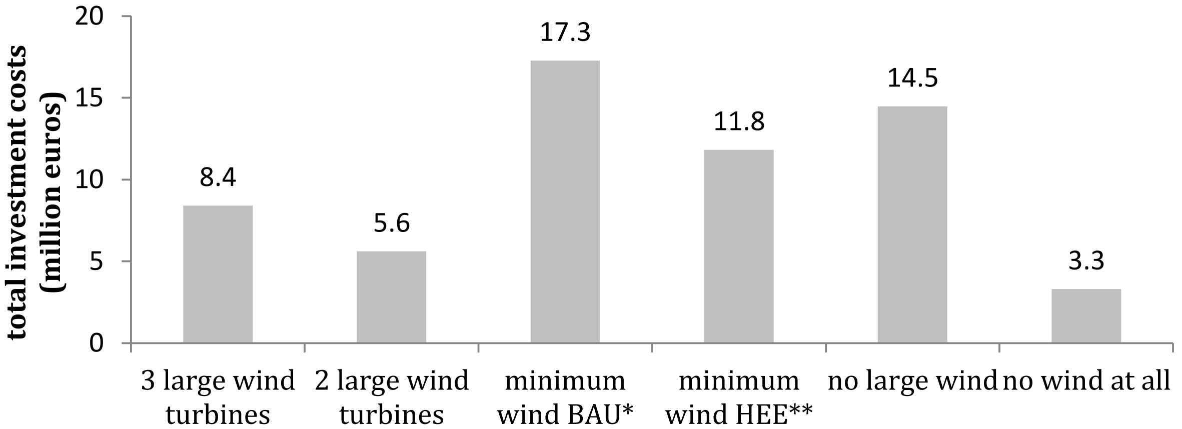
The weighted average internal rate of return (IRR) is highest for combinations with only large turbines or without any wind turbines (figure 3.9). The latter effect is explained by the relatively large share of PV panels on roofs. And as explained before, the high IRR of PV panels on roofs is due to the high price of electricity that is sold by households to the grid.



*Assuming a business-as-usual (BAU) estimate of energy demand in 2020; ** assuming a high energy efficiency (HEE) estimate of energy demand in 2020;

Figure 3.9 *Internal rate of return of combinations of renewables (as presented in figure 3.7) based on the weighted average of the individual technologies' internal rates of return.*

The total investment costs are highest for combinations with small wind turbines (figure 3.10). Small wind turbines have relatively high investment costs (figure 3.10), but lower O&M costs (see appendix XV). The no wind at all option has relatively high investment costs, while not meeting the 2020 energy demand. The options with large wind turbines have relatively low investment costs, while still meeting demand.



*Assuming a business-as-usual (BAU) estimate of energy demand in 2020; ** assuming a high energy efficiency (HEE) estimate of energy demand in 2020;

Figure 3.10 *Total investment costs of combinations of renewables (as presented in figure 3.7) based on the weighted average of the investment costs of the individual technologies.*

Large wind turbines are the most attractive options to invest in. They have both relatively low investment costs and a high internal rate of return. Moreover the underlying production costs (in the form of the net specific costs) are also low, meaning that the IRR is predominantly based on the economics of the turbines themselves, rather than external factors like the energy price. All in all, options with solely large turbines are the most economically sound options and they add up to energy independence too.

Options with small wind turbines have reasonably high IRRs, but their investment costs are also higher. So more capital needs to be acquired and less profit on this capital can be made as compared to large turbines. This will make it harder to financially realise options with many small wind turbines.

Installing PV panels on roofs and a solar farm together forms a good investment opportunity because of their high combined IRR, but do not add up to energy independence and have relatively high investment costs for the amount of electricity produced. They have the additional downside of high net specific costs: the high IRR is solely based on the high price for electricity that households receive when selling to the grid; a price that could change due to policy changes. However the fact that PV panels have a high IRR, lowest absolute investment costs and low public resistance could still make them a good first step towards energy independence for a smaller party like Vlieland's energy cooperation.

4. Discussion

The quality of the data used and assumptions made in the definitions and calculations of this study are discussed first. Next, a comparison with previous studies is made and the feasibility of the 2020 ambition and its barriers are examined. Lastly, recommendations for further research are given.

4.1 Data quality and assumptions

The definition of energy independence (see footnote 9) is one of the most important foundations of our research approach. It was based on previous studies on energy independence of Wadden Sea Islands (Suurmeijer et al., 2010; Van de Weerdhof, 2011). According to this definition, energy independence is achieved if the amount of energy produced on Vlieland has a primary energy equivalent that is equal to or larger than the total primary energy requirement of Vlieland's energy demand. For two main reasons it is arguable whether this could be considered true energy independence. Firstly, energy carriers other than electricity (produced with wind or PV) are required on Vlieland[55]. Secondly, even if electricity could cover all energy functions, the intermittent character of the proposed renewables would require even more renewables and energy storage. When these two arguments are considered criteria of energy independence, the expected result would be an energy *autarkic* Vlieland, i.e. an island that could be cut off entirely from the main land. On a short timescale energy autarky would be highly inefficient if not impossible, as for instance all automotive fuels would have to be produced on the island. On a longer timescale, when all heat demand could possibly be met by low-carbon options such as heat pumps or geothermal energy (DECC, 2012) and all transport could be electrified, autarky is not a sensible goal either. It would require large electricity storage capacity which would be inefficient to operate for Vlieland on its own. The definition of energy independence as used in this study on the other hand avoids these issues and leads to more practical and realistic plans that result in energy being produced in the most efficient way and traded with the mainland. Nevertheless, for future research it would be insightful to focus more on the end-use functions of energy and investigate specifically how heating and transport could be powered with local energy, for instance via electric transport and heat pumps.

Considering our research boundaries, it may be debated whether it is fair to fully include the primary energy use of ferry operator *Doeksen*. Technically spoken, *Doeksen* operates outside the set geographical boundaries of this research. Therefore, the choice of partial or full exclusion of this operator could be equally valid as well. This would have a dramatic effect on energy use, as the ferry operator uses 30% of the total (see section 3.1).This would yield that one large turbine less is required for all technology combinations in the energy vision section. As a consequence, the proposed definition for energy independence given the high energy efficiency trend would then be achievable without large wind turbines.

The primary energy equivalent of energy produced on Vlieland was based on the primary energy requirement of energy carriers that it replaces (see section 2.3). This was analogous to a previous report on Vlieland's energy independence (Van de Weerdhof, 2011). Moreover, this calculation of primary energy equivalents makes sense, as 1) Vlieland's energy production actually would replace energy carriers produced on the mainland, and 2)

[55] Heating for instance requires natural gas and Vlieland's vehicles do not run on electricity (yet).

its production is so small compared to the Netherlands as a whole[56] that the average primary energy requirement of energy carriers in the Netherlands is practically unaltered by Vlieland's production. Because of this calculation, electricity has a relatively large primary energy equivalent compared to other energy carriers (see appendix III). This leads to the counterintuitive result that producing predominantly electricity allows equalling the primary energy requirement of demand and hence reaching energy independence, while not producing more actual joules on the island than are used. It must be noted here that primary energy use is in fact still avoided and Vlieland would be energy independent according to the definitions used here.

The two energy use trends were based on different assumptions and literature (see section 2.5). Where the business as usual trend assumed continuation of historic trends and relatively little action on energy efficiency improvement, the high efficiency trend are more ambitious and would require a deviation from historic trends (see section 2.5). There are however financial incentives for energy efficiency on Vlieland (for an overview seeappendix XXIV). The true energy use in 2020 may very well be somewhere between the two estimates. The two energy trends should therefore be considered directions, rather than predictions. If higher energy efficiency is achieved, substantially less renewables would have to be implemented. The calculations based on the high energy efficiency trend allow for a quantitative estimate of how much less implementation is required compared to a business as usual trend. This difference is probably the practical maximum that energy efficiency can contribute to energy independence, at least up until 2020.

In this report, the focus lies on achieving energy independence by using renewable energy technologies. Little attention is given to the possibility of implementing individual energy efficiency measures and their effect on energy use and independence. Energy efficiency is solely considered as a whole in the high energy efficiency trend for Vlieland's 2020 energy demand. A more thorough analysis on energy efficiency measures that could be implemented on Vlieland in 2020 is needed to give a more accurate estimate of the potential decrease in energy demand. Energy savings options like more public transport, energy saving campaigns or prohibiting cars on the island were outside the scope of this study, as they are often social rather than technological options. Including these options as well could give a more complete overview of the potential energy savings and efficiency options for Vlieland to become energy independent.

For the public perception criterion, only 32 of the 1,105 inhabitants (CBS, 2014a) are represented in the questionnaire results. This is only a small fraction of the population. Therefore, uncertainties in the outcomes cannot be ruled out. Due to the limited spread of location and time for the sampling of questionnaires, it is possible that some groups of the population have been overrepresented, while others may have been underrepresented. This may have led to (slightly) skewed results.

In the stakeholder perception methodology, four out of seven responding stakeholders were represented by two people (see section 3.5). They were also counted twice in the results. Besides, *Staatsbosbeheer* and *WoonFriesland* did not see the opportunity to give a response and were therefore not included in the stakeholder opinion results. Because of this the stakeholder perception results should be considered a good indication, rather than a solid result.

[56] Vlieland's 271 TJ_P/year in 2013 compared to 3241 ***PJ_P***/year for the Netherlands as a whole in 2013 (CBS, 2014e)

More generally, the question formulation in some of the statements could have been interpreted ambiguously by the respondents. Questionnaires performed by experts on communication would lead to more solid results in a similar future research.

Also, this study focuses on perception of inhabitants and stakeholders. However, as Vlieland is largely dependent on tourism, it would also be insightful to dig into the opinion of tourists on the eventual implementation of renewable energy technologies on the island and whether this would affect their behaviour.

Techno-economic analysis

All data used except for the available roof area was obtained from literature. This means that it is all secondary data and was not measured in our own research. Despite that the data was selected with care and where possible always compared with other literature, some uncertainty remains, especially when extrapolating results to Vlieland.

In this study, no learning factor was taken into account while for wind and especially solar energy the learning rate is volatile and can be very high (Candelise et al., 2013). This could result in lower costs of the technologies in the near future. On the other hand, as the implementation of the technologies is expected to take place in the next years, disregarding the learning factor of technologies probably resulted in a minor divergence from actual costs. Wiesenthal et al. (2012) give an elaboration on the use of technological learning in energy studies.

The subsidy schemes used from the national government and province are sensitive to the political situation and can be subject to change by different governments or policy. The *SDE+* subsidy scheme has a duration of fifteen years and policy changes within this timeframe are possible. It can be hard to predict a policy change, but a cutback in subsidies would lead to a rise in net levelised costs. The *EIA* scheme is based on a single return of investment and should be requested within three months after the investment (RVO, 2014c). This scheme is less likely to affect our results, as the investments will be executed already at the start of implementation.

Wind

Two assumptions were made for wind turbines in general. Firstly, hourly average wind data were used in this study. However these do not account for any variability in the wind within the hourly time frame. With higher variability the average power in the wind increases as it scales with third power of the wind speed (Twidell & Weir, 2006). Thus, relative highs in wind speed lead to disproportionally more energy production compared to equally deviated lows. The potential of wind energy may therefore be higher than estimated here. Secondly, wind potential was estimated assuming that a stretch of land near the military base at Vliehors on the edge of Oost-Vlieland could be used. Wind turbines do not have a huge impact on the land use (as they require relatively little surface area, especially in the case of large turbines), but land availability could form a constraint. We interviewed a representative of *Staatsbosbeheer*, which owns most of the suggested land for wind turbines, and found out that *Staatsbosbeheer* is not against wind power on Vlieland, but has its reservations (for interview summary see appendix VI). If wind energy were to be implemented, one of the first steps would be to further investigate local land availability.

Some main assumptions were made for large wind turbine calculations specifically. Firstly, formula 7 is less accurate at higher altitudes (>50 m hub height; Twidell & Weir, 2006), but still gave the best estimate, as no wind data at higher altitudes was available. By itself this assumption leads to an overestimation of potential (Twidell & Weir, 2006). Secondly, 2 MW turbines are a standard size used in literature (EWEA, 2009) and several large manufacturers produce them (see table 2.2). However, more detailed knowledge of the exact wind regime over Vlieland may lead to the conclusion that other sizes are more cost-optimal. If wind turbines are to be implemented, performing a detailed wind survey is a next key step. Thirdly, the investment costs were estimated using various literature sources, as extensively discussed in appendix XIV. Vlieland being an island is not a standard location. The resulting additional transport and infrastructural costs are thus difficult to estimate. We conservatively rounded investment costs to a higher value to account for these additional costs (see appendix XIV). Lastly, it was assumed that no more turbines would be built than required to meet the entire 2020 primary energy demand. However, more turbines could be built and more power could be sold. Considering large turbines' internal rate of return of 10.2% (see table 3.5), this may prove to be an attractive option for investors. This could include Vlieland's Energy Cooperation (ECV).

The main assumption for the small turbines calculations was that the power curve, investment costs and O&M costs were based on a single turbine model, the WES100. Other models were investigated as well, but this model was selected because it has a relatively high power output at a low hub height (see table 2.3), which has the benefit of a limited visual impact. In fact this ratio was much higher compared to any other model encountered, so we think a model like the WES100 would be most suited. Still other models could be investigated if other requirements prove to be more important (for instance if the province of Friesland does not agree with the hub height of 18 metres).

PV

In this report the assumption was made that the electricity price of €0.23/kWh would be constant over the lifetime of PV on roofs. However, WIP-RE (2012) concluded in their review study based on four scenarios that EU-27 electricity consumer prices will continuously increase towards 2020-2030 at least (IEA, 2010c; EC, 2011; EPIA, 2011; Greenpeace/EPIA, 2011). This would benefit the long-term PV profitability, as electricity from the grid is saved on when PV on roofs is installed.

A perfect supply-demand structure is assumed in the calculations. In reality this is not the case, as Dutch household electricity peak demands generally occur in the morning and early evening during winter (ZonneEnergie, 2012). On the supply side, PV delivers electricity during the day and particularly in summer. However, a Dutch offset implying that each produced kWh of solar electricity is subtracted from the annual electricity bill is currently active (Greenem, 2012). This is perfectly in line with the small user benefit calculations included in this report. However, the Dutch Ministry of Economic Affairs (2013) is considering cutting back this subsidy scheme after 2017. An eventual future cutback on this scheme would not affect the levelised costs of energy, as these only depend on project costs and not on benefits. If the price of redelivery would drop to €0.07/kWh, which is currently the case for consumers of electricity suppliers EON and Nuon when they produce more PV electricity than they use on an annual basis (EON Benelux, 2014; Nuon, 2014), the profitability of PV on roofs would severely deteriorate unless the demand would fit the supply in a nearly perfect way.

