Groningen 2.0 Screening Study

Alternatives to the base case approach of NAM to maintain pressure in the Groningen reservoir by nitrogen injection, with a focus on surface measures

Summary Report prepared by the Steering Committee

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Final Report

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Disclaimer

This report summarises the work performed by a group of experts that investigated alternatives to the base case of injection nitrogen into the Groningen reservoir to maintain reservoir pressure. The reports provided by these experts served as input for this summary report (see appendices), as well as discussions with several experts. The content of this summary is the sole responsibility of the Steering Committee of the Groningen 2.0 Screening Study.

Contents

Attachments to this report

I: Wytze Sloterdijk & Robert Mellema (DNV GL): NAM Groningen 2.0 WP1 Final report, August 2014.

II: Cindy Visser (IVEM/RUG): Final report Groningen 2.0 Pressure maintenance Work package 2, September 2014.

III: Chris Hendriks & Wouter Meindertsma (Ecofys): Groningen 2.0 Energy and Infrastructure Improvement Options for Nitrogen Injection, November 2014.

IV: Harry Croezen & Martijn Blom (CE): Overarching Impact Analysis for the Groningen 2.0 initiative, December 2014.

Beknopte samenvatting

Introductie tot de studie

Aardgaswinning in Groningen veroorzaakt een drukafname in het Groningenveld. Daardoor treedt ondergronds compactie op die geïnduceerde seismische activiteit (of seismiciteit) tot gevolg heeft. NAM neemt momenteel verschillende maatregelen om de seismiciteit en de effecten ervan te verlagen. Een van de mogelijkheden die overwogen wordt om geïnduceerde seismiciteit te verlagen, is drukhandhaving in het Groningen-veld door injectie van stikstof. NAM heeft deze mogelijkheid in 2013 onderzocht via een verkennende studie. Hieruit bleek dat de kosten en het energiegebruik van stikstofinjectie in het Groningen-veld zeer hoog zijn. Daarom rees de vraag bij NAM of er mogelijkheden zijn om deze stikstofcase op een creatieve en innovatieve wijze te benaderen, waarmee een besparing op kosten en op energiegebruik kan worden behaald en waarbij tevens toegevoegde waarde ontstaat voor de regio. Om dit te onderzoeken heeft NAM in oktober 2013 een stuurgroep opgericht die als opdracht kreeg om alternatieve mogelijkheden te identificeren en te verkennen die kunnen leiden tot optimalisering van de aanpak van stikstofinjectie zoals in november 2013 door NAM geschetst. Dit resulteerde in de Groningen 2.0 Screening Study waarover hier wordt gerapporteerd.

Doelstellingen van de studie

De Groningen 2.0 Screening Study onderscheidt de volgende doelstellingen:

- Onderzoeken welke alternatieven er zijn voor het basisscenario waarbij drukhandhaving in het veld wordt gerealiseerd via grootschalige productie, distributie en injectie van stikstof in het Groningen-veld, als ook voor de verwijdering van stikstof uit het geproduceerde aardgas en herinjectie van deze stikstof in het veld om compactie te voorkomen;
- Onderzoeken of deze alternatieven additionele voordelen kunnen bieden voor regionale economische, technische en milieuhygiënische ontwikkelingen en activiteiten, zoals de ontwikkeling van hernieuwbare energiebronnen, het realiseren van een duurzaam energiesysteem en stimulering van nieuwe industriële en economische activiteiten. Randvoorwaarde daarbij is dat het oorspronkelijke doel van het project – drukhandhaving – wordt gerealiseerd.

In het basisscenario voor de productie, distributie en injectie van stikstof en de verwijdering en herinjectie van stikstof uit het gewonnen gas, wordt de benodigde stikstof centraal geproduceerd, bijvoorbeeld in de Eemshaven, via luchtscheiders[1]. De stikstof wordt vervolgens naar 20 tot 25 injectieputten gedistribueerd waar injectie in het Groningen/veld plaatsvindt. Verwijdering van stikstof uit het gewonnen gas[2] vindt in het basisscenario plaats bij twintig reeds bestaande productieclusters. De energiebehoefte voor de stikstofproductie bedraagt bij aanvang 1000-1416 MW (bij winning van 30-42 miljard kuub aardgas per jaar). Voor stikstofverwijdering is maximaal 640 MW aan capaciteit nodig. Investeringen in het basisscenario worden geschat op € 5,7-10 miljard,

[1] Hiervoor worden ASUs ingezet (air separation units) die stikstof uit de lucht halen
[2] Dit gebeurt via NRUs (nitrogen rejection units) die stikstof uit het aardgas halen

operationele kosten bedragen jaarlijks € 740 tot 930 miljoen. De zogenaamde ´lost reserves´ (verlies aan aardgas dat niet meer winbaar is) als gevolg van stikstofinjectie worden in dit scenario geschat op 110 miljard kuub. Het basisscenario levert ook een kostenvoordeel op omdat toekomstige investeringen in drukverhoging ten behoeve van de gaswinning niet meer nodig zijn. De hiermee samenhangende besparingen worden op bijna € 1,8 miljard geschat.

Aanpak van de studie

De stuurgroep heeft ter ondersteuning van haar werk een expertgroep samengesteld die tot taak kreeg studies uit te voeren naar opties en alternatieven voor de oorspronkelijke aanpak die kansrijk zouden kunnen zijn. Het werk was verdeeld in 5 werkpakketten, te weten:

- WP1: Alternatieven voor de conventionele stikstofproductie en stikstofverwijdering uit het gewonnen gas
- WP2: Valorisatie van bij- en restproducten van stikstofproductie en stikstofverwijdering en alternatieve commercialisatie van stikstofrijk aardgas
- WP3: Opties om het energiegebruik voor stikstofproductie en stikstofverwijdering te dekken (incl. energieopslag)
- WP4: Alternatief gebruik van de infrastructuur (netwerken, putten, installaties)
- WP5: Schatting van de milieugevolgen, risicoaspecten, economische gevolgen, energetische gevolgen en wellicht andere impacts van kansrijke alternatieven (doorsnijdend thema voor WP1-4)

Het werk van de stuurgroep richtte zich alleen op de bovengrondse alternatieven voor het basisscenario. Daarbij ging het zowel om opties die op de korte tot middellange termijn inzetbaar kunnen zijn, als om opties die op de lange termijn een ‘game changer’ zouden kunnen zijn. Op basis van de studies en rapporten van de expertgroep, heeft de stuurgroep haar conclusies geformuleerd en in het onderhavige eindrapport verwoord. Er zijn diverse mogelijkheden geïdentificeerd die kunnen leiden tot kostenreductie, tot een betere performance van de oorspronkelijke opzet, tot vergroting van innovatieve mogelijkheden in de regio, tot versterking van bestaande activiteiten in de regio, en tot het leveren van een bijdrage aan economische ontwikkeling van de regio.

Conclusies van de studie

In het algemeen kan worden geconstateerd dat het totale systeem in het basisscenario zodanig hoge investeringen kent en zo groot van omvang is, dat het lastig is om voor alle onderdelen van het systeem verbindingen te leggen met andere (mogelijke) ontwikkelingen in de regio. Er zijn geen alternatieven geïdentificeerd voor de productie van stikstof of de verwijdering van stikstof uit het gewonnen gas die binnen het basisscenario tot een substantiële verlaging van de investeringskosten of de operationele kosten leiden. De enige mogelijkheid waarmee de kosten substantieel verlaagd kunnen worden, is aanpassing van de injectiestrategie en daarmee van de strategie van aardgaswinning. Dit was echter geen onderdeel van deze (bovengrondse) Screening Studie. Wel doet de NAM hier studie naar waarover separaat door haar zal worden gerapporteerd.

Er zijn wel opties gevonden die tot optimalisering van het basisscenario kunnen leiden en die voordelen kunnen opleveren voor de regio. Sommige opties zijn in hoge mate innovatief maar hebben zich nog niet bewezen op de schaal die nodig is in het kader van dit project. Andere opties, waar bijvoorbeeld synergie bereikt kan worden door combinaties te maken met bestaande ontwikkelingen en activiteiten in de regio, lijken kansrijk maar zouden in de praktijk erg complex kunnen worden waardoor er additionele technische en financiële risico's ontstaan. De kosten en milieu-impacts van deze kansrijke opties vallen binnen een 10%-marge van de waarden uit het basisscenario. De onzekerheidsmarges in het basisscenario zijn echter groot (minstens 30%) waardoor het lastig is om hier met de huidige kennis solide conclusies aan te verbinden.

1. Kansrijke alternatieven die verder onderzoek behoeven

Stikstofinjectiestrategie:

- Wanneer wordt besloten om in de beginjaren een kleiner volume aan stikstof te injecteren, vermindert dit de totaal benodigde capaciteit van luchtscheidingsinstallaties (ASU's), evenals het energiegebruik en de milieu-emissies in deze jaren. Een andere optie is om stikstof, geografisch gezien, in specifieke gebieden en clusters van putten in het Groningen-veld te injecteren, bijvoorbeeld beginnend vanuit het Noorden. Een analyse van deze mogelijkheid viel echter buiten de scope van deze Screening Study. De Stuurgroep noemt deze optie echter expliciet omdat daarmee de kosten, het energieverbruik, de milieu-impacts en de 'lost reserves' aanzienlijk zouden kunnen worden verminderd. Echter, er is eerst meer kennis nodig over de impact van dergelijke alternatieve injectiestrategieën op de grootte en het aantal van de bevingen in de regio zodat deze optie op waarde kan worden beoordeeld.

Stikstofproductie:

- Productie van stikstof uit de rookgassen van een elektriciteitscentrale in de regio lijkt een interessant alternatief, zeker wanneer er een combinatie kan worden gemaakt met het afvangen en opslaan van CO_2 als restproduct van het proces voor stikstofafscheiding. Stikstof en CO_2 kunnen op deze manier relatief goedkoop beschikbaar komen. Vanwege het huidige beperkte maatschappelijke draagvlak voor ondergrondse CO_2-opslag op land, ligt offshore opslag voor de hand, bijvoorbeeld in veld Q1 voor de kust van Noord-Holland.
- Stikstofproductie door G-Gas in een speciaal daarvoor aangepaste productie-eenheid te gebruiken kan ook interessant zijn. Deze optie is echter niet uitgebreid bekeken. Er is meer technisch en economisch onderzoek nodig om de potentiële waarde van deze optie te kunnen evalueren.
- Het flexibel produceren van te injecteren stikstof met de luchtscheidingsinstallaties kan interessant zijn, daar het mogelijkheden biedt in te spelen op sterke variaties in de prijs van elektriciteit die via het net wordt geleverd . Daarmee kan een optimale integratie van variabele hernieuwbare energiebronnen in het energiesysteem (m.n. zon- en windvermogen) worden gefaciliteerd. Anderzijds moet worden beseft dat de grote elektriciteitsbehoefte in het

basisscenario juist goede mogelijkheden kan bieden om een economisch aantrekkelijke deal te maken met aanbieders van elektriciteit.

Gebruik van bijproducten:

- Het gebruik van zuurstof, dat vrijkomt bij de productie van stikstof, lijkt een interessante optie, vooral als zuurstof tegen lage kosten beschikbaar zou worden gesteld. Potentieel interessante processen zijn de toepassing van zuurstof in een oxyfuel-elektriciteitscentrale in combinatie met CCS (afvang, transport en opslag van CO_2), het gebruik van zuurstof voor vergassingsprocessen (bijvoorbeeld vergassing van biomassa) voor de productie van synthesegas dat als grondstof voor chemische processen kan dienen of als brandstof. Daarnaast is het gebruik van zuurstof voor afvalwaterbehandeling een mogelijkheid. Deze opties helpen om de economische prestaties en de milieuhygiënische condities van de regio te versterken, nieuwe werkgelegenheid te creëren, bij te dragen aan een schonere inzet van fossiele brandstoffen, en de transitie naar een biobased economy in de regio te ondersteunen.

Stikstofverwijdering:

- Membraantechnologie kan een alternatief zijn voor, dan wel gecombineerd worden met cryogene verwijdering van stikstof uit gas dat wordt gewonnen. Er is echter meer informatie nodig om de technische en economische mogelijkheden van deze optie te kunnen evalueren. Deze informatie is helaas lastig te achterhalen omdat fabrikanten niet erg toeschietelijk zijn om gedetailleerde informatie te verstrekken ten behoeve van haalbaarheidsstudies.
- De benodigde elektriciteit kan lokaal worden geproduceerd via gasmotoren of stoomcycli. Indien goedkope elektriciteit beschikbaar is van variabele bronnen zoals wind en zon, dan kunnen deze vrij eenvoudig (gedeeltelijk) afgeschakeld worden om het benutten van hernieuwbare energie maximaal te faciliteren.
- De installaties die bij de productieputten gebruikt worden om het stikstofrijke aardgas naar G-gas op te werken, kunnen ook ingezet worden om G-Gas naar H-Gas te converteren. Dit kan interessant zijn om flexibel in te kunnen spelen op de behoeften naar H- en G-gas in Nederland en het buitenland.

Gebruik van stikstofrijk aardgas:

- Conversie van H-gas naar G-gas via het mengen van H-gas met stikstofrijk aardgas kan interessant zijn omdat daarmee kosten kunnen worden bespaard op de stikstofverwijdering terwijl Gasunie/GTS lagere operationele kosten hoeft te maken voor de conversie van H- naar G-gas. Op het totaal is deze optie echter van beperkte betekenis omdat de G-gasmarkt in omvang langzaam afneemt. Indicatieve berekeningen geven aan dat NAM in haar basisscenario tot 2031 de totale verwijderingscapaciteit voor stikstof met 1-1,5 miljard kuub per jaar kan beperken.
- Gebruik van stikstofrijk aardgas in de chemische industrie voor bijvoorbeeld ammoniakproductie is ook een optie. De omvang van regionale markten en de economische haalbaarheid verdienen nader onderzoek. Daarbij is onder meer van belang wat de verkoopprijs van het stikstofrijke aardgas zal zijn evenals de mogelijkheid om voor de levering van dit gas langetermijncontracten aan te gaan (t.b.v. investeringszekerheid).
- Het stikstofrijke aardgas kan ook in een special daarvoor toegeruste energiecentrale (eventueel in eigen bedrijf) worden ingezet om stikstof te produceren. Het voordeel hiervan kan zijn dat op

de productie van stikstof kan worden geoptimaliseerd. Marktontwikkelingen, economie en winstgevendheid moeten daarvoor worden geanalyseerd.

- Meer inzicht is nodig in de opbrengsten van het gebruik van stikstofrijk aardgas versus de extra kosten voor infrastructuur en de kosten die gemaakt moeten worden om stikstof te produceren ter compensatie van het drukverlies in het Groningenveld. Als bij omzetting van G-gas naar H-gas met behulp van NRU's stikstof, dankzij inzet van membranen, tegen lagere kosten kan worden afgescheiden dan realiseerbaar is met luchtafscheiders (ASU's), kan dit een interessante optie zijn. Nader onderzoek moet dit uitwijzen. Een optie op termijn is wellicht ook de mogelijkheid om additioneel CO_2 uit elektriciteitscentrales en de industrie te gebruiken om de druk in het Groningenveld te handhaven. Hiervoor zijn maatschappelijke acceptatie en economische haalbaarheid leidend.
- De beschikbaarheid van stikstofrijk aardgas kan nieuwe kansen voor de chemische industrie creëren als dit gas in waardevolle producten en halffabrikaten kan worden omgezet.

Warmte-integratie:

- De integratie van warmtevraag en -aanbod tussen de luchtscheidingsinstallaties, elektriciteitscentrales, de regionale industrie en de tuinbouw is interessant. De technische en economische haalbaarheid hiervan dient nader te worden bepaald. Het regionale Flexiheat-initiatief kijkt reeds naar mogelijkheden van warmte-integratie in de regio; bij dit initiatief zou moeten worden aangesloten. Voordelen voor de regio liggen in lagere energie- en productiekosten voor de industrie en verlaging van de milieu-emissies.

2. Alternatieven die interessant lijken maar waarschijnlijk niet haalbaar zijn

Stikstofproductie via membranen of PSA-technologie is een optie om de productiekosten voor stikstof te verlagen maar het is zeer waarschijnlijk dat deze technieken niet de vereiste (strenge) specificaties kunnen bereiken voor de hoeveelheid zuurstof die bij injectie in het stikstofgas mag zitten (in de ppm-range).

Flexibiliteit bij de stikstofverwijdering kan tot kostenvoordelen leiden. Echter, de capaciteit van de NRU's zal, zeker in de winter, waarschijnlijk volledig benut moeten worden. Meer onderzoek is nodig om vast te kunnen stellen of er mogelijkheden voor een flexibele inzet van NRU's zijn en wat hiervan de voordelen kunnen zijn.

3. Alternatieven die niet haalbaar worden geacht

Een decentrale opzet van de stikstofproductie biedt goede mogelijkheden voor bijvoorbeeld lokale warmte-integratie. Echter, voordelen die samenhangen met schaalgrootte gaan hierdoor verloren. Daarom lijkt deze optie niet interessant.