Branker et al. (2011) note in a review on the levelised cost of PV electricity that a 20-year lifetime corresponds to the general lower limit of the manufacturer's guarantee period (Wohlgemuth, 2003; Brearley, 2009). Branker et al. (2011) found researches reporting lifetimes "well beyond" 25 years, even for old-technology panels. In other words, the lifetime chosen in this report is conservative.

Optimal panels are both higher in efficiency and lower in specific investment costs than the panels used for our calculations, and should therefore yield even more cost-effective results than presented here (Van Sark et al., 2013a). The reason to choose averages of below-average priced modules was to ensure that 1) the calculations are not dependent on a select range of panels in a volatile market (Van Sark et al., 2013a), and 2) no separate priority to either module efficiency or specific investment costs had to be made. The same reasoning holds for the upper-average efficiency panels.

PV systems are generally installed in a fixed fashion in The Netherlands (Wattisduurzaam, 2012). Therefore, solar trackers were not used in this techno-economic analysis.

A single average value for the installed capacity of PV and solar heating per roof was used. In reality, it is unavoidable that individual residences will install different capacities on their roofs depending on personal budgets, willingness and available residential roof space. It is acknowledged that using an average dwelling-methodology may have led to some inconsistencies.

Solar thermal

The assumption was made that solar collectors exactly cover the heat demand for warm tap water. The possibility of a surplus of heat demand was excluded from this research as it was assumed to be unpractical due to the absence of an integrated heat grid that is expensive to build (Milieuadviesdienst, 2012). Hence the possibility of the construction of a heat grid was not further investigated. The use of solar thermal was confined to roofs, while in theory solar thermal collectors could be placed on a solar farm as well. Without the earlier mentioned integrated heat grid this is not feasible. This assumption limits the potential of solar thermal energy to 2% of the total primary energy use[57], while more would be theoretically possible. Due to the relatively high weight[58] of potential, the resulting scores of the MCA of this technology were on the low side, but practically more solid.

Data on techno-economic parameters were hard to find. Often data for a specific type of collector were not complete[59]. Data on the thermal output of a collector and cost data of large-scale installations was obtained from a report by ECN on techno-economic parameters (Lensink, 2012). However, this report does not explicitly state how these parameters were determined. Apart from the different investment costs between small- and large-scale installations, no other scale effects on investment costs were assumed, which may in reality be the case.

In the research both small- and large-scale solar thermal installations were assumed to cover the heat demand for warm water. On large roofs large-scale installations were used. However, due to subsidies the small-scale installations become economically more attractive[60] and it may be more cost-effective to install small-scale solar thermal installations only.

Multi-criteria analysis

The main point of discussion of the MCA is the choice of weightings of the different perspectives. Especially the techno-economic weighting was chosen in line with the focus points of this research (net specific costs and potential). As the criteria of public and

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[57] Assuming a potential of 5.4 TJ_p/yr whereas the total primary energy use is 290 TJ_p/yr (business-as-usual energy demand trend).

[58] In all of the three different MCA-analyses more than one-fourth of the total weight was attributed to potential.

[59] E.g. investment costs of a specific collector was available, but thermal output was not.

[60] This attractiveness is compared to large-scale solar thermal installations. This is due to an additional subsidy scheme (Energie-investeringsaftrek).

stakeholder perception were evaluated with less detail than those on potential and costs. Weightings focusing on the latter two will thus give results with the highest reliability.

The sensitivity analysis makes use of uncertainty percentages for potential, public and stakeholder perception that are not compared with literature. The uncertainty percentages of these three criteria were estimated based on uncertainties of the results of calculations and analyses throughout this research. Furthermore, uncertainty could only be assigned to criteria, and not to an individual criterion of an alternative. For example uncertainty of costs could only be taken equal for large wind turbines and the solar farm, while in reality these calculations have their own individual uncertainties.

Energy vision

The techno-economically weighted MCA draws strongly from the core results of this study: the energetic potential and costs of the different renewable options on Vlieland. Despite the fact that the municipality and *Lab Vlieland* do not have wind energy as their most preferred option, it is still necessary to use wind turbines to complement the energy production in 2020. This invigorates our choice for a techno-economic viewpoint.

4.2 Comparison with previous studies

With the techno-economic analysis as core of this research it is clear that the focus lies on techno-economic feasibility rather than the implementation and social issues surrounding renewable energy technologies. Several reports on energy that are related to Vlieland have been published, including Suurmeijer et al. (2011) and Ambitiemanifest Waddeneilanden (2007), but these reports have a more policy-oriented approach. The Grontmij report (Van de Weerdhof, 2011) is most similar to our study, as it focuses on the technological and economic sides of energy independence. However, some crucial differences exist between this report and Van de Weerdhof (2011). The techno-economic analysis of this report is performed with a much more transparent methodology, in contrast to Van de Weerdhof (2011) where it was often not clear what assumptions were made. Furthermore the opinions of inhabitants and stakeholders are explored here. In this way, an indication of the societal support for different renewable options is provided. Moreover, this report bases its energy vision on a formal multi-criteria analysis.

As mentioned before, different literature sources providing secondary data cause slight differences in study outcomes. For instance, Van de Weerdhof (2011) presents an annual electricity use of 258 TJ_p on Vlieland against 271 TJ_p/year in our report.

On the Danish island of Samsø, wind turbines cover the entire electricity demand and compensate the energy used for transportation (Saastamoinen, 2009). Our study shows that a similar situation can be achieved on Vlieland. Also for Texel, the island next to Vlieland, large-scale developments in wind parks lie ahead in order to satisfy their equal ambition of energy independency in 2020 (Elswijk, 2010).

4.3 Meeting the 2020 deadline & main barriers

From this study it follows that Vlieland's energy ambition set for 2020 can be met by using a mix of options, as long as wind is included. In practice however this might be hard to realise with less than six years until 2020. Various barriers exist that need attention in order to pave the road for implementation. Stakeholder and public support is important, especially in a small community like Vlieland. This support may be improved by actively involving both stakeholders and the community. Furthermore, legislative support is another crucial factor, as without legislative support, plans cannot be realised. Another challenge is capital for initial investments; potential investors need to be attracted. Considering the progress towards the formulated ambitions for 2020 so far, it might be questioned whether a reformulation of the proposed ambitions would be suitable for Vlieland. For instance, the final time horizon could be expanded or a lower percentage of progress towards energy independency could be set for 2020. In this study, flexibility in the goal definition of energy independency is not accounted for.

4.4 Further research

In this section, a list of possible further research is provided. It is important to investigate local support for each technology option more extensively, as it was only treated as a minor part in this research. It can be researched how local stakeholders and inhabitants be involved in the implementation of wind energy technologies on Vlieland. For instance, one could investigate what role the energy cooperation (ECV) can play to increase local support. Also, a study goal could be to assess how the visual hindrance of for instance wind turbines can be minimised (e.g. by merging a technology into the landscape). As the opinion of tourists on energy technologies is not mapped for Vlieland, this provides another excellent research opportunity.

In our study, seasonal fluctuations of energy demand on the island are not treated. However, as the ratio of tourists per inhabitant fluctuate greatly over the year, this could be worthwhile to dig into. This is particularly relevant for optimising current and future supply and demand of energy.

Energy efficiency was covered only in general; this could be another subject of future research. A detailed investigation of current local efficiency measures and the potential of efficiency options is advised. This could result in a list of possible individual energy efficiency options, including their energy savings potential and costs. Moreover, a better insight in energy savings measures on Vlieland could push the energy demand trend down further and at the same time improve its reliability. It could be investigated what the current situation on Vlieland concerning energy efficiency is, and what the possibilities for implementation of individual efficiency measures are.

A concrete planning of the technological options is needed to make possible plans easier to realise. It could be investigated where and when renewable energy technology options can be implemented on Vlieland. As an example, an inquiry on land availability for both a solar farm (or farms) and wind turbines are key steps forward.

For wind a detailed local survey is advised to assess what turbine is most cost-effective on Vlieland. This could lead to even more accurate values for the local wind energy potential and costs. Besides, a thorough analysis of the legislative restrictions and limitations is advised. Placement of wind turbines on the island is not likely to be prohibited beforehand, but legislative difficulties may be expected (see Appendix VI), these could be further investigated.

Furthermore, the influence of Vlieland's remote geographical location on investments and costs for operation and maintenance should be analysed to make cost estimates more accurate. A detailed market inquiry or literature research on logistics and economics of energy technologies on Vlieland would therefore be useful.

In terms of economics, a study mapping potential investors in local energy technologies besides ECV (for instance banks or investment companies) could be performed too. Also, an assessment on beneficial investment policies can be fulfilled. For instance, the PV stimulation programme of TexelEnergie (2014b) can serve as a guideline for setting up a similar programme on Vlieland.

5. Conclusion

In this report it was researched how Vlieland can realise its ambition of becoming energy independent in 2020. The study was conducted to advise our commissioner *Lab Vlieland* on how energy independence could be achieved using renewables and was performed from a techno-economic perspective. This aim of energy independence is ambitious, as large changes will be required to go from negligible production anno 2014 to meeting the primary energy equivalent of demand in 2020.

We found two options to achieve energy independence by 2020: 1) by installing two or three large (2MW) wind turbines; or 2) by installing one large turbine combined with a solar photovoltaic farm, several smaller (100kW) wind turbines and photovoltaic panels on all suitable roofs. Either way, wind turbines are inevitable. Both options have the energetic potential to meet the 2020 demand, when assuming a business-as-usual energy use trend and when assuming increased energy efficiency. Out of the two options the first one forms the most attractive investment opportunity due to low specific costs and a high internal rate of return. So from a techno-economic perspective, installing solely large wind turbines is the best way to achieve energy independence using renewables. Our findings on the island however indicated that wind turbines (large or small) are the least preferred technology according to both inhabitants and Vlieland's major stakeholders.

In conclusion, there are two ways forward: 1) the resistance to wind turbines is overcome, one of the options is implemented and the ambition is met; or 2) the ambition is not met or altered. The first way requires further research into public support for wind turbines and how it could be increased, and into concrete implementation of the suggested renewables.

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Appendix I Lab Vlieland (Dutch)

Lab Vlieland is een laboratorium waar wordt gewerkt aan innovatie en duurzaamheid. Een fysieke én virtuele plek waar de creatieve industrie, grote en kleine bedrijven, kennisinstellingen, eiland- en wereldburgers en de overheid elkaar ontmoeten en samenwerken aan het ontwikkelen van toegepaste kennis op het gebied van energie, water, grond- en afvalstoffen en (duurzaam) toerisme. In Lab Vlieland komen ideeën en best practices samen en worden toekomstgerichte en duurzame oplossingen bedacht, getest en toegepast. Wij noemen Lab Vlieland een werkplaats voor vernieuwing en verbeelding.

Als dynamische omgeving ontwikkelt Lab Vlieland vernieuwende projecten, stimuleert ze technische innovatie en brengt (inter)nationale ‘knappe koppen’ en gezelschappen bij elkaar. Lab Vlieland is hiermee een open source-platform dat met Waddenfestival Into The Great Wide Open (ITGWO) beschikt over een ideale proeftuin: een plek om nieuwe, duurzame ontwikkelingen te demonstreren en tegelijk een katalysator om innovatie en onderzoek te versnellen.

Doel is het op gang brengen van een serieus transitieproces dat de Waddeneilanden helpt bij het verwezenlijken van hun ambitie om in 2020 zelfvoorzienend te zijn op het gebied van energie en water.

Appendix II Non-grid connected energy use

Any non-grid connected energy production was ignored in this study. The reason for this is twofold. Firstly, the off-grid production is very limited. The only non-grid connected production found in this study were heat production by solar collectors in 27 rental houses accounting for half their heat demand (Boorsma, 2010) and the annual burning of 500 m^3 of wood cleared by inhabitants from *Staatsbosheer's* forestlands on the island (interview *Staatsbosbeheer*, see appendix VI) This amount was considered negligible compared to grid-connected production, which includes all Vlieland's residential PV panels and the largest non-residential decentralised producers of electricity (including the municipality, the harbour and the *Stortemelk* campsite). Secondly, even if off-grid production was taken into account, it would not make a difference in terms of the total amount of extra primary energy that needs to be produced by 2020. This is because including off-grid production would in this study increase energy use and energy production by the same amount, meaning that their difference (i.e. the extra amount of energy that needs to be produced by 2020) would not be altered.

Appendix III Input data for the calculation of Vlieland's current energy use and production

Table III.1 and III.2 show the input data for the calculation of Vlieland's current energy use and Vlieland's current energy production. How these data on the energy consumption of different carriers, the energy content of these carriers and the ERE and conversion efficiency of these carriers were obtained or calculated is described below the tables.

Table III.1. *Energy consumption on Vlieland in 2013*

	consumption		*energy content*		*secondary energy (TJ/yr)*	*ERE*	*conversion efficiency*
electricity	8,735,832	kWh/yr	3.6	MJ/kWh	31.4	1.09	0.38
natural gas	2,687,132	m^3/yr	33.34	MJ/m^3	90	1.02	-
gasoline	$5.7 \cdot 10^4$	L/yr	33	MJ/L	1.9	1.13	-
diesel	$1.7 \cdot 10^5$	L/yr	36	MJ/L	6.2	1.12	-
ULSD (ferry)*	$2.0 \cdot 10^6$**	L/yr	36	MJ/L	72	1.12	-
total							

*Ultra-low-sulphur diesel used by ferry operator Doeksen; ** Ferry operator Doeksen provided an estimate of its fuel use, the uncertainty of this estimate is unknown. It was assumed that precision of the estimate is high enough to yield two significant figures;

Table III.2 *Energy production on Vlieland in 2013*

	production		*energy content*		*secondary energy (TJ/yr)*	*ERE*	*conversion efficiency*
electricity	$48 \cdot 10^3$	kWh/yr	3.6	MJ/kWh	0.17	1.09	0.38
total							

All data on consumption and production of energy carriers were collected for the year 2013. Vlieland's (grid-connected) electricity and gas use and production data were obtained from *Energie in beeld* (Energieinbeeld, 2014), this website is run by (among others) the distribution system operator *Liander* and provides detailed energy statistics per municipality. Locally generated electricity (for instance from photovoltaic panels) is sold back to grid, this means that all grid-connected generation shows up in the statistics. Data on automotive fuel use were provided by the harbour office, which runs the island's only gas station and sells both to vehicles and ships. Ferry operator *Rederij Doeksen* provided an estimate of their fuel use of 2 million litres of ultra-low sulphur diesel (ULSD) annually for ferry traffic to and from Vlieland. *Rederij Doeksen* indicated that the fuel use had not changed since they provided the same estimate to Van de Weerdhof in 2011.

The energy content of all energy carriers was based on the lower heating value. For natural gas the Dutch natural gas energy content of 33.34 MJ/m^3 was used (IEA, 2013). Gasoline and diesel energetic contents of 33 and 36 MJ/litre respectively were obtained from Blok (2007).