Transport van stikstof via schepen of pijpleidingen van elders (Tata Steel, Roergebied) wordt niet haalbaar geacht vanwege de enorme stikstofvraag. Het deel dat van elders kan worden aangeleverd vormt maar een klein deel van de totale behoefte waardoor altijd lokale productie op grote schaal noodzakelijk is.

Het gebruik van de (stikstof)infrastructuur voor het transport van biogas lijkt niet haalbaar omdat de infrastructuur voor stikstof pas na 2050 beschikbaar komt, tenzij de injectiestrategie van stikstof zoals beschreven in het basisscenario aanzienlijk wordt aangepast.

Gebruik van het bijproduct helium: De winningskosten van helium uit lucht zijn substantieel. De verwachting is niet dat hier een business case voor te ontwikkelen is, mede gelet op de bestaande wijze waarop mondiaal in de vraag naar helium wordt voorzien.

4. Denkbare opties die nog niet of in onvoldoende mate zijn geanalyseerd

- Het leasen van luchtscheidingsinstallaties die niet langdurig nodig zijn;
- Alternatief gebruik van luchtscheidingsinstallaties wanneer deze niet meer nodig zijn voor de productie van stikstof t.b.v. drukhandhaving in het Groningenveld;
- Winning van vloeibare aardgascomponenten bij de stikstofscheidingsinstallaties (NRU's);
- Co-productie van LNG voor lokale markten bij de NRU's op basis van cryogene technologie (wordt reeds in Polen toegepast);
- Gebruik van gasgeneratoren voor de productie van stikstof uit G-gas.

Executive Summary

Introduction to the study

Induced seismicity in the Groningen field due to compaction of the reservoir, which is caused by a pressure drop in the gas field as a result of natural gas production, has led NAM to take several measures to deal with this problem. One potential measure is pressure maintenance by nitrogen injection into the Groningen field. This option has been investigated by NAM/Shell in 2013 with a first order base case scenario study. Because nitrogen injection is a costly and energy consuming operation, the question arose whether an innovative and creative approach could reduce costs and/or create additional benefits to the region apart from reducing seismicity. Consequently, in October 2013 NAM established a Steering Committee which was asked to investigate, manage and execute such an innovative and creative approach. This resulted in the so-called Groningen 2.0 Screening Study reported here.

Objectives of the study

The Groningen 2.0 Screening Study had the following objectives:

- To investigate what kind of pressure maintenance alternatives exist for the production, distribution, and injection of nitrogen into the Groningen field to prevent compaction of the reservoir (and consecutive reduce the strengths and frequency of tremors and earthquakes), as well as rejection of nitrogen from the natural gas produced, compared to the base case analysis;
- To investigate whether these alternative nitrogen process chains could offer additional benefits to regional economic, technical and environmental developments - such as development of renewable energy sources, realization of a sustainable energy system, and stimulation of new industrial and economic activities in the region - while maintaining the original purpose of keeping the reservoir pressure more or less stable.

In the *'Base case approach of nitrogen production, distribution, injection and rejection'* N_2 is produced at a central location (e.g. Eemshaven) by Air Separation Units (ASUs). N_2 is distributed to a large number (20-25) of injection wells by a dedicated infrastructure to be injected into the Groningen field. Rejection of N_2 from the produced gas is done at twenty existing gas production clusters. Power requirements to produce N_2 would be in the range of 1000-1416 MW (for extracting 30-42 BCM of natural gas per year). Rejection of N_2 would need 640 MW at maximum usage. Capital expenditures in the base case were roughly estimated at € 5.7-10 billion. Operational expenditures would range from roughly € 740 to 930 million per year. Lost natural gas reserves caused by nitrogen injection could be 110 BCM. A cost advantage would be that future investments in pressure maintenance to extract the natural gas in the reference case are no longer needed, saving nearly 1.8 billion Euro.

Approach of the study

To support the work of the Steering Committee a group of experts has been involved to perform screening studies on alternatives and options that appeared to be worthwhile to investigate. The work was divided into 5 work packages:

WP1: Alternatives for the conventional base case of nitrogen production & rejection
WP2: Valorisation of by/waste products of nitrogen production & rejection and alternative commercialisation of nitrogen rich gas
WP3: Covering the energy demand of nitrogen production & rejection (incl. energy storage)
WP4: Alternative use of infrastructure (networks, wells, equipment)
WP5: Environmental, economic, energy, risk and impact assessments: this is a cross-sectional topic which is relevant to all topics listed in WP1-4.

The study described in this report investigated surface alternatives for the base case scenario looking at both short to mid-term solutions and opportunities as well as long-term game changer options. Based on the detailed studies conducted by the group of experts, the Steering Committee defined overall conclusions regarding alternatives to the Groningen 2.0 base case of nitrogen production, injection and rejection. A number of options were identified to reduce costs and improve the performance of the base case approach, to challenge innovations in the region, to strengthen already existing activities in the region, and to contribute to the economic development of the region.

Conclusions of the study

Generally it can be stated that the base case system has such huge investments and is so enormous in size, that it will be difficult to combine in a substantial way all elements of the total project with other (possible) developments and activities in the region.
Options to significantly reduce base case investment and operational costs by applying alternative technologies to produce or reject nitrogen have not been found. The only option to reduce costs substantially can be achieved by changing the injection strategy. However, a detailed study of this option was outside the scope of the screening study reported here but will be presented by NAM in a separate publication.
Nevertheless a number of options were identified to improve the base case approach and enhance benefits for the region. Some of these options are innovative but not yet proven in practice at the scale required in the Groningen 2.0 initiative. Other concepts where synergy can be achieved with existing developments and activities in the region appear promising but may be rather complex inheriting additional technical and financial risks. Cost and environmental impacts of these optimization options are well within a 10% range of base case figures. However, the uncertainty in these calculations is huge (a least 30%) so it is difficult to draw solid conclusions at this stage.

1. Alternatives that appear to be interesting to investigate further

Nitrogen injection strategy:

- Starting with (much) lower nitrogen injection volumes would reduce the required installed capacity of air separation units, and therefore the energy consumption and environmental emissions in the initial phase of the project. Another alternative would be the injection of nitrogen in certain geographical parts of the Groningen field (e.g. starting in the North) or at specific clusters. A detailed look at the advantages and disadvantages of alternative injection strategies was outside the scope of this screening study. Nevertheless the Steering Committee is mentioning this option because indications are that they could reduce cost, energy consumption, environmental impacts and 'lost reserves' considerably. However, first more knowledge is needed about the impact of alternative injection strategies on the size and frequency of tremors and earthquakes in the region.

Nitrogen production:

- Production of part of the nitrogen from flue gases of power plants in the region seems interesting, especially in combination with capturing and storing CO_2 being a by-product of this N_2 production process. Consequently this CO_2 may come available at very low costs. The lack of public support for onshore CO_2 storage necessitates storage offshore, e.g. in field Q1 offshore the Province of North-Holland.
- N_2 production by using G-gas in a dedicated conversion unit may also be interesting. This option has only been touched briefly in this study so a more detailed technical and economic screening would be required to further evaluate this option.
- Flexible N_2 production using ASUs may be feasible to respond to strong variations in electricity prices and it could facilitate the full accommodation of electricity from renewable sources (wind and solar). However, given the high power demand for N_2 production, there is also an opportunity in the base case approach to negotiate a competitive power deal with suppliers.

Using by-products:

- The use of oxygen as by-product from N_2 production using ASUs seems interesting, especially if it could be made available at low cost. Potential processes are the use of oxygen to combust fuel in an oxyfuel power plant in combination with CCS, the use of oxygen in (biomass) gasification processes to produce syngas as a feed stock for chemicals and/or fuels, and the use of oxygen for waste water treatment. Applying these options could enhance the economic and environmental performance of the region, create new employment, contribute to a cleaner fossil fuel use, and support the transition to a bio-based economy in the region.

N_2 rejection:

- Membrane technology may be a competitive alternative to, or combined with, cryogenic N_2 rejection. More information is needed to assess the economics and technical possibilities. Unfortunately this information is difficult to retain because manufacturers are not keen to provide detailed information for feasibility purposes.

- Power for the NRUs could be produced on-site by gas engines or downstream steam cycles. The engines could be shut-down partially when cheap grid-electricity comes available from intermittent sources (wind and solar).
- NRUs can also be used to convert G-gas to H-gas. This option could be interesting to adjust the produced G-gas to developments in H- and G-gas markets in the Netherlands and abroad.