An energy requirement for energy (ERE) value is a factor greater than one that compensates for any energy losses or energy inputs required to obtain and transport an energy carrier (Blok, 2007). The ERE values of the energy carriers produced on Vlieland were based on the ERE of the carriers they replace (for the reasoning behind this see section 2.3). All ERE estimates were based on Blok (2007). Natural gas has a relatively short transportation distance in the Netherlands, so its ERE was estimated at the low end of the range, at 1.02. Gasoline and diesel on the other hand have long transportation distances (as they have to be imported as crude oil) and have relatively large energy losses during refining (conversion from crude oil was considered part of the ERE, following the approach used in Blok, 2007), so their ERE was estimated at the high end of Blok's (2007) range. Gasoline is lighter than diesel, this means relatively more energy is lost in refining. Gasoline was therefore given a slightly higher ERE of 1.13 as compared to diesel at 1.12. The ERE of electricity consisted of transmission losses and the ERE of the fuels used in the power plants. Transmission losses were estimated at 5%, at the lower end of the range indicated by Blok (2007), as the Netherlands has short transportation distances and well-designed infrastructure. Power plants in the Netherlands are predominantly gas (52.7%) and coal (23.6%) fired (CBS, 2014d; data for 2012), other larger sources are renewables and nuclear. Since gas, nuclear and most renewables have relatively low ERE, based on Blok an average ERE of 1.04 was assumed. The transmission losses and ERE of the fuels combined yield an ERE of 1.092, this was rounded to 1.09.

As mentioned above, the conversion from crude oil to gasoline and diesel was included in the ERE of these carriers. The conversion efficiency from fuels to electricity also had to be accounted for and was based on the Dutch average. The conversion efficiency was calculated by dividing total electricity output by total heat input (based on CBS, 2014c). This required some assumptions. Firstly, the heat input of combined heat and power (CHP; Dutch warmte-krachtkoppeling) is fully allocated to the electricity output and heat is considered a by-product. CHP plants form a tiny share of total electricity production in the Netherlands. Secondly, non-thermal renewables (wind, PV and hydro) and nuclear plants do not have a direct heat input. To account for this the non-thermal renewables were considered 100% thermally efficient and the nuclear plant 33% (IEA, 2013). The heat input, based on these percentages and the contributions of these sources to the total electricity production (CBS, 2014d), was then added to the total heat input as given by the Dutch Statistics Agency (CBS, 2014c). Overall efficiency was calculated as the total electric output (of all sources) divided by the overall heat input (total input + non-thermal and nuclear "heat input"), resulting in an average conversion efficiency for electricity of 0.38.

Appendix IV Energy carrier use on Vlieland over the past 20 years

Figure IV.1 shows the consumption of differnet energy carriers over the past 20 years. Missing data was never recorded, has been lost over time or is fully confidential. The conversion to primary energy was made as described by formula 2, using values from appendix III. The overall trend is that energy use stays roughly the same for fuels, but increases slowly for electricity and natural gas.

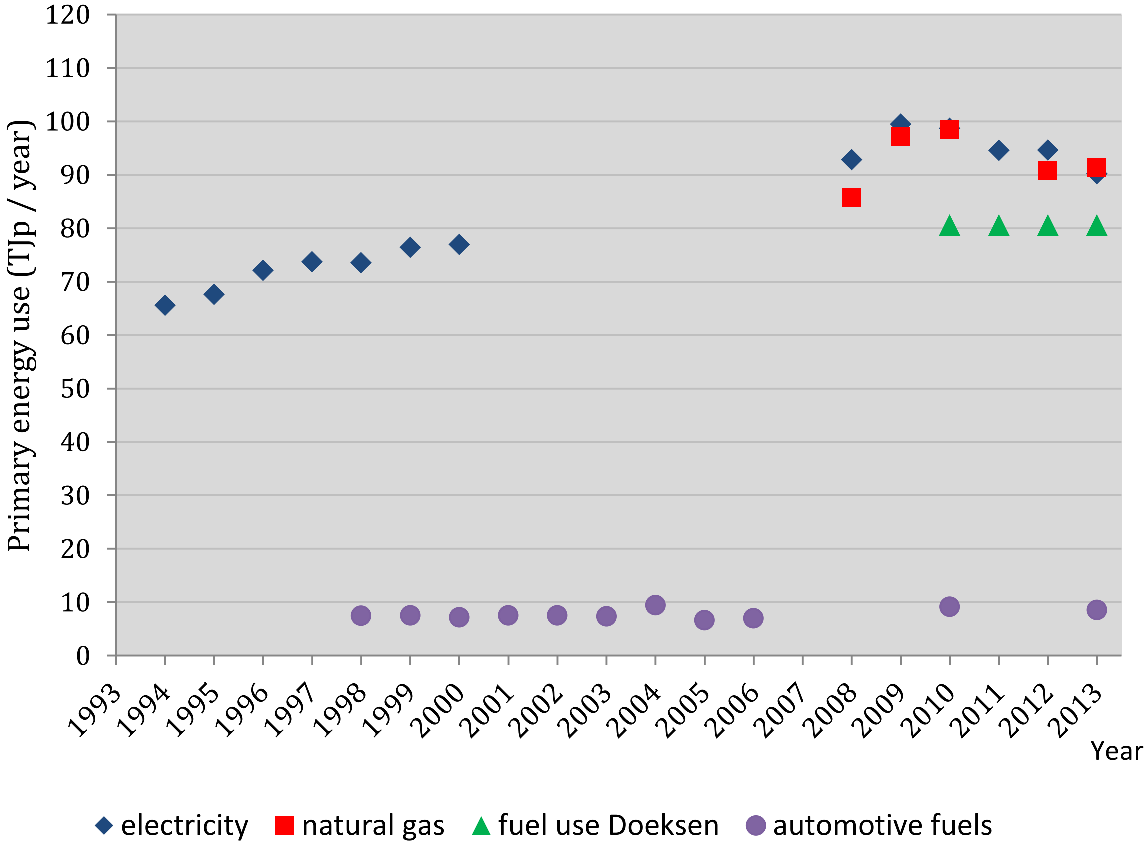

Figure .. *Primary energy equivalents of energy carriers used on Vlieland over the past 20 years.*

Sources: electricity use 1998-2006[61] from: Nuon (2001); electricity use 2008-2013 from: Energie In Beeld (2014); natural gas use 2008-2013 from: Energie In Beeld (2014); fuel use Rederij Doeksen 2010-2013 from: correspondence with Rederij Doeksen; automotive fuels 1998-2006, 2010, 2013: obtained from Vlieland harbour office.

[61] Before the connection to mainland electricity grid in 2008, electricity on Vlieland was generated with diesel generators.

Appendix V Interview questions (Dutch)

Standaard vragen

Introductie en uitleg waarom interview

Lengte interview 1 uur

Is opnemen toegestaan?

Welke positie beoefent u, en hoe lang zit u in deze positie?

In hoeverre bent / uw instantie bezig met duurzame energie (zon, wind en geothermie)?

In hoeverre vindt u Vlieland op het moment duurzaam en energie-onafhankelijk?

Hoe ziet u Vlieland in 2020 op het gebied van energie?

Hoe belangrijk vindt u energieonafhankelijkheid op een schaal van 1 tot 10 en waarom (waarbij 10 hoogste is)?

Zijn er in uw bedrijf/instantie doelen of ambities vastgesteld omtrent duurzame energieopwekking, dan wel energiebesparende maatregelen? Zo ja, welke?

Wat voor bijdrage aan de gestelde doelen levert uw bedrijf (momenteel / vaststaand gepland)? En in de toekomst?

Als zonne-energie de beste oplossing blijkt, hoe staat u daar dan tegenover?

Als geothermie de beste oplossing blijkt, hoe staat u daar dan tegenover?

Als windenergie de beste oplossing blijkt, hoe staat u daar dan tegenover?

Weet u hoeveel energie uw bedrijf jaarlijks verbruikt? En hoeveel daarvan is duurzaam geproduceerd?

Vind u het goed als we u benaderen voor een vervolggesprek?

Specifieke vragen voor individuele stakeholders

Gemeente en Energiecoöperatie Vlieland (ECV) (Joke Weeda en Bram commandeur respectievelijk)

Welke rol kan de gemeente en de energiecoöperatie spelen in de ambitie van 2020?

Wat verwacht u van het resultaat van de energiecoöperatie?

Hoe leeft de ambitie onder de inwoners van Vlieland?

Wat zegt u van een inspraakavond over ons project?

Zijn er rapporten beschikbaar over energie?

Zijn er rapporten beschikbaar voor energie uit biomassa?

Is er een kaart/bestemmingsplan beschikbaar met gas- en elektriciteitsleidingen?

Is het mogelijk om de inloggegevens van energieinbeeld.nl te verkrijgen?

Jan van der Veen (SRV Stortemelk)

Wat is het energieverbruik van camping Stortemelk?

Hoe wordt het afval verwerkt?

Hoe zit uw elektriciteitsnetwerk in elkaar?

Jachthaven

Zijn er energieverbruik gegevens van de jachthaven?

Hoeveel brandstof wordt er getankt per jaar?

Herman Brink (Staatsbosbeheer)

Heeft u een idee hoeveel biomassa beschikbaar is op Vlieland onder de hoede van Staatsbosbeheer?

Wat vind u van de implementatie van geothermie, zonne- en windenergie? Kan Staatsbosbeheer hier ruimte voor bieden?

Welke rol kan Staatsbosbeheer spelen in de ambitie voor 2020?

Zijn er duurzaamheidsplannen vanuit Staatsbosbeheer?

Appendix VI Interview summaries

Joke Weeda (municipality Vlieland) and Bram Commandeur (ECV)

- Joke Weeda is 'regieambtenaar' since 3 years
- Bram Commandeur is an intern at the municipality, helping to set up the ECV
- Goal of ECV is to delicer renewable energy to the community of Vlieland, any profit will be invested in renewable energy supply
- The current situation is not yet sufficient, the renewable energy supply is average compared to The Netherlands as a whole, there are only some small-scale initiatives in this area.
- The municipality has privatised the public housing (WoonFriesland) with the agreement to improve the energy label from D/E towards B.
- Only few houses use geothermal heat at the moment. Another idea is to use it for the housing of WoonFriesland.
- At the 'Dorpsstraat' and the 'Kerkplein' it is forbidden to place solar panels on roofs due to the 'welstandsafspraak'. This is a measure of the municipality that could be changed. But is 'difficult' due to administrative barriers.
- Vision of Joke Weeda on 2020: All houses of WoonFriesland have solar panels on their roofs, the 'welstandsafspraak' is not operative anymore. There is a solar field of 0.5 to 1 MW and some wind energy. Electric vehicles do local transport of luggage. City lights are sustainable and with sensors. The public school and sports centre will be (nearly) energy neutral. But it is questionable if this is enough.
- Wind is a good option to generate electricity, there are only minor political obstacles on Vlieland itself, but the provincial government is a major barrier just like the Waddenvereniging. The Natura 2000 prohibits the placement of wind turbines on large parts of the island. The best place according to Joke Weeda is the industry park, the local companies there are in favour of it.
- Urgenda is a foundation that helps Texel with sustainability and now helps Vlieland as well. Without their expertise and advice the municipality could not have done what has been done until now. The person of Urgenda who supports Vlieland is Antoine Maartens.
- There has been an investigation whether there is a possibility to use the biomass produced on Vlieland to produce energy. It was concluded that there is not enough generation of biomass to make this an economic option. Biomass should be imported from elsewhere, that is not considered as an option according to the interviewees.

Jan Lever and Simon Visser (harbour Vlieland)

- Harbour receives tourists that pass by boat and supply electricity and services
- The harbour takes care of the petrol station on Vlieland
- The harbour has 2 wind balls (Home Energy Systems V200), within two months both wind balls where defect due to strong winds, sand and salt on Vlieland.
- The two interviewees disagree on wind energy, one thinks that wind turbines will not be powerful enough to withstand the rough conditions on Vlieland, the other thinks it is going to be a necessity towards the future.

Jan van der Veen (Campsite Stortemelk)
Campsite Stortemelk is part of the foundation Stichting Recreatiebelangen Vlieland, and can support up to 3500 visitors.

- Van der Veen started to implement renewables in 2001 with solar heating, in 2009 solar panels were placed at toilet buildings. In 2013 the roofs of the barn and the restaurant were equipped with solar panels
- There is a wind ball (Home Energy Systems V100), capacity negligible
- The owner's residence uses geothermal heat
- If the staff buildings are ready for replacement new energy efficient buildings will be placed, but not earlier.
- If possible, further separation of waste is prefered
- Van der Veen is able and willing to support other local sustainable initiatives financially and with experience

Herman Brink (Staatsbosbeheer)
The largest part of Vlieland is owned by *Staatsbosbeheer*

- Brink thinks biomass flows are negligible for Vlieland to be used for energy supply and thinks that this will not change in the near future
- *Staatsbosbeheer* has a positive attitude towards wind energy on the island as long as they are not situated in the dunes and no complete wind parks are realised
- Brink thinks the major barrier is convincing the local community that renewable energy has to be implemented. Next to this the province is a large barrier as well

Pieter Bruinink (Ministry of defence)
A quarter of the island is owned and actively used by the ministry of defence. Only 11 employees are present.

- The military replaced all street lighting on the base with LED lighting and sensors. Electricity use is low, because most of the terrain has no electricity grid. Fuel use is large due to the use of large machines for travelling through rough terrain.
- Bruinink has a positive attitude towards solar energy on the island and actively supporting a photovoltaic panels farm, which is planned to be installed on the defence terrain.
- Bruinink has a neutral attitude towards wind energy on the island. Will not support wind energy on the defence terrain but is fine with wind turbines placed elsewhere on the island

Ben Matoren (Principal secondary school)

- Ben Matoren, as principal, considers himself in the middle of the community thanks to the intensive contact with students and their families.
- The secondary school is active in promoting sustainability. They try to connect the students with sustainability through the use of a 3D printer and plans for recycling plastic waste into the 3D printer
- The secondary school building will be demolished and a new building will be built. The goal is to build an energy neutral building.

Leo Hans Sterenberg (municipality of Vlieland)
Responsible for technical service on Vlieland.

- Sterrenberg thinks that wind is a good option to generate electricity, there are only minor political obstacles on Vlieland itself, but the provincial government is a major barrier.
- Sterrenberg does not think that wind is a considered a reasonable option for the local community. High wind turbines on the island will result in local protests. An acceptable option would be to install wind turbines in the North Sea, 10-20 km offshore.

Broer Visser (Director ECV)
Director of the Energie cooperatie Vlieland (Energy Cooperation Vlieland - ECV). ECV originated three years ago from the “duurzame energie team” (sustainable energy team), a team created 10 years ago to support local sustainable activities and to create employment on the island. Visser envisions the ECV in 2020 as the responsible entitiy for the electricity and gas grid on the island.

- Visser considers building wind turbines a reasonable option, but foresees great resistance from the local community and NGOs.
- Visser has personally installed most of the solar boilers and solar panels on Vlieland
- For the photovoltaic panels farm on the military area, Visser suggests a capacity of 0.3 MW and 30 hectares of PV panels to provide the island’s electricity.

Gerwin Venema (programme manager Sustainable Innovations at Province of Friesland)

- Province of Friesland is part of Energy Valley, a network organization that works with private and public partners on regional growth opportunities in the energy sector. It originated with the aim of working together on gas, but for the province of Friesland focuses mostly on sustainable energy.
- In 2020 the Province of Friesland wants a 16% share of renewables in total energy supply and 20% energy savings as compared to 2014. Previously, the Province had the target of 100% renewables for 2020, but this target is now set for 2050.
- In 2013 the switch program was formulated which stated the ambition of a 21% renewable energy share 2020.
- Since 2009 a program exists to implement the policy made in order to meet the energy goals. The province of Friesland plays a facilitating and directing role.
- Since 2000 the Windstreek program exists in order to see where onshore wind turbines could be installed. The selection of three locations that were appointed for the installation of onshore wind turbines received a lot of opposition and the plan is currently being revised.
- The goal for onshore wind energy is set at 530 MW in 2020, whereas currently 180 MW is installed.
- The goal for solar energy is set at 500 MW in 2020, whereas currently 50 MW is installed. No subsidy program exists for solar energy.
- Currently the Province is working on an energy fund *Fonds Schone Friesche Energie*. €90 million is available for good business cases, for instance solar farms. The Province of Friesland can finance a maximum of 49%.
- Mr. Venema believes that it is not likely that the Province of Friesland will accept large wind turbines on Vlieland, but states that it is unlikely that it will stop the installation of small turbines on the island. The Province leaves the installation of small wind turbines up to the municipality of Vlieland.

- Currently the Province of Friesland is working on a program together with NHL Leeuwarden (a higher vocational education institute) and the Wadden Sea Islands to see if installation of solar panels in the protected rural area is possible. A pilot study will take place on Ameland.

Appendix VII Feasibility assessment of energy production from biomass on Vlieland

Energy can be obtained from biomass in several ways. The biomass can either be purpose-grown or originate from waste flows (e.g. municipal waste, agricultural waste or landscape management). Considering the fact that large parts of Vlieland are nature reserves or military grounds, and that currently no agricultural production takes place, it is highly unlikely that energy from purpose-grown biomass would be a practical and economically feasible option. It was therefore decided to focus on energy from biomass waste flows.

Biomass can be processed in various ways to produce either heat (or indirectly electricity), char, pellets, liquid fuels or biogas. Based on Twidell & Weir (2006) it was decided that the anaerobic digestion would be the most suitable option for Vlieland. Anaerobic digestion is a process in which biomass is anaerobically reduced by several types of bacteria to yield predominantly methane (the main component of natural gas) and some carbon dioxide. This gas mixture (also called biogas) can then be injected into the regular gas grid (sometimes some additional cleaning is needed). The benefits of anaerobic digestion are that no drying step is required (as would be necessary for pyrolysis methods like gasification or for pellet production), no further thermochemical treatment is required (which would require additional energy inputs) and the fact that the anaerobic digestion process can easily be downscaled (Twidell & Weir, 2006). Fermenting biomass to produce ethanol is not considered here because Vlieland's biomass flows are waste flows which tend to consist of predominantly ligno-cellulose. Plants to convert ligno-cellulosic biomass to ethanol have been built and the technology is commercialising, however the capital costs of these plants and specific costs of the produced ethanol are still high compared to for instance first generation (crops-based) bioethanol (Janssen et al., 2013). It is therefore likely that ligno-cellulosic ethanol will not be the most cost-effective biomass conversion pathway. Especially on a small island like Vlieland, where a down-sized plant would further decrease cost-effectiveness, due to economies of scale (based on: Blok, 2007).

Method

The sizes of annual biomass waste flows on Vlieland were identified through interviews with the municipality and *Staatsbosbeheer*, and some further data was obtained from an internal report on biomass flows in the Wadden Sea islands municipalities in 2007. Potential methane yields from anaerobic digestion of biomass depend on the volatile solids (VS) content of the biomass and the conversion efficiency of these volatile solids to methane. Exact VS values depend on the biomass type and exact efficiencies depend on biomass type, the bacteria added and conditions in the digester, like the temperature regime (see for example Davidsson et al., 2006). Therefore besides a best estimate value, a range of the possible methane yields was calculated using the lowest and highest efficiencies and VS values found in literature (see table VII.1). This provided an overview of the potential annual methane yield from biomass, which was then compared with the annual natural gas use to assess whether biomass can contribute a significant amount of energy. Economic viability was assessed based on literature examples.

Results

Biomass flows on Vlieland are limited. Forests managed by *Staatsbosbeheer* yield about 500 m^3 of wood annually, but this is already used by Vlieland's inhabitants as firewood. No agriculture takes place. *Staatsbosbeheer* clears between 900 and 1200 m^3 of grass each year as part of landscape management (according to the municipality report this is 750 m^3

annually). Different municipal waste flows are not separated on Vlieland. In an internal report of biomass flows in the Wadden Sea islands municipalities it was estimated based on waste ratios of the other islands that Vlieland would have 110 tonnes of VGF waste (Dutch: GFT-afval) and 51 tonnes of organic material in the remaining waste, if waste was to be separated.

Since the firewood is already used, the remaining biomass flows are landscape management grass and organic municipal waste. Landscape management grass could at most yield $4.0 \cdot 10^4$ m^3 of methane, this could replace roughly the same amount of natural gas (which is predominantly methane), in reality are probably closer to $2.5 \cdot 10^4$ m^3 of methane (table VII.1).

Table VII.1 *Potential methane yield from anaerobic digestion of landscape management grass on Vlieland*

quantity	range	value	unit	source
grass harvest	900 – 1200	$1.05 \cdot 10^3$	m^3 / year	1
grass (wet) bulk density	-	159	Kg / m^3	2*
grass (wet) water content	-	0.42	kg water / kg wet grass	2
grass dry solids / total weight	-	0.58	kg DS / kg wet grass	2**
grass volatile solids/ dry solids	-	0.92	kg VS / kg DS	3
volatile solids to methane conversion efficiency	0.300***; 0.128-0.392; 0.215 - 0.263	0.3	m^3 CH_4 / kg VS	3, 4, 5 resp.
total methane yield from anaerobic digestion of grass	$8.1 \cdot 10^3 – 4.0 \cdot 10^4$	$2.5 \cdot 10^4$	m^3 CH_4 / year	

[1] Staatsbosbeheer interview; [2] McNulty & Kennedy, 1982; [3] Smyth et al., 2009; [4] Amon et al., 2007; [5] Blokhina et al., 2011; *measured in a silo with average depth 1.5 m, comparable to compaction during truck transport on Vlieland; **Dry solids content was assumed to be all content other than water; ***Smyth et al. (2009) made an overview of previous literature and came to 0.300 m^3 CH_4/kg VS

If municipal is separated in the coming years, the VGF fraction (110 tonnes, see table VII.2) could be anaerobically digested to yield methane. The 51 tonnes of organic content of the remaining waste (digestable but not part of VGF) could also be digested, but it is more difficult to obtain as it cannot be separately collected. The remaining organic waste is only included in the calculation of the upper bound of the range of potential methane yields (table VII.2). Anaerobic digestion of the VGF waste is likely to yield about $4.9 \cdot 10^3$ m^3 of methane annually. If conversion efficiency turns about to be like the higher values found in literature and all remaining organic waste is also included the methane yield could be $1.8 \cdot 10^4$ m^3 of methane at highest (table VII.2).

Table VII.2 *Potential methane yield from anaerobic digestion of the organic fraction of municipal solid waste (MSWOF) on Vlieland*

quantity	range	value	unit	source
MSWOF	$1.10 \cdot 10^5$-$1.61 \cdot 10^5$	$1.10 \cdot 10^5$	kg / year	*
MSWOF dry solids / total weight	0.03-0.3*; 0.05**	0.1	kg TS / kg	1
MSWOF volatile solids / dry solids	0.60-0.92*; 0.81-0.92**	0.87	kg VS / kg DS	1
volatile solids to methane conversion efficiency	0.20-0.40*; 0.30-0.40**	0.35	m3 / kg VS	1
total methane yield from anaerobic digestion of MSWOF	$4.0 \cdot 10^2$- $1.8 \cdot 10^4$	$4.9 \cdot 10^3$	m3 /year	

[1] Davidsson et al., 2007; *Based on an internal report on biomass flows in the Wadden Sea islands municipalities. Waste is not seperated on Vlieland, based on waste ratios of the other islands it was estimated that Vlieland has 110 tonnes of VGF waste (Dutch: GFT-afval) and 51 tonnes of organic material in the remaining waste. The 110 tonnes of VGF waste was taken as the default value.

Anaerobic digestion of landscape management grass and municipal organic waste taken together could at best yield $5.8 \cdot 10^4$ m^3 of methane annually, or about 2% of the annual natural gas demand. A methane production of $3.0 \cdot 10^4$ m^3 would be more likely though (using the default values in tables VII.1 and VII.2), which would only meet 1% of the current natural gas demand. Either way, less than one percent of the 2020 total *energy* demand would be realised by anaerobic digestion of biomass. The energy potential of biomass is therefore considered too small to further investigate in this study. Besides a low potential, energy from biomass has relatively high costs at small scale. Even though it is technologically easy to scale an anaerobic digester down to Vlieland's biomass input, it is difficult to make small-scale digesters cost-effective (Blokhina et al., 2011).

Conclusion

In conclusion, biomass is not a feasible option to make a cost-effective and significant impact on the reduction of energy import.

Appendix VIII Feasibility assessment of geothermal energy on Vlieland

Geothermal energy from deep aquifers is energy stored in high-temperature water-bearing reservoir formations in the subsurface. This energy resource can be extracted to provide heat or even to drive turbines and generate electricity.

Method

The feasibility of geothermal energy on Vlieland was explored by investigating various literature sources including studies by TNO, a Dutch research institute with large expertise on geothermal energy. TNO recently developed a 3D potential assessment tool, ThermoGIS, which allows for an in-depth geothermal assessment below Vlieland (ThermoGIS, 2013). Insights gained from this assessment were combined with those of the mentioned literature review.

Results

Geothermal energy from deep aquifers can be used either directly to meet heat demand or to generate electricity. There are no examples of the latter option in the Netherlands; no deep aquifer geothermal power plant is currently in operation nor planned before 2017 (EGEC, 2013), therefore we consider this option to be commercially unfeasible for Vlieland towards the 2020 targets.

The potential for district heating from geothermal energy from deep aquifers is labelled as “moderate indication > $5MW_{th}$” on Vlieland (ThermoGIS, 2013). This potential is large enough to replace all the natural gas used for heating on Vlieland. This promising potential is confirmed by a recent assessment on geothermal feasibility for Vlieland (Milieuadviesdienst, 2012).

However there are other important physical factors to consider besides this initial promising potential. The permeability of potentially interesting aquifers – one of the crucial factors determining the possible heat flow rate (Van Wees et al., 2013) – is for instance highly uncertain. Estimations for the permeability of aquifers below Vlieland (Rijnland/Schieland groups) are 8.0 - 9.0 mD (milliDarcy) but may turn out to be a factor 100 higher or lower in extreme cases (ThermoGIS, 2013). Another problem is the fact that the available heat is subdivided between two distinct depth horizons: the Rijnland/Schieland Group at ~2 km depth on one hand; the Rotliegend group at ~3 km on the other (ThermoGIS, 2013), which would complicate the extraction process.

Besides physical difficulties geothermal heating proved to be economically challenging. A preliminary calculation by Milieuadviesdienst (2012) shows that the investment costs of a plant on Vlieland are in the range of tens of millions of euros, and that pre-production (and thus economically high-risk) well drilling contributes to the majority of these costs. Also, project lifetimes are highly debated: a time span of 30 years is chosen for Texel and Vlieland case studies (Hagedoorn et al., 2009; Milieuadviesdienst, 2012), although projects with over 100 years of production have also been reported in the US (Matek & Schmidt, 2013). Another factor to consider is the varying heat demand throughout the year. In 2009, average Dutch residents used 14.8% of the annual gas demand in January alone (Delta, 2014). Vlieland has the additional complicating factor of a large influx of tourists in the summer. Tourists could compensate for lower per capita heat demand in summer, but this is highly unsure as there are no monthly heat demand data available. Heat demand may vary substantially, which would mean that the geothermal (district) heating network would often operate on part load, further reducing economic viability.

Implementation time is a third important issue for the feasibility of geothermal energy on Vlieland. Hagedoorn et al. (2009) expect a general geothermal implementation time of five years, which means that Vlieland would have to start this capital-intensive project within the year to meet their ambitions.

Conclusion

All in all, deep aquifer geothermal energy extraction is not considered a feasible option for Vlieland to reach energy independency by 2020.

Appendix IX Feasibility assessment of tidal energy on Vlieland

Tidal power converts energy of tides into electricity. Two different types of tidal energy exist, tidal range power (using basins) and tidal stream power (using submerged turbines). In this study the potential of both these technologies was assessed.

Methodology
To determine the potential of tidal range power, data from *Rijkswaterstaat* on the sea level during high and low tide in Oost-Vlieland in the period May 2013-April 2014 were used (Rijkswaterstaat, 2014a). In order to determine the range the difference between high and low tide was taken. The average range was calculated and the following formula 18 was used to calculate the average power produced:

$$P_{average} = \frac{\rho A g}{2\tau} R_{average}{}^{2}, \quad (18) \qquad \text{(Twidell \& Weir, 2006)}$$

Where:
$P_{average}$ = *average power produced (W)*
ρ = *density of seawater (kg/m³)*
A = *area of the basin (m²)*
g = *gravitational constant (m/s²)*
τ = *tidal period (s)*
$R_{average}$ = *average range (m)*

Input data to calculate the average power produced can be found in tableI IX.1. As no estuaries are present on Vlieland, the basin must be artificially constructed and was assumed to have an area of 10 m^2, which is an area that seemwhich is in the right order of magnitude possible in the sea near Vlieland due to the scale of the Wadden Sea and courses of navigation (Twidell & Weir, 2006). After determining the potential of tidal range power, the investment costs of a tidal power plant were compared with the costs of a technology of similar potential.