Use of nitrogen-rich methane:

- H to G-gas conversion using N_2-rich G-gas looks interesting as it saves cost for N_2 rejection and Gasunie/GTS has lower cost for H- to G-gas conversion. Timing is important as well as the exact market demand. The overall potential of this option is limited due to decreasing market demand of G-gas. Our study indicates that this option may reduce the need for N_2 rejection with 1 to 1.5 BCM per year until 2031.
- Use of (very) N_2-rich natural gas in the chemical industry for e.g. ammonia production may be an alternative. Regional market developments and economics need to be assessed. Also the final price at which the N_2 methane mixture is to be sold as well as the possibility of long-term contracts (to enable serious investments) are key factors for this option.
- Another option is the use of N_2-rich methane in a dedicated (self-owned) power plant that also produces the nitrogen. Market developments, economics and profitability need to be assessed.
- Detailed studies should show whether gains in revenues exceed extra costs for pipelines and the costs to produce N_2 to compensate for the pressure loss in the Groningen reservoir. Alternatively however, this pressure may also be maintained by injecting cheaper N_2 from NRUs using membranes or N_2 that is obtained from NRUs when they are used to produce H-gas out of G-gas. An additional option to maintain field pressure may become the use of captured CO_2 from power plants and industrial processes when opportune, feasible and acceptable.
- The availability of N_2-rich methane may create new business opportunities in the chemical industry by transforming this gas into valuable products.

Heat integration:

- Heat integration may be interesting, especially between ASUs, power plants, the regional industry, and horticulture. The technical and economic feasibility of heat integration needs to be assessed in relation to the regional Flexiheat Initiative and based on a realistic case to understand the full potential. Benefits for the region are that heat integration may reduce production and energy cost for regional industry and reduce environmental emissions.

2. Alternatives that appear interesting but are probably not feasible

N_2 production by membranes or PSA technology may be interesting to reduce the costs of N_2 production but most probably these technologies cannot meet the oxygen specifications of the N_2 gas.

N_2 rejection flexibility by a more flexible operation of the NRU could save on power cost. However, basically the NRU will be fully utilised (at least during winter). Therefore a more detailed technical and economic assessment would help to determine the possibilities and advantages of flexibility.

3. Alternatives that appear not to be feasible

Decentralised configuration of N_2 production may facilitate the use of local heat integration but opportunities are limited due to lack of scaling benefits (economy of scale).
Transporting N_2 by ship or pipeline from elsewhere (Tata Steel of Ruhr area) is not deemed feasible due to the enormous nitrogen demand. The share of nitrogen that could be delivered from elsewhere would only be a small part of total demand necessitating local production.

Use of (N_2) infrastructure for biogas transport is not feasible because the N_2 pipelines may only come available for biogas after 2050 unless the base case injection strategy would be changed.

Use of the by-product helium: The helium recover costs are substantial. It seems unlikely that further analysis towards selling helium will provide a solid business case.

4. Potential options not yet analysed or not analysed in enough detail

- Short term lease of air separation units;
- Alternative use of ASUs when no longer needed to produce N_2 to be injected in the Groningen reservoir;
- Production of natural gas liquids at cryogenic NRUs;
- Co-production of LNG for local use by cryogenic NRUs (as already applied in e.g. Poland);
- Using gas generators to produce N_2 by combusting G-gas.

1. Introduction to the Groningen 2.0 Screening Study

1.1. Background of the study

Induced seismicity in the Groningen field due to compaction of the reservoir, which is caused by a pressure drop in the gas field as a result of natural gas production, has led NAM to consider taking three types of initiatives to deal with this:

1. Set-up of a more extensive study, data acquisition and monitoring programme for seismic activity and subsidence;
2. Set-up of a programme for preventive strengthening of buildings in the area;
3. *Further studies of measures that could reduce the seismic hazard (frequency and especially magnitude of earthquakes caused by the extraction of natural gas); one of these options could be reservoir pressure maintenance using nitrogen injection into the Groningen field to compensate pressure reduction due to natural gas production.*[3]

The Groningen 2.0 Screening Study is targeted at measure no. 3 only: pressure maintenance using nitrogen injection. The study concentrates on potential alternative N_2 production technologies and surface activities. The impact of N_2 injection on tremors and earthquakes in the region is not part of this study, but is investigated separately by NAM/Shell.[4]

The possibility of nitrogen injection into the Groningen field has been investigated by NAM / Shell in 2013 with a first order ('base case') study. The study is part of the reports delivered to the Ministry of Economic Affairs in November 2013. First indications are that nitrogen injection to mitigate severe tremors and earthquakes can be done but it will be a costly option with high investment costs, energy use, potential surface impacts and lost natural gas reserves. Therefore a question is whether an innovative and creative approach to nitrogen injection could reduce costs and/or create large additional benefits to the region apart from reducing seismicity.

1.2. Objectives of the study

The objectives of the present Groningen 2.0 Screening Study are:

- to investigate what kind of pressure maintenance alternatives exist for the production, distribution, and injection of nitrogen into the Groningen field to prevent compaction of the reservoir (and consecutive reduce the strengths and frequency of tremors and earthquakes), as well as rejection of nitrogen from the natural gas produced, compared to the base case analysis;

[3] The question could be ask whether the Groningen reservoir could be used to store CO_2 – when opportune, feasible and socially acceptable – after the field is not used anymore to extract natural gas and if it is assumed that the pressure of the field is maintained at the present level (about 70 bar) by injecting N_2. The answer is positive but the volume of CO_2 gas that can be stored depends on the compressibility of the reservoir. When it would be save to increase the pressure to for example 100 bar, in total 300-400 BCM CO_2 could be stored. For 150 bar this volume would be 900-1200 BCM CO_2.

[4] By the time of writing this Steering Committee report the sub-surface work by NAM/Shell, executed in parallel, was not yet finished. For the Steering Committee this is a pre-condition in order to assess the true value of interesting alternatives presented and discussed in this report.

- to investigate whether these alternative nitrogen process chains could offer additional benefits to regional economic, technical and environmental developments - such as development of renewable energy sources, realization of a sustainable energy system, and stimulation of new industrial and economic activities in the region - while maintaining the original purpose of keeping the reservoir pressure more or less stable.

The *'Base case of nitrogen production, distribution, injection and rejection'* in this project, as described by NAM in November 2013, can be summarized as follows. Nitrogen is produced at a central location (e.g. Eemshaven) by Air Separation Units (ASUs). The nitrogen is distributed to a large number (20-25) of injection wells by a dedicated infrastructure to be injected into the Groningen field. Rejection of nitrogen from the produced gas is done at the existing gas production clusters – in total twenty. Power requirements to produce N_2 would be 1416 MW when extracting 42 BCM natural gas per year from the Groningen reservoir and 1000 MW when extracting 30 BCM per year. Power requirements for the Nitrogen Rejection Units (NRUs) would be 640 MW at maximum usage. Capital expenditures (CAPEX) in the base case were roughly estimated at 6.5-10 billion euro for 42 BCM natural gas production per year and 5.7-8.5 billion euro for 30 BCM. Operational expenditures (OPEX) would range from roughly 740 to 930 million euro per year.[5] In addition, pressure maintenance by N_2 injection would result in 'lost reserves' of about 110 BCM natural gas.[6] However, the base case of nitrogen injection would also save substantial costs in comparison to the reference case as there would be no need any longer to invest in pressure maintenance to extract the natural gas still available. These saving are estimated at about 1.77 billion Euro.

The study described in this report investigates alternatives for the base case, looking at both short to mid-term solutions and opportunities as well as long-term game changer options.[7] The alternatives investigated were limited to the production and injection of nitrogen. Other potential options, including injection of water, CO_2 or flue gases from a power plant, have been discussed but were not part of the study because of disadvantages or inappropriateness of these technologies in comparison with injecting N_2. Nevertheless it might be that N_2 injection could be combined with an additional approach in a later stage, when opportune, attractive and acceptable.

Within phase 1 of the Groningen 2.0 study, a first screening and assessment of potential options, technologies and approaches was made. The screening may allow a profound selection of alternatives to be investigated in more depth in phase 2 of the study. No decision has been taken yet about phase 2.

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[5] During the course of the Screening Study the base case figures where about 10% reduced because pressure maintenance would require less nitrogen than anticipated originally.

[6] Assuming a highest tolerable N_2 concentration for producing natural gas form the Groningen reservoir of 80% in the base case approach. Depending on the injection strategy the lost reserves might become substantially lower (less than 70% of the bass case lost reserves). A detailed analysis of this issue is however outside the scope of the Screening Study reported here.

[7] In the meantime NAM/Shell investigates alternatives to the original base case of the nitrogen injection and rejection plan. The current report is based on the original set-up as presented by NAM in November 2013.

1.3. Governance of the study

To investigate alternatives to the base case nitrogen chain, to investigate opportunities for local development and to evaluate and report the outcomes, a Steering Committee for the Groningen 2.0 Screening Study was established. The committee was responsible for the management and execution of the study. The members of the Steering Committee are listed in Appendix A.