Table IX.1 *Input data used to calculated the potential of tidal range power*

Quantity	Unit	Value
Density of seawater	kg/m^3	1025[1]
Area of the basin	km^2	10
Gravitational constant	m/s^2	9.81[1]
Tidal period	hours	12.25[1]

[1]Twidell & Weir, 2006

In order to calculate the potential of tidal stream power on Vlieland data on water current velocity for locations near Vlieland were needed. However, these data were not available, therefore data from IJmond (North-Holland, The Netherlands) were used, as IJmond was the only location for which Rijkswaterstaat provides data on the current velocity every 10 minutes (Rijkswaterstaat, 2014b). The yearly average current velocity near IJmond was used to calculate the power density using formula 19:

$$q = \frac{\rho u^3}{2} \quad (19) \quad \text{(Twidell \& Weir, 2006)}$$

Where:
q = *power density (W/m²)*
ρ = *density of seawater (kg/m³)*
u = *current velocity (m/s)*

After the power density of tidal stream power was determined the costs of tidal stream power were compared to the costs of a technology with a power density of the same order of magnitude.

Results

The potential of tidal range power is calculated using formula 18 The average range of the sea level in the period May 2013-April 2014 in the harbour of Vlieland is 1.86 m. The average power produced would therefore be 3.3 MW. This potential is comparable to a large-size wind turbine, which has a significantly higher power density (0.03 W/m^2 for tidal range power compared to 518 W/m^2 for wind energy) and lower investments costs (€1.06-1.18 million for onshore wind energy and €6.5-16 million for tidal energy) (Salvatore, 2013). Enlarging the reservoir could increase the potential of tidal range power; however, the reservoir area used of 10 km^2 is an estimate that is in the right order of magnitude possible in the sea near Vlieland due to the scale of the Wadden Sea and courses of navigation. Moreover, according to the Ocean Energy Council, a range of at least 7 m is needed for economically viable operation and sufficient water head for the turbines (OEC, 2014). Furthermore, the construction period of tidal power plants are typically about 10 years, which means that it is unlikely that a tidal power plant could be installed before 2020 (OEC, 2014). As a result of the low power density, spatial limitations, and the construction period, tidal range power is not considered a feasible technology to install on Vlieland.

The potential of a tidal stream power plant cannot be calculated for a location near Vlieland as a result of a lack of data on current velocities in this area. Therefore, the current velocity measured near IJmond (0.49 m/s) is used to get an indication of a power density near Vlieland. By using formula 19 a power density in IJmond of 60.3 W/m^2 was found. This is almost 10 times smaller than the power density of wind turbines on Vlieland, which as already mentioned before have significantly lower investment costs (Salvatore, 2013). Due to a lack of data on current velocities near Vlieland it is not possible to accurately estimate the potential of tidal stream power on Vlieland; however, the estimate by means of the potential on a different location in the Netherlands indicates that tidal stream power does probably not have large potential in the Netherlands. Furthermore, just like tidal range power, the construction period of tidal power plants is typically about 10 years (OEC, 2014), which means that it is unlikely that a tidal stream power could be installed before 2020.

Conclusion

Because of the relatively low potential for tidal stream power compared to relatively high investment costs and the construction period, tidal stream power is not considered a feasible technology to install in the period up to 2020. Nevertheless, tidal stream power is considered a possible feasible technology on Vlieland in the future if costs go down.

Appendix X Feasibility assessment of wave energy on Vlieland

Wave energy technology converts motions of waves to electrical energy.

Method

To assess feasibility of this technology on Vlieland, the local wave energy potential was determined from literature first. Subsequently, and analogous to the choice of the study of Fernández-Chozas et al. (2013), three renowned wave technologies were considered: Wave Dragon, Wavestar and Pelamis. For these three technologies, a short assessment on the degree of commercialisation was made. This degree of commercialisation was based on the activities of the three mentioned companies. For instance, if all three companies would exclusively focus on experimental projects, no achievement of commercialisation was inferred in our study.

Results

The wave energy potential at *Eierlandse gat*, just offshore from Vlieland, is 9.86 kW/m (Beels et al., 2007). Of the three wave energy-producing companies taken into account, Wave Dragon currently only builds demonstration devices and is not commercial yet (Wave Dragon, 2011). Wavestar mentions examples of 1:2 scaling tests (Wavestar, n.d.), where also no state of commercialization has been achieved thus far. Pelamis is conducting a full-scale North Sea project near Shetland, Scotland, which has not reached commercial cost-effectiveness yet (PelamisWave, n.d.), even though the local wave potential is 42 kW/m (Beels et al., 2007), more than four times higher than on Vlieland (Beels et al., 2007).

Conclusion

In conclusion, wave energy will very likely not be commercially feasible for Vlieland towards 2020 considering Vlieland's low local wave energy density. Only if the costs drop greatly and if the maturity of the technology develops, this technology may become worthwhile in the (long-term) future.

Appendix XI The SDE+ subsidy scheme

For large-scale renewables, like the solar farm and both types of wind turbines, the *SDE+* (Stimulation Renewable Energy*)* is applicable; this scheme provides a premium on top of the electricity price (RVO, 2014a). This scheme provides a variable premium on top of the market price of electricity to top the price up to a basic amount (green dashed line in the example of figure XI.1. If the market price is above the basic amount however, no premium is awarded. If the market price is below the basic electricity price (blue dashed line in figure XI.1), the difference between the market price and the basic electricity price is not compensated for (see figure XI.1).

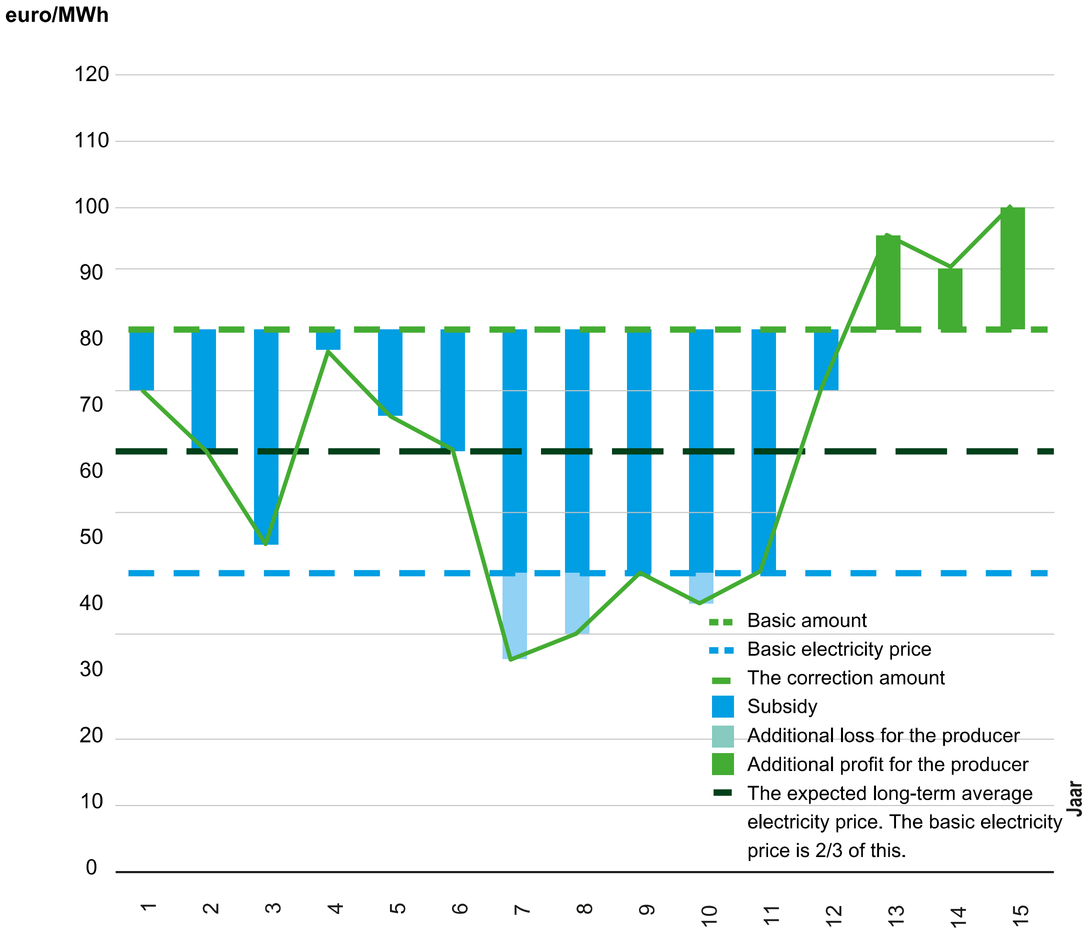

Figure XI.1 *Illustration of how the SDE+ subsidy scheme works (source: EU, 2009). Note: numbers are not representative for the technologies investigated here. The exact numbers are given in the technologies' individual sections below.*

Appendix XII Overview of the energy infrastructure on Vlieland

The energy infrastructure can be an important factor when deciding what renewables to implement where. Installation costs increase if renewables are implemented far from the main grid. To get an overview of the main energy infrastructure a map was created of all major pipelines and electricity cables on the island.

Method

This map was distilled from highly detailed infrastructure maps provided by municipality of Vlieland, which were viewed in the *KLIC viewer* software.

Result

The major electricity cables (10kV and 3 MW capacity) and gas pipelines (4 bar) are displayed in figure XII.1 Currently, the main pipelines and cables run along the major roads and cover the North-Eastern half of Vlieland, they stop at the military base at the Northern edge of the Vliehors military area. Installing large-scale renewables such as a wind park will require infrastructural change. Small scale renewables like photovoltaic panels could be installed within the existing infrastructure. Infrastructural requirements of specific renewable energy production and their associated costs are discussed in the techno-economic analysis. No district heating is present on Vlieland as it is very expensive (Milieuadviesdienst, 2012).

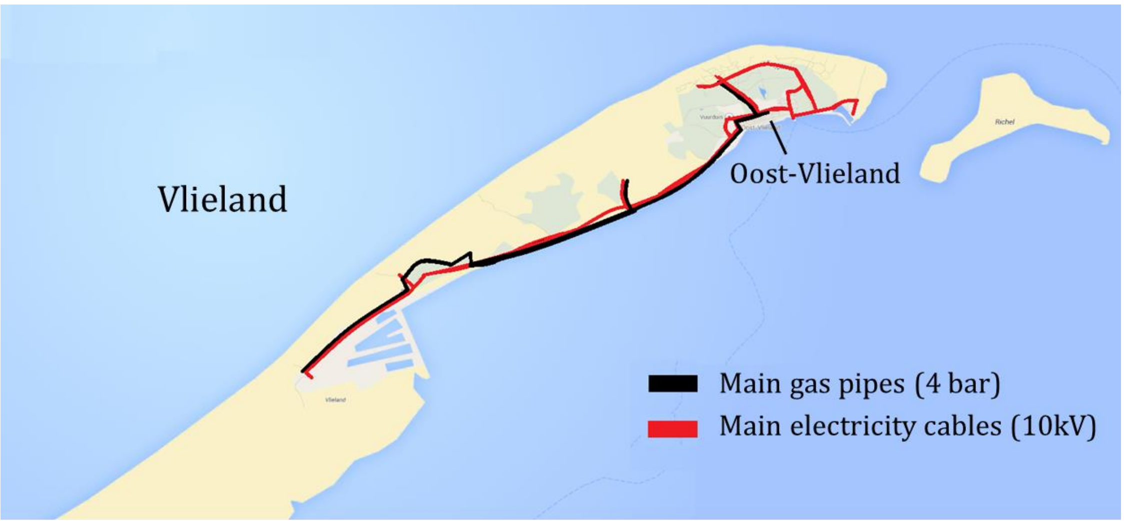

Figure XII.1. *Electricity and gas infrastructure on Vlieland. The Southern half of the island does not have major energy infrastructure.*

Appendix XIII Natura 2000 implications for the implementation of wind turbines

The EU-wide Natura 2000 legislatio is important as it frames the protected nature areas on Vlieland. The selection of Natura 2000 areas depends on size and density of population of targets species and ecological quality and area of target habitat types (EU, 2014c; EU, 2014b). New activities and development in Natura 2000 areas need to be considered on a case-by-case basis; hence, no *a priori* prohibition exists. Permits for the installation of a wind farm can be obtained, if it can be proven that a wind farm has no significant effect on threatened species/habitats. Also if the wind farm has negative consequences on threatened species/habitat it is still possible to obtain a permit on the condition that social/economic interests are at stake and no alternative solutions are available (RVO, 2014e). In figure XIII.1 an overview of Natura 2000 areas on Vlieland is given.

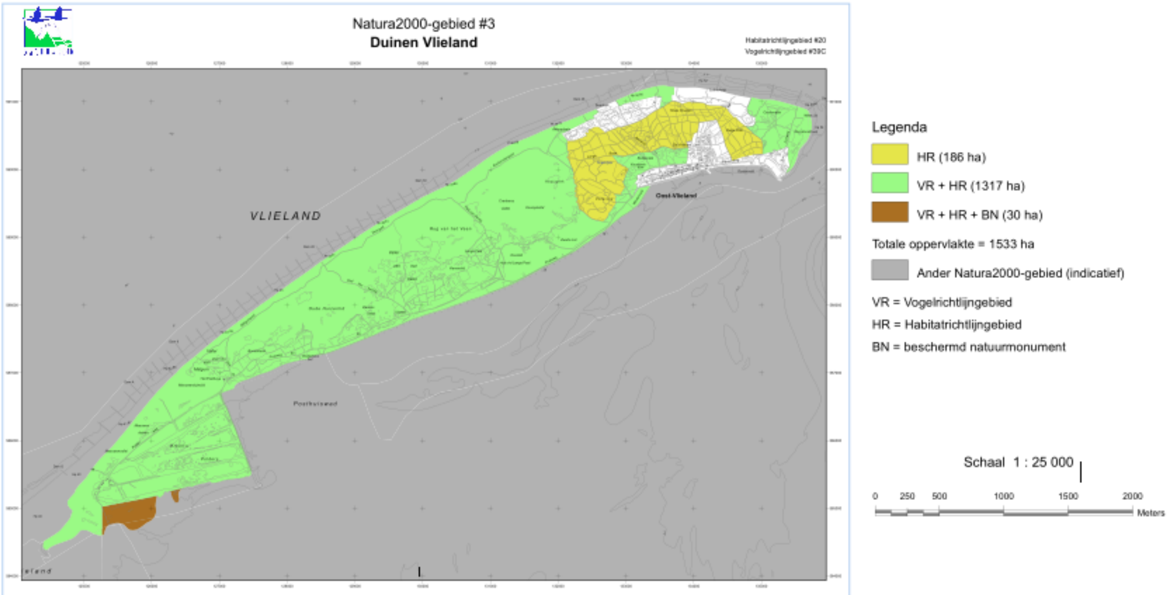

Figure XIII.1 *Natura 2000 areas on Vlieland (Natura 2000 Beheerplannen, 2014)*

Protection of the Ecologische Hoofdstructuur, a selection of protected nature areas by the Dutch government, is similar to protection of Natura 2000 areas. A permit is given for the installation of a wind farm under similar conditions as Natura 2000.