To support the work of the Steering Committee a group of experts has been involved to perform screening studies on alternatives and options that appeared to be worthwhile to investigate. The experts were selected from the Steering Committee's network and each of the experts was asked to investigate specific topics grouped into a work package (see chapter 2). The Expert Group, listed in Appendix A, reported directly to the Steering Committee.

1.4. Timing of the study

Preparation of the project started in October 2013. The first three months were spent on determining the objectives and scope of the project, the division of the work into work packages and the selection of potential experts to conduct the screening studies. Early February 2014 the project was kicked-off in a meeting of the Steering Committee together with the Expert Group. All work packages and their interrelations were explained and experts gave their view on the work to be done. Project execution started March 1st 2014 and final reports from WP1-4 came available in the period September till December 2014. January 14, 2015 the final draft of the report of the Steering Committee came available. The draft was discussed with NAM on January 19, 2015. Thereafter the report was finalized. More details are provided in Appendix A.

1.5. Contents of this report

Chapter 2 summarises the contents of the work to be done by the Expert Group, divided in five work packages. Chapter 3 presents the main results of the work summarized by the Steering Committee. Chapter 4 gives the conclusions of the Steering Committee.

2. Description of the work

At the start of the project the Steering Committee drafted a list of alternatives to conventional nitrogen production, distribution, injection and rejection as well as potential innovations and spin offs that appeared to be worthwhile to investigate in this study. These alternatives where logically grouped into five work packages (WPs). Selected experts were asked to provide a proposal how to tackle the work to be done within these packages. The experts were also invited to come up with additional views and ideas on the work packages during the course of the study. The (original) content of the work packages is briefly listed in this chapter. In Appendix B of this report a detailed description of all work packages is presented.

WP1: Alternatives for the conventional base case of nitrogen production and rejection

Background: In the preliminary base case, as described in the 'Technical addendum to the Winningsplan Groningen 2013' (here referred to as 'base case nitrogen production'), it is envisaged that nitrogen is produced at a central location and distributed to a number (20-25) of injection wells of the Groningen gas field. Rejection of nitrogen from the produced gas, that may contain varying and gradually increasing concentrations of nitrogen, is assumed to take place at the production clusters (about 20 locations). The capital expenditure (CAPEX) of the base was estimated at 5.7-10 billion euro, the operational expenditures (OPEX) at 740-930 million euro per year. The energy consumption of this option was estimated at 1.0-1.4 GW maximum for production, depending on the maximum amount of gas produced per year, and 0.6 GW maximum for rejection.

Objectives: To assess alternative nitrogen process chains, relative to the base case nitrogen production and rejection, that are cost effective, have lower energy consumption and lower GHG emissions, and may enable integration with specific regional or local processes and developments.

Experts: Wytze Sloterdijk, Martin Hommes (DNV GL)

WP2: Valorisation of by/waste products of nitrogen production & rejection and alternative commercialisation of nitrogen rich gas

Background: During production of nitrogen, several by and waste products become available such as oxygen (expected purity 60-70 percent), chemical components and products (e.g. Argon), and waste heat. These products might be used in new processes or products, or facilitate certain industrial and/or energy developments in the region. From a certain moment after injection of nitrogen into the Groningen field has started, the produced natural gas will contain increasing quantities of nitrogen. In general it may not be possible or attractive to use this mix of nitrogen and natural gas. This problem is solved by rejecting nitrogen. However, the nitrogen rich natural gas might be used in processes that are, for example, less critical to the nitrogen content. It may also be mixed with other products to make it suitable for specific industrial purposes.

Objectives: To assess what kind of by/waste products are produced in different nitrogen production and rejection processes (base case and alternatives), how these by/waste products can be used in other processes, products and markets, and how they could fit in or promote relevant regional developments. Another objective is to investigate what possibilities exist for utilisation of nitrogen rich natural gas in e.g. (new) industrial processes.

Experts: Cindy Visser, Ton Schoot Uiterkamp (RUG/IVEM)

WP3: Covering the energy demand of nitrogen production and rejection (incl. energy storage)

Background: The production and rejection of nitrogen is very energy intensive with associated costs and GHG emissions. One option could be to build a dedicated power plant for these processes. Another option could be to combine the power production for nitrogen production and rejection with power production processes in the region or to use surpluses of renewable energy. Given the increasing need of energy storage in the future, it might also be an option to combine nitrogen production and injection with some kind of energy storage.

Objectives: To investigate what kind of alternatives exist to a conventional power plant to provide the energy necessary for nitrogen production and rejection, how the energy demand could be used to promote sustainable local and regional energy developments, and what opportunities exist to combine these processes with energy storage.

Experts: Chris Hendriks, Wouter Meindertsma, Kornelis Blok, Frank Wiersma (Ecofys)

WP4: Alternative use of infrastructure (networks, wells, equipment)

Background: The energy intensive process of nitrogen production and rejection could offer new possibilities when combined with developments regarding the alternative use of infrastructure, such as wells, gas networks and equipment (e.g. compressors). An interesting option could be the use of wells and gas networks for geothermal activities, or the use of infrastructure for biogases.

Objectives: To investigate what the options are to use the existing and new infrastructure (networks, wells, equipment) for other purposes than nitrogen production and rejection.

Experts: Chris Hendriks, Wouter Meindertsma, Kornelis Blok, Frank Wiersma (Ecofys)

WP5: Environmental, economic, energy, risk and impact assessments: this is a cross-sectional topic relevant to all topics listed in WP1-4

Background: Work packages 1-4 will assess alternatives to the base case, being conventional nitrogen production and rejection. These studies are conducted by different experts from different organisations. Their approaches and calculation methods may differ. In order to be able to judge and compare the environmental and economic performance of alternatives as well as potential risks and impacts, it is necessary to use one common methodology to assess the alternatives that is consistent for all studies.

Objectives: To assess the environmental and economic values and key figures as well as potential impacts and risks of all interesting (surface) alternatives to conventional nitrogen production and rejection, in order to be able to compare all options on the same basis. The assessment should focus on energy, risk, and impact analyses, taking into account mass/material and energy balances, space requirements and impacts, GHG emissions and other environmental impacts (as required when providing an Environmental Impact Statement. The assessment is executed using elements of a LCA approach.

Experts: Harry Croezen, Martijn Blom (CE Delft)

Additional work executed

At the end of phase 1 of the Screening Study, the Steering Committee felt that some issues needed to be investigated in more detail. Ecofys was asked to execute this work, focusing on the following topics:

1. Potential use of oxygen in the Eemshaven and Delfzijl area
2. Membranes as alternatives for cryogenic separation of nitrogen
3. Opportunities to produce ammonia form nitrogen rich natural gas
4. Opportunities to integrate LNG production and distribution in the northern Netherlands

The results of this work have also been reported. They are integrated with the results presented in chapter 3 of this overview.

3. Presentation of the results

Based on the reports prepared by the Expert Group and the discussions between Steering Committee and Expert Group, the Steering Committee has made an overview of the main results and conclusions of phase 1 of the Screening Study. The outcomes are presented in this chapter. They address primarily the initial main question of the study: what are promising alternatives to, or extensions of, the nitrogen injection and rejection base case approach as described by NAM in November 2013. The conclusions are logically divided into the following sections:

- Alternatives for the base case of nitrogen injection strategy (3.1)
- Alternatives for the base case of nitrogen production from air (3.2)
- Alternatives for the base case of cryogenic nitrogen rejection (3.3)
- Alternative supply of energy to nitrogen production and rejection operations (3.4)
- Alternative use of nitrogen rich gas (3.5)
- Use of by-products from cryogenic air separation (3.6)
- Use of waste heat from ASUs (3.7)
- Alternative use of infrastructure (3.8)
- Impact assessment of alternatives (3.9)
- Potentially interesting optimization options not yet investigated (3.10)

In Appendix C of this report the conclusions of each of the WP1-5 and the additional work as they appear in the expert reports are summarized.

3.1. Alternatives for the base case of nitrogen injection strategy

This screening study is based on the original base case scenario of large scale nitrogen production at a central location by ASUs with nitrogen production volume at the start of 37.5 BCM, gradually reducing to 3 BCM in 2048. The nitrogen is distributed to a large number (20-25) of injection wells to be injected into the Groningen field. Rejection of nitrogen from the produced gas is done at twenty existing gas production clusters.

Alternative time dependent injection strategies: Indicative calculations have shown that an injection strategy with lower maximum nitrogen volumes would lead to considerably lower costs and energy consumption. As an example a maximum of 13 BCM N_2 should be injected annually in a flat rate approach instead of 37.5 BCM in the first year in the base case approach. This would result in large savings on production cost because of (much) lower investments in ASUs and longer full utilization of the nitrogen production plant(s). It would also allow a larger share of nitrogen to be produced from flue gases as discussed in 3.2.