Appendix XIV Input data for the techno-economic analysis of large wind turbines

Input data for energetic potential calculations

Hub heights (table XIV.1) and power curves (figures XIV1,2,3) were among the input data for the calculation of the potential of large wind turbines on Vlieland. Vlieland's wind speed data were obtained from the KNMI hourly wind database (KNMI, 2014a).

Table XIV.1 *Hub heights of the selected 2MW turbines*

Manufacturer	Turbine model	Hub height (m)	Source
Vestas	V80 2.0 MW	80	Vestas (2013)
Gamesa	G80	80	Gamesa (2014)
Senvion	MM82	82	Senvion (2014)

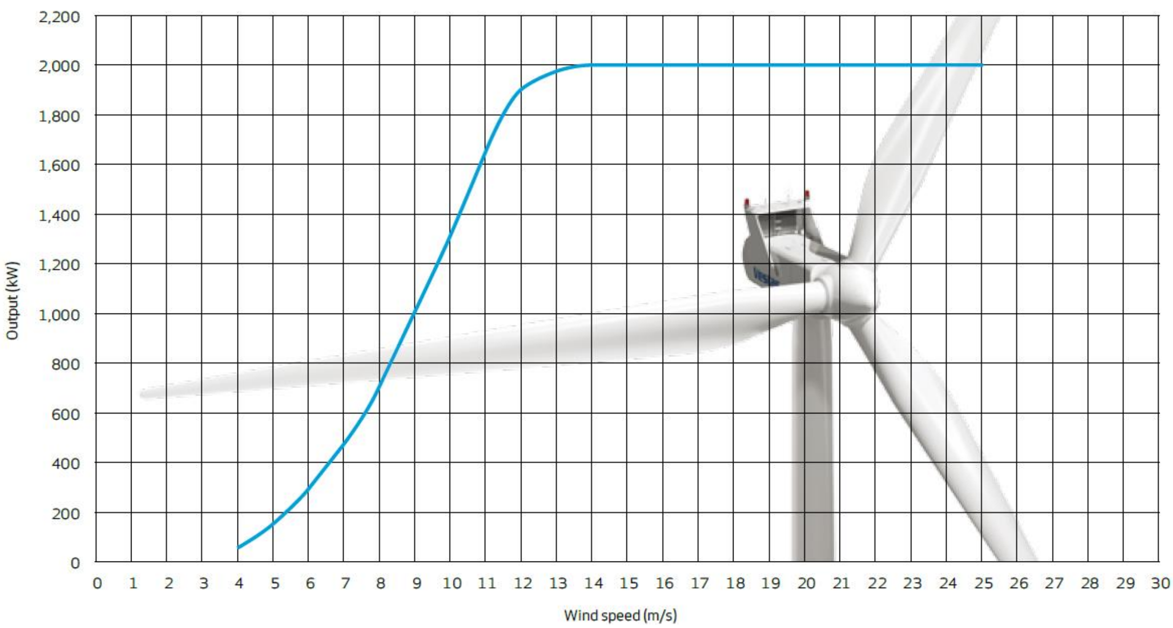

Figure XIV.1 *Power curve of the Vestas V80 2.0MW turbine.*

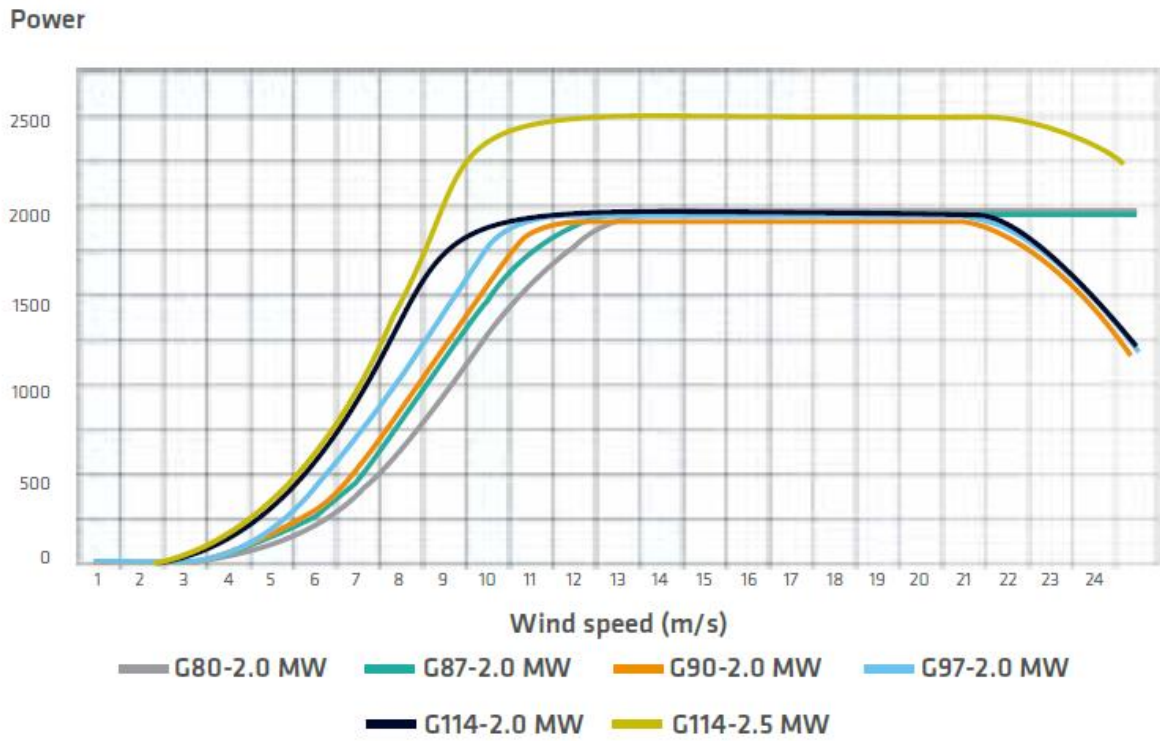

Figure XIV.2 *Power curves of Gamesa wind turbine models. In this study the power curve of the G80-2.0MW turbine was used. Source: Gamesa (2014).*

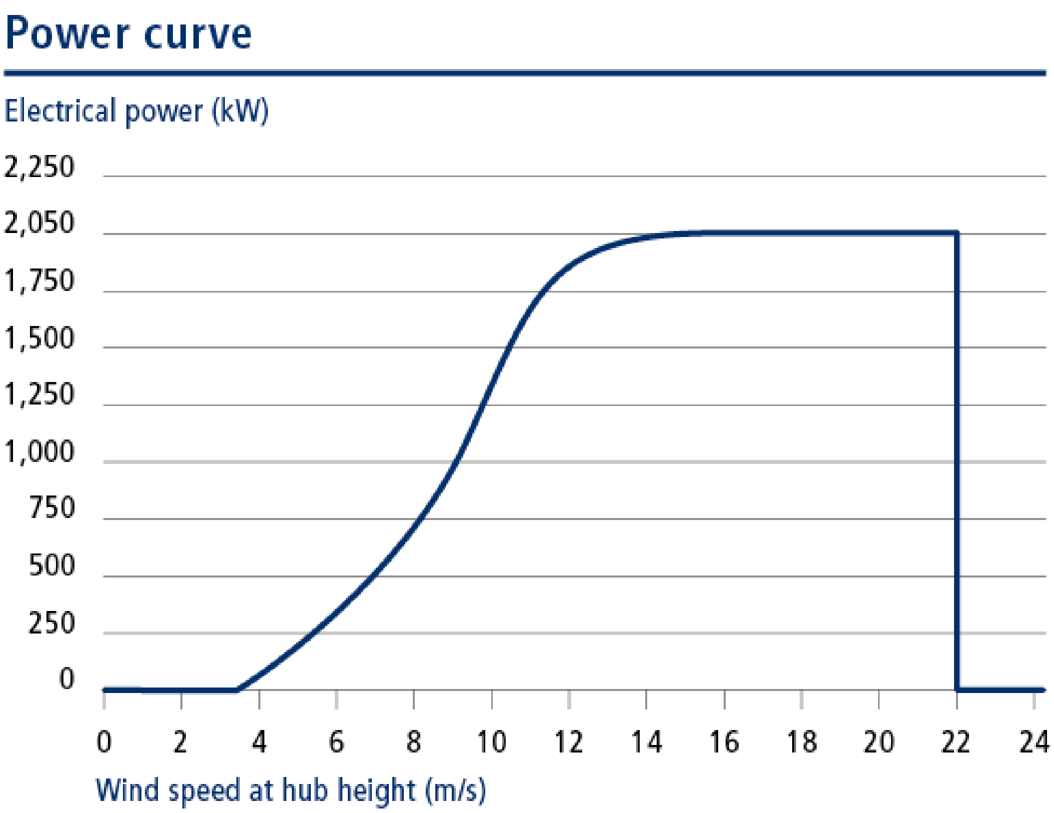

Figure XIV.3 *Power curve of the Senvion MM82 2.05 MW turbine. Source: Senvion (2014b).*

Input data for net specific costs and internal rate of return calculations

Table XIV.2 shows the input values, below it is explained how these values were obtained

Table XIV.2 *input data for net specific costs and internal rate of return calculations of large wind turbines.*

Quantity	value	unit	based on:
Investment costs	1400	euro/kW	1,2,3,4,5,6
O&M costs	$4.17 \cdot 10^5$	euro/year*	1,3,6
Lifetime	20	years	3
Annual electricity production	10.4	GWh/year*	**
Lifetime energy production	208	GWh*	**
Discount rate	5%	-	3,7
Electricity price	0.058	euro/kWh	8

[1]IEA (2010b); [2]EWEA (2009); [3]Blanco (2009); [4]IEA (2012); [5]US dep. of Trade & Industry (2007);[6]Statbureau (2014);[7]IEA (2010a);[8] RVO (2014a); *per turbine; **calculated using results of the calculations of energetic potential

Lifetime, discount rate and lifetime energy production

The lifetime was estimated at 20 years (Blanco, 2009) and the discount rate at 5% (IEA, 2010a; Blanco, 2009). Lifetime energy production was calculated by multiplying annual electricity production (obtained from results on potential) by the lifetime of 20 years.

Investment costs

The investment costs were determined using inflation corrected investment cost values of large onshore wind turbines found in literature (see table XIV.3). Inflation was corrected for using a CPI (consumer price index) based inflation calculator (statbureau, 2014) using each year's inflation figure for the month of January. There were several difficulties other than inflation with translating these values to the situation for Vlieland anno 2014. Firstly, there is a certain learning curve for wind turbines, meaning that the euro per kW rated capacity investment costs get lower over time as experience with building and installing turbines increases globally. Some older investment cost values (from for instance 2006) may therefore be too high. Some investment costs values may be too high, because they represent average EU values, whereas Dutch values tend to be lower (table XIV.3). On the other hand, Vlieland is fairly isolated and installing large turbines would require transport of parts over sea and, most likely, new infrastructure on the island. This would increase costs substantially, as infrastructure represents a significant share of investment costs (see table XIV.4). Moreover, considerable electricity infrastructure change would be required to connect the turbines to the grid (current cables can only handle up to 3 MW) and grid connection too forms a large share of the investment costs (see XIV.4). Taking these difficulties into consideration, a conservative estimate of the investment costs of 1400 $euro_{2014}$/kW rated capacity was made, on the high end of the inflation corrected range found in literature (see table).

Table XIV.3 *Investment costs of large onshore wind turbines*

investment costs		description	source	inflation corrected*** investment costs	
1000-1600	$euro_{2008}$/kW	NL 2008	1	$1.4 \cdot 10^3$	euro $_{2014}$/kW
1227	$euro_{2006}$/kW	EU 2006-2008	2	$1.4 \cdot 10^3$	euro $_{2014}$/kW
950	$euro_{2006}$/kW	EU projection 2014	2	$1.1 \cdot 10^3$	euro $_{2014}$/kW
1100	$euro_{2006}$/kW	NL 2006 – 2008	2	$1.3 \cdot 10^3$	euro $_{2014}$/kW
1100-1400	$euro_{2008}$* /kW	EU 2009	3	$1.4 \cdot 10^3$	euro $_{2014}$/kW
1350	$euro_{2012}$**/kW	NL 2012	4	$1.4 \cdot 10^3$	euro $_{2014}$/kW

[1]IEA (2010b); [2]EWEA (2009); [3]Blanco (2009); [4]IEA (2012); *year not specified assumed 2008;
** year not specified assumed 2012; ***using Statbureau (2014)

Table XIV.4 *Components of investment costs of large onshore wind turbines*

turbine ex works*	grid connection	civil works/other infrastructure	other costs**	source
71%	12%	9%	8%	1
75.6%	8.9%	8.9%	6.7%	2
59%	15%	12%	14%	3

[1]Blanco (2009); [2]EWEA (2009); [3]US dep. of Trade & Industry (2007); *includes turbine manufacturing, transport and installation, excludes foundation and grid connection; **main other costs are consultancy, management and financial costs

Operation & Maintenance costs

O&M costs were also obtained from literature. Blanco (2009) estimate a 1 to 1.5 $eurocent_{2009}$ per kWh electricity produced. The IEA (2010b) estimate fixed O&M costs of 25 $euro_{2008}$ per kW per year and additional variable O&M costs of 0.9-1.2 $eurocent_{2008}$ per kWh. These three values were first corrected for inflation (using Statbureau, 2014). Then they were converted to euro per year values by multiplying variable O&M by the annual electricity production (in kWh) and multiplying fixed O&M by the rated capacity (in kW). It was conservatively estimated that O&M costs had not decreased in time through technological progress and the average $euro_{2014}$ per year value was used as the O&M costs of large wind turbines.

Electricity price

The long-term average electricity price of 0.058 euro/kWh, as determined by the Dutch government to calculate SDE+ subsidies, was used here (note this price is very different from the higher price consumers pay, this difference is due to intermediate parties and taxes) (RVO, 2014a).

Appendix XV Input data for the techno-economic analysis of small wind turbines

Input data for energetic potential calculations

WES100 turbines have a hub height of 18 metres. Figutr XV.1 shows the power curve of a WES100 turbine (WES, 2014). Vlieland's wind speed data were obtained from the KNMI hourly wind database (KNMI, 2014a).

Wind speed (m/s)	Power kW
0	0,0
1	0,0
2	0,0
3	1,0
4	2,9
5	6,0
6	11,0
7	17,7
8	27,3
9	39,2
10	53,8
11	68,4
12	82,8
13	89,1
14	95,9
15	98,7
16	99,5
17	100,0
18	100,0
19	100,0
20	100,0
21	100,0
22	100,0
23	100,0
24	100,0

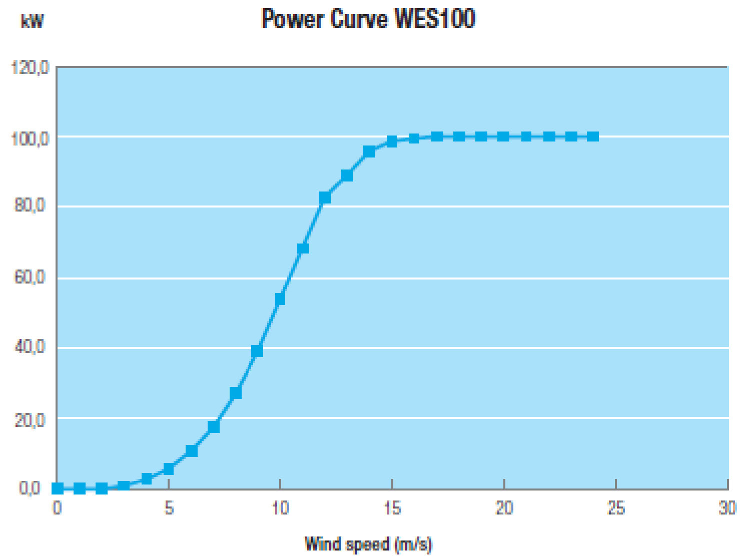

Figure XV.1 *Power curve of a WES100 turbine. Source: WES (2014).*

Input data for net specific costs and internal rate of return calculations

Table XV.1 shows the input values, below it is explained how these values were obtained.

Table XV.1 *input data for net specific costs and internal rate of return calculations of small wind turbines*

Quantity	value	unit	based on:
Investment costs	$2.6 \cdot 10^3$	euro/kW	1
O&M costs	$3.75 \cdot 10^3$	euro/year*	1
Lifetime	20	years	2
Annual electricity production	0.357	GWh/year	**
Lifetime energy production	7.15	GWh	**
Discount rate	5%	-	2,3
Electricity price	0.058	euro/kWh	4

[1]Correspondance with *Wind Energy Systems*; [2]Blanco (2009); [3]IEA (2010a); [4]RVO (2014a);*per turbine; **calculated using results of the calculations of energetic potential

The lifetime was estimated at 20 years (Blanco, 2009) and the discount rate at 5% (IEA, 2010a; Blanco, 2009). Lifetime energy production was calculated by multiplying annual electricity production (obtained from results on potential, section 3.4) by the lifetime of 20 years. Wind Energy Systems gave an investment cost estimation of $2.6 \cdot 10^5$ $euro_{2014}$ per 100 kW rated WES100 turbine, and an O&M cost range a of $3.5 \cdot 10^3$ to $4 \cdot 10^3$ $euro_{2014}$ per 100kW rated per year . For the investment costs the provided value was used; for O&M costs the average of the given range of $3.75 \cdot 10^3$ $euro_{2014}$/100kW per year was used. The long-term average electricity price of 0.058 euro/kWh, as determined by the Dutch government to calculate SDE+ subsidies, was used here (note this price is very different from the higher price consumers pay, this difference is due to intermediate parties and taxes) (RVO, 2014a).

Appendix XVI Input data for the techno-economic analysis of photovoltaic panels

Capacity category	Unit	Small PV		Solar farm	
		Average case	HP case	Average case	HP case
SIC [< 1 kW_p]	$€_{2013}/W_p$	1.84[a]	1.69[a]	-	-
SIC [1 – 5 kW_p]	$€_{2013}/W_p$	1.49[a]	1.36[a]	-	-
SIC [> 5 kW_p]	$€_{2013}/W_p$	1.36[a]	1.25[a]	1.36[a]	1.25[a]
η_{module}	W_p/m^2	145[a]	157[a]	145[a]	157[a]
η_{conv}	%	95.4[a]	98[a]	95.4[a]	98[a]
η_{other}	%	90[a]	90[a]	90[a]	90[a]
C_{ref}	$W_{p, ref}$	1,000[a]	1,000[a]	1000[a]	1000[a]
SI_{ref}	$€_{2013}/W_{p, ref}$	0.45[a]	0.45[a]	0.45[a]	0.45[a]
η_{grid}	J_e/J	0.38	0.38	0.38	0.38
ERE_{grid}	J_p/J	1.09	1.09	1.09	1.09
p_e	$€_{2013}/kWh$	0.23[b]	0.23[b]	0.11[c]	0.09[c]
A_{roof}	m^2	14,000	14,000	-	-
$c_{O\&M}$	-	0.015[d,e]	0.01[a]	0.015[d,e]	0.01[a]
N_{dwell}	-	1,016[f]	1,016[f]	-	-
G_{ann}	$kWh/m^2/yr$	1,065	1,065	1,065	1,065
L	yr	20[d]	20[d]	20[d]	20[d]
r	-	0.05[h]	0.05[h]	0.05[h]	0.05[h]
d_{BO}	-	-	-	0.20[g]	0.30[g]

[a] Van Sark et al., 2013a; [b] Milieucentraal, 2014; [c] RVO, 2014a (on SDE+ subsidy for PV); [d] Ossenbrink et al., 2013; [e] Enbar, 2010; [f] CBS, 2010 (document on Vlieland stats); [g] SMZ, 2013; [h] IEA 2010a

Where:
SIC = *specific investment costs* ($€/W_p$)
η_{module} = *module efficiency* (W_p/m^2)
η_{conv} = *converter efficiency (%)*
η_{other} = *combined efficiency of other system components (%)*
C_{ref} = *reference system installation capacity* ($W_{p, ref}$)
SI_{ref} = *reference specific installation investment costs* ($€/W_{p, ref}$)
η_{grid} = *grid efficiency* (J_e/J)
ERE_{grid} = *energy requirement for energy on grid* (J_p/J)
p_e = *price of energy produced/avoided* ($€/kWh$)
A_{roof} = *available roof space* (m^2)
List continues on next page

$c_{O\&M}$ = *annual costs of operation and maintenance (fraction of total investment)*
N_{dwell} = *number of dwellings*
G_{ann} = *annual local insolation (kWh/m²/yr)*
L = *lifetime of the technology (yr)*
r = *discount rate*
dBO = *"big order" discount*

Appendix XVII Roof surface estimation

In order to calculate the potential of solar energy on roofs with a satisfactory degree of certainty, an estimate of the suitable roof area for panels on Vlieland was made in the field. Only the surface areas of roofs sloping in a Southerly direction (135° SE - 225° SW) were estimated, as these have the highest solar potential (Agentschap NL, 2010). A compass was used in order to determine which roofs had the correct orientation. Dormers, chimneys, windows, and other objects on the roof were excluded from the measurement. Buildings with roofs made of reed or uneven materials were excluded too. Installing solar panels on monumental buildings and buildings in the protected area (Dorpsstraat and Kerkplein) is prohibited by municipal legislation (based on an interview with the municipality, see appendix VI). Furthermore, small triangular corners and bending surfaces were excluded because they also were considered unsuitable for the installation of solar panels.

The estimation of roof surface areas of holiday houses and rental houses was done by counting the number of tiles; a typical tile is 340 by 420 mm (Eternit, 2007; Nelskamp 2012). In order to limit the degree of personal bias and mistakes, two project team members made an estimate of the same roof, after which the results were compared directly. When the difference was less than 2 m^2, the average of both estimates was taken. If this was not the case, the measurement was discussed and repeated until a satisfactory degree of consensus was reached.

The roof areas of larger buildings (the dock area, sport centre Flidunen, the hotel Seeduyn and the residential care centre de Uiterton) were estimated using Google Maps. This could not be done with the same level of accuracy as for the smaller buildings. However, as all these large buildings have flat roofs, it was possible to make an accurate estimation of their respective roof areas.

Appendix XVIII Solar irradiance & solar energy density

Methodology

Official local solar irradiance data of Vlieland were absent. However, the KNMI weather station in De Kooy provides decadal (ten day) solar global irradiance cumulatives, averaged over the period 1981-2010 (KNMI 2011a). Next to its relative proximity to Vlieland and likewise near-sea area conditions, an interpolated global insolation map for The Netherlands showed that The Kooy exhibits similar annual totals compared to Vlieland (figure XVIII.1). (KNMI, 2011b). Van Sark (2014) also placed De Kooy in the same regional irradiance zone as Vlieland. For these reasons it was assumed that the measurements of De Kooy could be considered representative for Vlieland.

The KNMI pyranometer measurements represent global irradiance on a horizontal plane as standardized by the World Meteorological Organisation (WMO, 1981). For more details on pyranometers and their specific properties, please consult for instance Velds (1992).

First, the decadal totals for global solar irradiance with unit J/cm^2 provided by KNMI (2011a) were translated to kWh/m^2. Then, all decadal values were summated in order to produce an annual cumulative. Lastly, this annual cumulative was converted to an average incoming solar energy flow [W/m^2] according to the following expression:

$$G_{ann,th} = E_{th} \cdot \frac{3.6 \cdot 10^6}{3600 \cdot 24 \cdot 365}$$

Where:

$G_{ann,\,th}$ = annually averaged total irradiance power flux on a horizontal plane (W_{avg}/m^2)
E_{th} = local global solar irradiance (kWh/m^2)

In order to obtain a validation of the calculation results, an annual irradiance estimate for Vlieland based on the KNMI irradiance interpolation map (see figure XVIII.1) was conducted to check whether this matched our results.

Results

The solar potential calculation results in a total irradiance of 1065 kWh/m^2/yr and an average energy flow of 122 W/m^2. Figure XVIII.2 shows the irradiance distribution over the year and its average.

The estimation from the irradiance interpolation map is determined at 3775 MJ/m^2/yr = 1050 kWh/m^2/yr. The difference between this value and the original calculation is only about 1.5 – 2%, which is lower than the 3% absolute output accuracy of a pyranometer (the irradiation measurement device) (Twidell & Weir, 2006, p. 105). This indicates that the obtained results are representative for Vlieland.

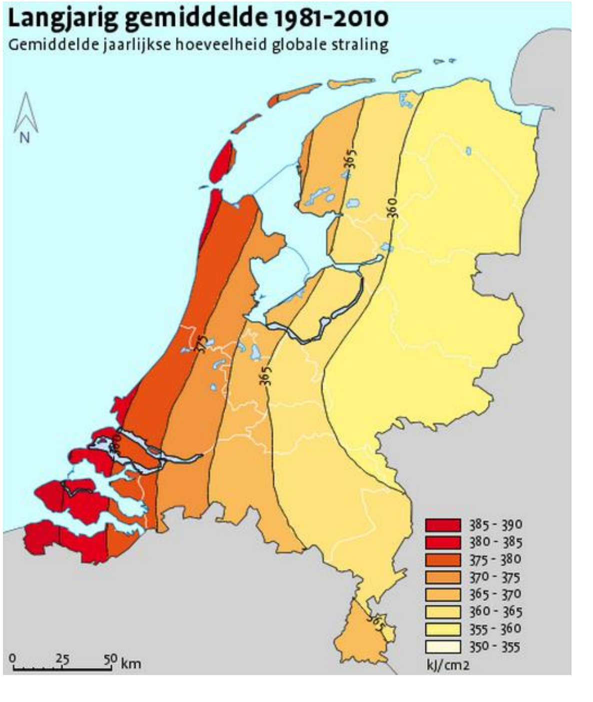

Figure XVIII.1 *Average annual global irradiance over The Netherlands – 1981-2010 long-term average. Interpolation map based on available irradiance data of KNMI weather stations throughout The Netherlands. From: KNMI, 2011b.*

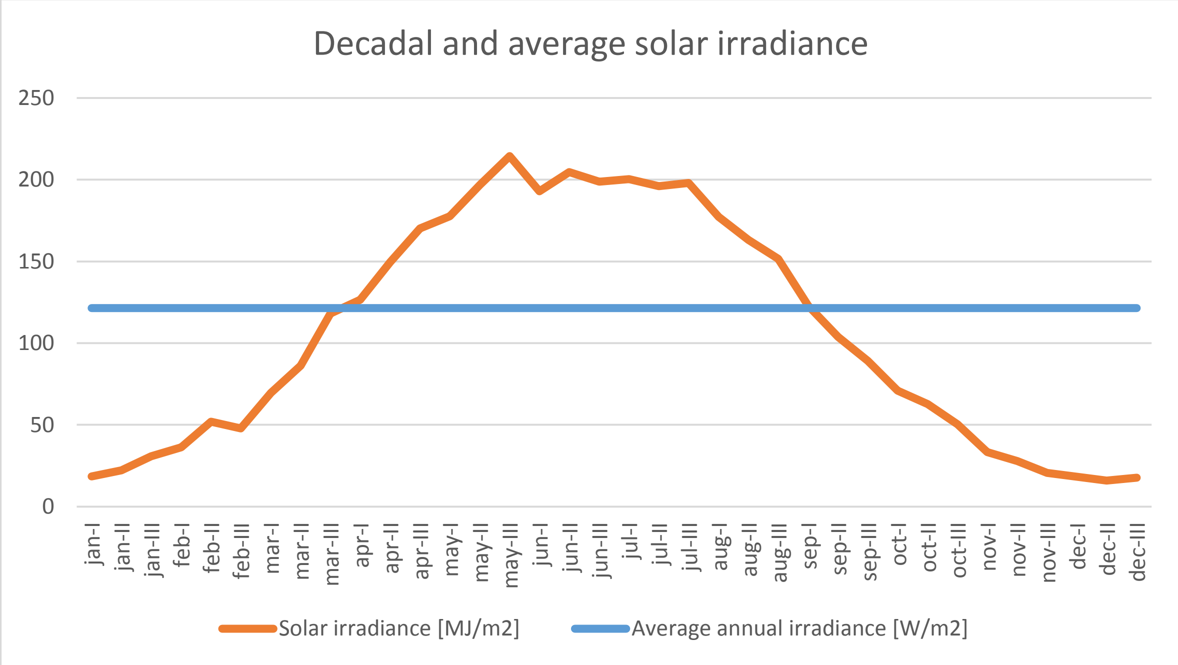

Figure XVIII.2 *Decadal-summated global irradiance distribution over the year (long-term average of 1981-2010) and its annually averaged value. Note the peak in May.*

Discussion

The insolation values on straight horizontal planes as reported here are approximately 85% of the maximum solar irradiation values attainable in The Netherlands (Agentschap NL, 2010, p. 29). Also shown in the aforementioned report is that roofs oriented somewhat southward (dip-slope direction > 135° SE; < 225° SW) have an average irradiance of about 85% of the achievable maximum. The irradiation diagram also demonstrates that the Dutch maximum attainable insolation potential falls onto a southward oriented surface with a slope of approximately 35 degrees. Mousazadeh et al. (2009) remark that tracking is not recommended for certain types of solar panels due to “high energy losses in the driving systems”.