The adaptation described here would of course imply a much lower natural gas production and consequently much lower incomes in the first years. In later years this would be compensated, leading to a similar total production of natural gas as in the base case but overall with a different, probably substantial lower, net present value of the generated incomes from the natural gas production. Another consequence would be that opportunities to reduce costs by load management, i.e. buying electricity and operating ASU units at moments of low electricity prices (see 3.4), become less.

Obviously, also intermediate injection strategies can be analysed, like injecting 21 BCM nitrogen at the start down to 8 BCM in the year 2048.

Alternative geographic injection strategies: In the base case approach nitrogen is injected through 20-25 injection wells simultaneously. An alternative might be that nitrogen is injected in certain geographical parts of the Groningen field (e.g. starting in the North and generally moving to the South of the Groningen field) or at specific clusters where compaction of the reservoir is more than in other clusters. Such a strategy would basically lead to lower production volumes of nitrogen to be injected at the start as well as fewer injection wells. This again could reduce cost and energy consumption considerably.

Both options described above, especially the option of a geographically adapted strategy, have not been investigated in detail in this screening study. However, the steering committee feels the need to mention these options because indications are that these alternatives could reduce cost, energy consumption and environmental impacts considerably. It may also reduce the amount of 'lost reserves' caused by nitrogen injection. A crucial issue though is that these option are only worth considering if they meet the original purpose of reducing the strength and frequency of tremors and earthquakes by maintaining pressure in the Groningen field to reduce or prevent further compaction.

3.2. Alternatives for the base case of nitrogen production from air

N_2 production by air separation using other techniques: In the base case, nitrogen is produced by Air Separation Units (ASUs) using cryogenic techniques to separate N_2 from O_2 and other components. The maximum allowed oxygen concentration in the Groningen field is crucial, which is in the ppm range (5-10 ppm). Cryogenic technology appears to be the only feasible nitrogen production technology that meets this requirement. PSA technology has (much) lower production cost for nitrogen but cannot achieve the required low oxygen concentration. Membranes are at present not suitable to produce very high purity nitrogen cost-effectively.

A drawback in the screening study was that manufacturers of membranes are not very keen to share information which meant that the available information is at present too limited for a detailed and proper assessment of the membrane option.

N_2 production from flue gases: Producing nitrogen from flue gases of power plants situated in the region appears interesting, especially when power production from fossil fuels has to be combined with carbon capture and storage in the future. The most promising option is nitrogen production from an RWE type coal-fired power plant, with flue gases having a much lower concentration of oxygen than e.g. a gas-fired power plant like the Magnum plant of Vattenfall (3.8% versus 15.8% oxygen). Applying this option would reduce the need for air separation units to produce nitrogen. Adaption of the base case nitrogen injection strategy is a prerequisite to fully utilize the potential of this option.

To produce nitrogen that can be injected in the Groningen field, both oxygen and CO_2 (and in the case of a coal-fired plant also other components) have to be removed from the flue gases. However, both oxygen removal techniques and removal of carbon dioxide by post-combustion capture techniques are not yet (fully) proven at such a large scale and integrated in power production. The technology for removal of oxygen is in the research phase. For CO_2 removal it is in the demonstrations phase, see the Boundary Dam Project in Canada, with Shell being involved. Nevertheless, first indications show that the costs of nitrogen production from flue gases could be comparable to the nitrogen production costs from air separation units.

The CO_2 emissions associated with the energy consumption to produce nitrogen from flue gases are very low. When separating nitrogen from CO_2 in the flue gases, it would be very interesting to combine this option with CO_2 capture and storage as it would increase the environmental performance of nitrogen production as well as power production substantially. The CO_2 might be stored offshore, in for example reservoir Q1 not far off the Dutch coast near Alkmaar. On the other hand CO_2 compression, transport and storage is still a costly option – the estimated costs are 20 euro per tonne of CO_2 in total - and current ETS-prices for CO_2 (5-6 euro per tonne of CO_2) - are nowhere near the range of a business case. Synergies might be achieved when for example the transportation of CO_2 could be connected to a potential gas extraction project of Tulip Oil. In this project natural gas containing CO_2 would be extracted from a small field at or near Terschelling. If this project would be realized, the CO_2 from the gas needs to be separated, transported and stored in the underground.

Other N_2 supply options: Regarding siting/location: the majority of the necessary nitrogen volumes should be produced in the region on a large scale. Local production seems not very likely due to lack of benefits that economy of scale offers with cryogenic technology as well as the potential local environmental impacts and permitting complexity. Transporting nitrogen from other sources and regions, such as by shipment or pipeline transport from Tata Steel IJmuiden or from the Ruhr area, is most likely not interesting as their contribution to the total amount of nitrogen needed is too small to justify additional pipeline infrastructure or transport to the Groningen region. Delivering all required nitrogen quantities by ship (such as large LNG carriers) seems not feasible as nitrogen quantities are simply too large, causing infrastructure challenges and high demand of LNG carrier capacity which is expensive and probably even not available for nitrogen.

3.3. Alternatives for the base case of cryogenic nitrogen rejection

An important difference with nitrogen production from air is the fact that oxygen is not, or only in very low concentrations, present in the methane nitrogen mixture. Consequently the use of other technologies becomes feasible, such as separation of nitrogen (or methane) by membranes, as oxygen is no longer a barrier.

N_2 separation at NRUs using membranes: An advantage of using membranes is that systems can be constructed modularly which makes it easy to adapt the system to gradually increasing nitrogen concentrations and flow sizes of the natural gas. Membrane separation could replace but also complement cryogenic separation. Compression is a major cost factor when membranes are used, so this is a clear question mark as far as economics are concerned. Currently membrane systems are under development that approach the scale of application required in the Groningen case (1-2 BCM/year). However the feasibility of this option could not be assessed thoroughly in this screening study, due to the fact that quantitative information about membranes is very difficult to obtain. It is believed that membrane systems with a nitrogen reduction up to 60% (e.g. from 70% down to 30%) could be cost competitive with cryogenic processes, but confirmation requires simulation. For a

detailed assessment, however, it is first necessary that more information comes available about selectivity, design, costs and energy use of the membranes.

3.4. Alternative supply of energy to nitrogen production and rejection operations

Alternative energy supply to ASUs: Instead of operating in base load mode, it was assessed whether the flexibility of the nitrogen production (ASUs) and rejection units (NRUs) can be used to actively respond to fluctuating energy prices caused by surpluses and shortages of electricity due to large scale implementation of solar and wind. Thus the Groningen 2.0 project could serve as a facilitator for renewable electricity production. The application of this option may have more potential at ASUs than at NRUs, because it is expected that the NRUs will be fully or near fully utilised when installed due to increasing quantities of nitrogen to be rejected so there is little flexibility when time progresses. Calculations suggest that with flexible use of ASUs considerable savings can be obtained, close to 1 billion euro or more, depending on the level of flexibility of each ASU. However, it should be noted that energy costs are subject to contract and price negotiations, which could already result in substantial energy cost reductions in the base case, reducing the attractiveness of this option.

On site power production at NRUs: Purchasing power for the NRU's from the public grid or from a base load (coal-fired) power plant may not be needed when the power is produced on-site, at each of the gas production clusters, by gas engines and downstream steam cycles. Engine waste heat is utilized for absorption cooling of produced gas, reducing depletion compression power consumption. The engines can be shut down partially in periods with oversupply of renewable power to the public grid and low prices of grid electricity. This would enable an optimum balance between power purchase and on-site power generation.

3.5. Alternative use of nitrogen rich gas

Blending nitrogen-rich gas with high calorific gas: Nitrogen-rich methane could be used for quality conversion of H-Gas to G-Gas (pseudo G-Gas) to comply with (long-term) commercial obligations. This could save on both NRU cost and quality conversion cost of Gasunie/GTS. It is worth considering this option for part of the nitrogen rich gas, enough to fit commercial obligations to deliver G-gas. As this quantity doesn't have to go through the NRUs, saving on (energy) costs can be achieved as well as on H-Gas conversion to G-Gas. On the other hand more production of nitrogen is necessary as less will be recovered at the NRUs. A detailed cost analysis and comparison with alternatives is necessary to determine the real feasibility of this option, especially comparing CAPEX and OPEX cost savings of quality conversion of H to G-Gas and nitrogen rejection at the NRUs versus additional costs for nitrogen production to maintain reservoir pressure.