Although a decadal representation exhibits inhomogeneity of different time period lengths of solar irradiance, this does not lead to inconsistencies in the calculations. This is because by cumulating periodic data to annual data, these differences are levelled out.

Appendix XIX Input data for the techno-economic analysis of solar thermal heating

Table XIX.1 shows general input data for the techno-economic analysis of solar thermal energy, table XIX.2 shows input data that are specific for either large or small solar thermal installations.

Table XIX.1 *Data used for the techno-economic analysis of solar thermal energy*

quantity	value	source
Total gas demand on Vlieland(TJ/yr)	90	section 3.1
Average gas consumption household (m^3/yr)	1669	ING, 2013
Average gas consumption for water heating per household (m^3/yr)	220	van Dril, 2012
$ERE_{ng.}$	1.02	Blok, 2007
Conversion efficiency natural gas to heat	85%	Blok, 2007
Suitable roof area on Vlieland (m^2)	14000	Appendix XVII
Thermal output solar thermal collector (MW/m^2)	0.7	Lensink, 2012
Load hours solar thermal collector	700	Lensink, 2012
Lifetime solar thermal collector (yr)	20	Twidell & Weir, 2006
Number of dwellings on Vlieland	550	CBS, 2010
Gas price (€/m^3)	0.65	Van Dril, 2012
Energy density natural gas (MJ/m^3)	33.34	IEA, 2013
Discount rate (%)	5	IEA, 2010a

Table XIX.2 *Data used for the techno-economic analysis of solar thermal energy – specific data for small- and large scare installations*

	Large-scale solar thermal installations (>100 m^2)	Small-scale solar thermal installations (<100 m^2)
Investment costs ($€_{2013}$/kW_{th})	700 (Lensink, 2012)	-
Fixed O&M costs ($€_{2013}$/kW_{th}/yr)	5 (Lensink, 2012)	-
Average investment cost per collector (€)	-	1950 (Zegers, 2013)
Variable O&M costs ($€_{2013}$/GJ)	1.6 (Lensink, 2012)	-
O&M costs (% of total investment)	-	0.75% (NREL, 2014)
Average surface area (m^2)	-	3.2 (Lensink, 2012)

Appendix XX Questionnaire on perception of renewables

Vlieland Energie onafhankelijk

Naam: Functie:

	Totaal oneens						Totaal mee eens
Algemeen	---	--	-	0	+	++	+++
Vlielanders vinden onafhankelijkheid belangrijk							
Vlieland moet energie onafhankelijk worden							
Investeren in duurzame energie is belangrijk							
Ik ben bereid te investeren in energie onafhankelijkheid op Vlieland							
Zonne-energie							
Om Vlieland energie onafhankelijk te krijgen zijn zonnepanelen en zonnecollectoren een goede oplossing							
Zonnepanelen en zonnecollectoren op alle zuidelijk georiënteerde daken zijn visueel hinderlijk							
Een zonneweide op het terrein van defensie is visueel hinderlijk							
De voordelen wegen op tegen de nadelen							

Vlieland Energie onafhankelijk

	Totaal oneens						Totaal mee eens
Besparing door efficiëntie	---	--	-	0	+	++	+++
Om Vlieland energie onafhankelijk te krijgen is energie efficiëntie een goede oplossing	☐	☐	☐	☐	☐	☐	☐
Het belangrijk om efficiënt met energie om te gaan d.m.v. isolatie, dubbel glas etc.	☐	☐	☐	☐	☐	☐	☐
Investeringen in energie efficiëntie maatregelen zijn het overwegen waard als deze rendabel zijn	☐	☐	☐	☐	☐	☐	☐
De voordelen wegen op tegen de nadelen	☐	☐	☐	☐	☐	☐	☐
Windenergie							
Om Vlieland energie onafhankelijk te krijgen zijn windmolens een goede oplossing	☐	☐	☐	☐	☐	☐	☐
50 Kleinschalige windmolens (15 m hoog) zijn visueel hinderlijk	☐	☐	☐	☐	☐	☐	☐
2 Grootschalige windmolens (75 m hoog) zijn visueel hinderlijk	☐	☐	☐	☐	☐	☐	☐
De voordelen wegen op tegen de nadelen	☐	☐	☐	☐	☐	☐	☐

Appendix XXI: public and stakeholder perception questionnaire results (Dutch)

Below the results are shown of the questionnaires on the topics of energy independence and energy efficiency filled in by the public (tables XXI.1 and XXI.2) and major stakeholders (tables XXI.3 and XXI.4). Please note that the total number of respondents is 32 for the public perception part and 11 for the stakeholder perception part. Red indicates scores which oppose a certain technology or option, while green represents positive opinions relative to certain technologies or options.

Table XXI.1 *Public perception: questions on energy independence – results (number of respondents giving a certain score and relative scores; negative = red, positive = green)*

	-3	-2	-1	0	1	2	3	Con	Neutr.	Pro
Vlielanders vinden onafhankelijkheid belangrijk	**0**	0	0	2	7	11	**12**	0%	6%	94%
Vlieland moet energie-onafhankelijk worden	**1**	1	1	8	9	5	**7**	9%	25%	66%
Investeren in duurzame energie is belangrijk	**0**	0	0	1	11	7	**13**	0%	3%	97%
Ik ben bereid te investeren in energie-onafhankelijkheid op Vlieland	**1**	4	2	11	4	4	**6**	22%	34%	44%

Table XXI.2. *Public perception: questions on energy efficiency – results (number of respondents giving a certain score; negative = red, positive = green)*

	-3	-2	-1	0	1	2	3	Con	Neutr.	Pro
Om Vlieland energie-onafhankelijk te krijgen is energie-efficiëntie een goede oplossing	**0**	0	0	3	7	6	**16**	0%	9%	91%
Het is belangrijk om efficiënt met energie om te gaan d.m.v. isolatie, dubbel glas etc	**0**	0	0	1	5	9	**17**	0%	3%	97%
Investeringen in energie-efficiëntemaatregelen zijn het overwegen waard als deze rendabel zijn	**0**	0	0	0	6	13	**13**	0%	0%	100%
De voordelen wegen op tegen de nadelen	**0**	0	0	7	5	8	**12**	0%	22%	78%

Table XXI.3. *Stakeholder perception: questions on energy independence – results (number of respondents giving a certain score and relative scores; negative = red, positive = green)*

	-3	-2	-1	0	1	2	3	Con	Neutr.	Pro
Vlielanders vinden onafhankelijkheid belangrijk	**0**	0	0	1	1	4	**5**	0%	9%	91%
Vlieland moet energie-onafhankelijk worden	**0**	1	0	1	1	4	**4**	9%	9%	82%
Investeren in duurzame energie is belangrijk	**0**	0	1	0	1	3	**6**	9%	0%	91%
Ik ben bereid te investeren in energie-onafhankelijkheid op Vlieland	**0**	2	0	0	3	1	**5**	18%	0%	82%

Table XXI.4. *Stakeholder perception: questions on energy efficiency – results (number of respondents giving a certain score and relative scores; negative = red, positive = green)*

	-3	-2	-1	0	1	2	3	Con	Neutr.	Pro
Om Vlieland energieonafhankelijk te krijgen is energie efficiëntie een goede oplossing	**0**	0	0	0	1	7	**3**	0%	0%	100%
Het is belangrijk om efficiënt met energie om te gaan	**0**	0	0	0	1	4	**6**	0%	0%	100%
Investeringen in energie efficientie maatregelen zijn het overwegen waard als deze rendabel zijn	**0**	0	0	0	1	5	**5**	0%	0%	100%
De voordelen wegen op tegen de voordelen	**0**	1	0	2	0	8	**0**	9%	18%	73%

Appendix XXII Input data and detailed results of the multi-criteria analysis (MCA)

Table XXII.1 shows the input data of the MCA, i.e. the criteria scores of each renewable energy option. Table XXII.2 shows the weigthings of these criteria that were used in this study.

Table XXII.1 *scores of the selected renewable energy alternatives on the MCA criteria (note that these were used as input data and amount of significant numbers was therefore not relevant).*

Criteria	Large wind turbines	Small wind turbines	Solar farm	PV panels on roofs	Solar thermal
Potential BAU (%)*	100	55	1.3	7.2	1.9
Potential HEE (%)*	100	75	1.7	9.9	2.5
Specific costs (euro/TJ_p)	4700	4800	5600	14,600	19500
Public perception (%)	14.84	18.75	6.25	9.38	9.38
Stakeholder perception (%)	25.00	15.91	0	0	0

*The maximum score is 100%, all numbers above will be set to 100; BAU: assuming business as usual; HEE: assuming high energy efficiency

Weight distribution of the techno-economic view was focused on costs and potential. Costs were considered most important; smaller scale but low-cost alternatives can therefore be attractive to use as diversifier of the electricity mix. Furthermore, the public and stakeholder perception were allocated less weight from this point of view.

Table XXII.2 *Three different criteria weightings*

Criteria	Techno-economic	Municipality	Lab Vlieland
Specific costs	45	30	15
Potential	35	30	27
Public perception	10	25	25
Stakeholder perception	10	15	33

Note: for each weighting, 100 points were distributed over the four criteria.

Sensitivity analysis

In tables XXII.3,4 and 5 probability tables are shown with all numbers of all sensitivity analyses per energy trend.

Table XXII.3 *Probability table following from the sensitivity analysis performed in BOSDA for the "business-as-usual" energy demand trend.*

Weight	Alternatives / Position	1	2	3	4	5
Lab Vlieland	Large-scale wind	0	0.02	0.11	0.76	0.12
	Small-scale wind	0	0	0	0.12	0.88
	Solar Farm	1	0	0	0	0
	PV on roofs	0	0.98	0.02	0	0
	Solar heating	0	0	0.88	0.12	0
Municipality	Large-scale wind	0.42	0.54	0.03	0.01	0
	Small-scale wind	0	0.04	0.57	0.37	0.02
	Solar Farm	0.58	0.42	0	0	0
	PV on roofs	0	0	0.4	0.6	0
	Solar heating	0	0	0	0.02	0.98
Techno-economic	Large-scale wind	0.92	0.07	0.01	0	0
	Small-scale wind	0.08	0.66	0.27	0	0
	Solar Farm	0.01	0.27	0.72	0	0
	PV on roofs	0	0	0	1	0
	Solar heating	0	0	0	0	1

Table XXII.4 *Probability table following from the sensitivity analysis performed in BOSDA for the "high efficiency" energy demand trend.*

Weight	Alternatives / Position	1	2	3	4	5
Lab Vlieland	Large-scale wind	0	0	0.14	0.49	0.37
	Small-scale wind	0	0	0.04	0.33	0.63
	Solar Farm	1	0	0	0	0
	PV on roofs	0	0.99	0.01	0	0

	Solar heating	0	0	0.81	0.18	0.01
Municipality	Large-scale wind	0.42	0.44	0.12	0.02	0
	Small-scale wind	0.03	0.12	0.6	0.24	0
	Solar Farm	0.55	0.42	0.03	0	0
	PV on roofs	0	0.01	0.26	0.73	0
	Solar heating	0	0	0	0	1
Techno-economic	Large-scale wind	0.76	0.22	0.02	0	0
	Small-scale wind	0.23	0.68	0.08	0	0
	Solar Farm	0	0.1	0.9	0	0
	PV on roofs	0	0	0	1	0
	Solar heating	0	0	0	0	1

Table XXII.5 *Score and weight uncertainty as input for the uncertainty analysis.*

Criterion	Score uncertainty (%)	Weight uncertainty (%)
Costs	25*	30
Potential	20	10
Public perception	20	15
Stakeholder perception	20	20

*from a lecture by Faaij (2013)

The uncertainty score of potential, public and stakeholder perception were best estimates from our point of view of the uncertainty. For weight uncertainty, the largest differences between the techno-economic weighting and weightings of *Lab Vlieland* and municipality are used as percentage.

Appendix XXIII Steps taken in BOSDA software for MCA analysis

The *format* of the scheme below was based on Jansen & Van Herwijnen (2007).

Step 1: Problem definition

Step 1.1. The 5 technological options from section2.7 were inserted

Step 1.2. The 4 MCA criteria from table 2.4 were inserted

Step 1.3. The scores from tableXXII.1 were inserted

Step 2: Multi Criteria Analysis

Step 2.1. The following standardisations were added in bosda

Criteria	Standardisation
Net specific costs	Maximum
Potential	Maximum
Public perception	Interval
Stakeholder perception	Interval

Step 2.2. The five technological options were standardised with the function of BOSDA

Step 2.3. The three different weightings from table XXII.2 were added

Step 2.4. The weighted summation of the different options were calculated with BOSDA and the results were copied in a separate word document

Step 2.5. The weighted summation of the different options were calculated with all three different weightings and the results were copied in a separate word document

Step 3: Sensitivity analysis for Multi Criteria Analysis

Step 3.1. The uncertainty of the criteria from table XXII.5

Step 3.2. BOSDA was used to calculate different scores with uncertainty of criteria. The results were copied in a separate word document

Step 3.3. BOSDA was used to calculate different scores with uncertainty of different weightings. The results were copied in a separate word document

Appendix XXIV Financial incentives for energy efficiency

Subsidies, investments, loans, and other possible forms of financial stimulation are provided by four levels of government: European, national, provincial, and municipal (see table XXIV.1).

Table XXIV.1 *Overview of funding possibilities for efficiency measures on Vlieland*

institute/organisation – programme	*criteria*	*budget*	*time period*	*type of funding*
European Union				
Horizon 2020	Stimulation of clean, secure and efficient energy	€5931 million	2014-2020	Subsidy
Dutch government				
Nationaal Energiebespaarfonds	Energy savings measures for private house owners	€300 million	-	Loan
Province *(basend on Provincie Friesland, 2014b)*				
Provinces of Groningen, Friesland and Noord-Holland. Waddenfonds (Wadden Sea fund)	Stimulation of sustainable energy transition, Wadden Sea Islands, and Wadden Sea harbours	€560 million	2012-2026	Subsidy
Provinces of Groningen, Drenthe, Friesland & Stimuleringsfonds Volkshuisvesting Nederlandse gemeenten**	Improve energy index with at least 0.75 to at least energy label C	€2.500-15.000 per loan	-	Loan
Province of Friesland Frisian energy premium	For private house owners – energy saving measures	€11.2 million*	-	Subsidy
Province of Friesland	Purchase of electric/hybrid boats	€270.000	-	Subsidy
Province of Friesland	For municipality and companies – installation of electric charging stations boats	€300.000	-	Subsidy
Province of Friesland	For boat rental companies - rebuild rental boats to electric/hybrid boats,	€300.000	-	Subsidy
Province of Friesland	For municipality of Vlieland - set up an energy cooperation	€9808	-	Subsidy

*including €1.4 million for solar heaters; ** includes municipalities