Using nitrogen-rich gas to produce ammonia and fertilizers: Nitrogen-rich gas could also be used in the chemical industry as a feedstock to produce ammonia and fertilizers. Existing ammonia plants are not suitable to use natural gas with a high N_2 content. For that purpose, a new production facility would have to be built, while knowing that N_2-rich gas will only be available for about 20 years. The gradually increasing nitrogen content will have an impact on reactor size and catalyst requirements, leading to higher investment costs per unit of production. Scientific literature suggests that a nitrogen content of 15-30% is most effective to produce NH_4. At higher concentration, N_2 should be removed. The WP4 study suggests that, for a plant of 2,000-3,000 ton per day output and N_2 concentration of 70%, the costs for nitrogen-rich natural gas may not exceed 6 €/GJ to be competitive with a standard ammonia plants using natural gas at a cost of 8 €/GJ. Therefore the question is whether this option is economically feasible. Moreover, given the large quantities of nitrogen rich gas involved, only part of the produced gas can be used in this way. More important, however, it should be noted that nitrogen is taken away and therefore not available for re-injection in the Groningen reservoir. Consequently new nitrogen production for injection into the Groningen field to maintain its pressure is necessary leading to increased costs. It is therefore doubtful whether there are perspectives for developing this option.

Using 'lost reserves' as a fuel: At a certain moment, the nitrogen concentration in the produced gas will become too high (80% assumed in the base case). Production will be ceased as it is not economical anymore to reject the nitrogen. A question is whether these 'lost reserves' can still be used for dedicated purposes, such as fuel for a power plant. A potential candidate could be the RWE coal-fired power plant, although it probably requires some modifications of the power plant. Another potential candidate is the natural gas fired Magnum plant of Vattenfall. However, it is quite uncertain whether this fuel can be used in a NGCC as it may require too costly modifications of the gas turbine system.[8] In the future, maybe another option could become the use of this gas in a fuel cell system (a PEM cell or high temperature fuel cell system) or in different combined heat and power (CHP) systems.

To have the supply of this gas gradually available and not all at once, the injection strategy as applied in the base case needs to be adapted. Injection should start at one end of the Groningen field and gradually move to another part (see also 3.1). An additional benefit would be that it requires less NRUs. Detailed study is necessary to assess the technical, social and economic feasibility of this strategy as it may influence the pressure maintenance objectives. Also it requires amongst others additional infrastructure (so investments).

As discussed before, this option also influences the energy costs of the Groningen 2.0 initiative, because new nitrogen (or another appropriate gas) must come available to maintain the pressure in the Groningen reservoir. However, the cost involved might be acceptable when nitrogen could be obtained from NRUs using membranes. Besides, it might become an option in the future to use (in addition) captured CO_2 from a power plant instead of N_2 from an ASU or an NRU.

3.6. Use of by-products from cryogenic air separation

Feasible by-products from cryogenic air separation that can be valorised elsewhere could be oxygen and perhaps helium. All other products either lead to market distortion (due to the large quantities involved compared with the current European or world market which could reduce price levels very significantly) or are very small with limited opportunities (e.g. due to complex processes).

Oxygen production and demand: A main by-product of the air separation units is oxygen. For each BCM of nitrogen, approximately 0.25 BCM of oxygen is produced. In the base case 37.5 BCM nitrogen is produced in the first year with co-produced oxygen of about 9 BCM. In 2040 these figures are close to 5 and 1 BCM respectively. The current market size of oxygen is 2.8 BCM/year in the Netherlands and 70 BCM/year globally. The co-produced oxygen could be used in combustion processes,

[8] At the time of writing this report the steering committee is awaiting more detailed technical information regarding the suitability of specific power plants for nitrogen-rich natural gas.

gasification processes, metallurgy, production of chemicals, wastewater treatment, and medicine. The market for oxygen in Groningen is small and the demand in the current chemical industry is low. There is potential use of oxygen for dispersed waste water treatment of about 6 MCM per year in Groningen and about 2 BCM per year in the Netherlands in total. Low-cost oxygen may create better economic conditions for new oxygen demanding industries in Groningen. But the economic feasibility of these industries will of course also depend on many other conditions. Large demands for oxygen exist in the steelmaking industry. It could be worthwhile to investigate transportation of oxygen from Groningen to locations where its use is possible (e.g. IJmuiden and Ruhr area).

Oxyfuel combustion: A potential large market is the use of oxygen in oxyfuel combustion. Oxyfuel combustion would allow capturing CO_2 from power plants rather easily, as demonstrated in three projects abroad. At present focus is on coal-fired power plants. Oxyfuel combustion typically reduces the conversion efficiency of the plant by 8 to 10 percent points. When oxygen is delivered 'for free' the plant efficiency drop is substantially less: 2 to 4%. When for free, the costs to avoid CO_2 emissions can be estimated at about 20 euro per ton CO_2. A potential candidate for oxyfuel combustion is the new RWE coal-fired power plant located in Eemshaven. When the whole plant would be converted to an oxyfuel plant, about 6.5 to 7 BCM of oxygen per year is needed which can be obtained with ASUs when producing 25-27 BCM nitrogen per year. The RWE plant consists of two units. It might be an option to convert only one unit to oxyfuel combustion (equivalent to 13 BCM nitrogen production per year by ASUs). When focussing on the RWE plant, it needs to be evaluated what the most promising option is: nitrogen production from the flue gases of the power plant combined with CCS, oxyfuel combustion using co-produced oxygen from ASUs, or a combination of these two (one for each of the two units of the RWE plant).

Oxygen based gasification: Availability of oxygen could fit very well with regional ambitions to make a transition to a bio-based economy. Oxygen could then be used for oxygen based biomass gasification thus reducing cost (as oxygen is usually very expensive) and adding benefits to the gasification process especially with respect to the output (syngas or SNG). There are some plans to install one or more gasifiers in Eemshaven. NAM could consider offering oxygen at a competitive price thus promoting this regional development. A very large gasifier of 200 MW would need about 0.2 BCM oxygen per year. Oxygen may also be used in a potential future (biomass) gasification process connected to the Magnum power plant.

Helium: Helium could be an interesting by-product in principal. When producing 37.5 BCM nitrogen using ASUs 250 thousand cubic meter of helium could come available, equivalent to roughly 0.1% of the global market (0.2 BCM a year). The market size of helium in the Netherlands is unknown. In 2012 the market value of helium was 3.37 euro per cubic meter. Currently helium is produced from natural gas fields some of which have a high helium density (up to 7%). It comes available by natural gas processing or when producing LNG. It seems not likely that helium separation from air using cryogenic ASUs can compete with helium separation from specific natural gas fields.

3.7. Use of waste heat from ASUs

In the base case, the air separation units would consume up to 1,400 MW_e of power. This power is mainly used to compress air to separate nitrogen from oxygen through a phase change, and to compress the nitrogen to 130 bars to feed it into the nitrogen distribution network. During the separation process, the air is cooled down to about minus 185 degrees Celsius. After separation, the gases need to be reheated to ambient temperatures. The heat flows in the ASUs are highly integrated to minimize energy loss. Theoretically, however, part of the generated heat and cold can be used outside the ASUs leading to energy savings. How large the benefits are and how this would affect the performance of the ASUs could not be determined in depth within the scope of this screening study so it needs further investigation.

Waste heat supply to the region: Using waste heat of the ASUs, investigated synergies might be achieved with heat distribution networks envisioned by the *Werkgroep Versterking Chemiecluster Eemsdelta (March 2014)*. The operation of the air separation units could potentially yield low-temperature waste heat of up to about 110 degrees Celsius. First order calculations indicate that about 150 to 300 MW_{th} of heat could come available.

Waste heat supply to power plants: A main use for the waste heat of ASUs could be (pre)heating of boiler feed water of the power plants close to the air separation units in the Eemshaven. Using waste heat instead of low-pressure steam from the power plant's steam cycles will increase plant efficiency. The estimated demand is in the order of 150 MW_{th} (120 MW_{th} RWE and 30 MW_{th} Magnum) which matches the expected availability.

Waste heat supply to other industries: Other potential use of waste heat is at the industrial site of Delfzijl where the potential demand for low-temperature heat in large industrial plants is estimated at 40 MW_{th}. The presence of waste heat may stimulate industries with high demand for low temperature heat to settle in the area, e.g. horticulture. Currently, within the Flexiheat Initiative (2012-2016) initiated by a number of research centres in the region, an assessment is made of infrastructure to exchange heat between industries. Further studies on the potential use of waste heat from ASUs should be related to this initiative.

3.8. Alternative use of infrastructure

In the Screening Study two options have been assessed for alternative use of infrastructure: 1) the use of nitrogen injection wells combined with exploitation of geothermal energy, and 2) later use of the nitrogen pipeline network for biogas collection and transport. No options were detected to combine the Groningen 2.0 initiative with a meaningful approach to store surplus energy from technologies using intermittent renewable sources (wind and solar).

Using injection wells to exploit geothermal energy: For the injection of nitrogen in the base case, approximately 23 additional wells are needed. By changing the diameter these wells could be used at the same time as geothermal wells. The only feasible geological formation to extract geothermal energy is the Bunter sandstone layer above the Groningen field. A first estimate suggests that such a well could have a capacity of 5 to 6 MW_{th} a year for water with a temperature of about 65 °C. The demand for low-temperature heat in Groningen – not too far from the wells – is mainly from residential areas (100-150 MW_{th} a year) and horticulture (at present about 16 MW_{th} a year). In principle there is sufficient geothermal energy available to cover the heat demand in the area but the technology of combining injection and geothermal wells needs to be tested. Whether it will be economically attractive depends very much on the local situation. Further study is needed to investigate this. Important factors to make this alternative attractive are availability of a heat infrastructure and distance from well to demand. When this option is further investigated it should be related to studies investigating in more depth the potential use of waste heat from ASUs. Also it should be related to the Flexiheat Initiative mentioned earlier.

Further use of nitrogen pipeline for biogas collection and transport: When pipes of the nitrogen transportation network are not in use anymore they might be used to transport biogas from local producers to a central collection location where the biogas gas can be upgraded (by removal of CO_2) and, for instance, be injected into the medium pressure (40 bar) natural gas pipeline system. This approach will save costs and improve the use of the biogas when compared with decentralized upgrading and use. The potential supply of biogas in the region is estimated to be in the order of 0.1 to 0.3 BCM per year in 2030. This is very limited compared with present natural gas supplies. Therefore pipeline capacity will be more than sufficient to handle this amount. In the base case it is not expected that pipelines are available before 2040-2050 so this potential use will not have a large effect on the economics of nitrogen injection (as the net present value of future incomes is very low). Moreover in 2040-2050 a targeted biogas infrastructure may already exist. It should be noted that this situation may change when the base case injection strategy of nitrogen is changed.
The idea of collecting biogas through a centralized pipeline is not new. A consortium (BioNoF) with industrial parties and governmental bodies, including Gasunie and the province of Friesland, is evaluating the possibility to construct a 32 km biogas pipeline in the North of Friesland, from Dokkum to Stiens or Leeuwarden. In addition pipelines from the producers to the biogas pipeline with a total length of 40 km need to be constructed. The capacity of the biogas pipeline will be 10,000 cubic meter per hour (about 85 MCM/year). The initiative started in 2009. Without government subsidies the project is not feasible.

3.9. Impact assessment of alternatives

The impact assessment of WP5 (executed by CE Delft) focussed on five alternatives:

1. The base case nitrogen production, injection and rejection as originally proposed by NAM;
2. Partial production of nitrogen from flue gases of a coal-fired power plant (like the RWE plant) by catalytic removal of oxygen and the use of MEA (*Econamine Plus*) to remove CO_2 (excluding costs for CO_2 compression, transport and storage);
3. Production of nitrogen from flue gases of a coal-fired power plant like the RWE plant by catalytic removal of oxygen and the use a physical absorbent (*Selexol*) for flue gas treatment (excluding costs for CO_2 compression, transport and storage);
4. Supply of waste heat from the ASUs to a coal-fired power station like the RWE plant (used for preheating boiler feed water) combined with partial production of N_2 from the flue gases using MEA (see alternative 2);
5. On-site generation of power for the NRUs and the existing clusters for gas treatment and depletion compression, using gas engines and downstream steam cycles. Engine waste heat is utilized for absorption cooling of produced gas reducing power consumption for depletion compression. Power is produced from natural gas delivered by the NRU in periods of high power prices whereas electricity from the grid is used during low power prices;
6. Supply of oxygen from the ASUs to a gasification plant (e.g. Magnum Power Plant in Eemshaven) to save on oxygen production cost.

Appendix C contains a table illustrating the results of all alternatives assessed by CE Delft.

Compared with the entire Groningen 2.0 project the costs of various alternatives are clearly small due to the high total investments in N_2 infrastructure, ASUs and NRUs of the base case. It should also be noted that the Groningen 2.0 initiative is in a very preliminary stage with a lot of general first order assumptions being made leading to many uncertainties as far as costs, emissions and impacts are concerned. Therefore the results from the assessment of CE Delft should be interpreted with great care. The uncertainty in the costs calculations, made in the assessment, is estimated at 30% and it can even be questioned whether all certainties are within this range.

- Main indicative results are: Investment costs of the base case are estimated at 8.36 B€. Investments of the 5 alternatives range from 8.33 B€ (with nitrogen from flue gases using Selexol) to 8.88 B€ (with on-site power production at the NRU's). These cost results are all within a 10% range of the base case.
- Aggregated annual economic cost (net present value) are the highest for the case with nitrogen production from flue gases using MEA (15.34 B€) compared to 14.35 B€ for the base case. Lowest aggregated annual economic cost are found for the alternative with on-site power production (14.02 B€).
- Aggregated environmental cost (net present value) are 2.29 B€ for the base case. Lowest environmental cost are found for the case with on-site power production (1.85 B€) and the highest cost (2.29 B€) for the case with nitrogen production using MEA.
- Aggregated energy consumption for the base case is 0.87 EJ. The lowest energy consumption is found for the case with oxygen use (0.84 EJ), the highest for the case with nitrogen production using MEA (0.90 EJ).
- Overall CO_2 emissions are 126 Mtonnes for the base case. Lowest CO_2 emissions are found for the case with on-site power production (105 Mtonnes CO_2), the highest for the case with nitrogen production using MEA (131 Mtonnes CO_2).
- Overall NO_x emissions are 34 ktonnes for the base case. Lowest NO_x emissions are found for the case with oxygen use (33 ktonnes NO_x), the highest for the case with on-site power generation (42 ktonnes NO_x).

3.10. Potentially interesting optimization options not yet investigated

During the course of the Screening Study several other potential optimization options were identified that may yield benefits compared with the base case. However, within this first phase of the Groningen 2.0 study a (detailed) screening of these options was not feasible. The identified options are presented below.

Local LNG production and distribution: LNG is being introduced by a consortium of parties in the North of the Netherlands as a future fuel for trains, trucks and ships. In their approach, the LNG is imported from the Rotterdam Gate Terminal. The NRUs proposed in the base case can be redesigned to produce (also) LNG. Issues to be addressed are the reduction of the N_2 content of the gas and the need to maintain the LNG at a low temperature. Detailed engineering is needed to assess the feasibility of a further development of this idea. Production of LNG at cryogenic NRUs is already carried out at e.g. the KRIO Nitrogen Rejection Plant in Odolanów, Poland

Lease constructions: Short-term lease of air separation units might be an option worthwhile to investigate in order to reduce costs.

Alternative later use of ASUs: After termination air separation units might be used to produce oxygen instead of nitrogen for specific purposes in the region. The ASUs could also be used for N_2-EGR (Enhanced Gas Recovery) if the De Wijk project is successful and will be followed by other similar projects. This is an option if ASUs (or ASU capacity) becomes available in the next 10 to 15 years as a result of reduced natural gas production from the Groningen reservoir and reduced N_2 demand.

Production of NGLs: Production of natural gas liquids (NGLs) at cryogenic NRUs, especially propane and butane, could be an interesting option. The LPG-fraction can be sold at a higher market value and may be utilized as a feedstock for steam cracking. Cheap ethane could also be produced as a liquid by-product at the NRUs (0.2-1.4 Mton/year) and delivered by ship to steam crackers in for example Geleen, Moerdijk and Terneuzen, enhancing their competitiveness.

Using gas generators to produce nitrogen: A potentially interesting option is to combust (nitrogen-rich) G-gas in gas generators to produce nitrogen. As G-gas already contains 14% nitrogen and air is used in the combustion, it may make sense to capture the nitrogen from the flue gas. Although the idea is congruent to obtaining nitrogen from flue gases of a power plant, the difference is that in power plants the main product is electricity with nitrogen from the flue gases as a by-product. When applying gas generators, it would be the other way around. This change may allow a different and cheaper system to separate and capture the nitrogen from the flue gases.

Using NRUs to convert G-gas to H-gas: NRUs can be used to convert G-gas to H-gas. This would reduce the need for N_2 production by ASUs and increase the flexibility of Dutch gas markets (which are in transition towards H-Gas). This approach could therefore add value to the production of G-gas. However it is uncertain what the additional costs of removing N_2 are compared to the price difference between H-gas and G-gas.

4. Conclusions

In this chapter overall conclusions of the Steering Committee are presented regarding alternatives to the Groningen 2.0 base case of nitrogen production, injection and rejection. It should be noted that some of the alternatives discussed here are innovative and have not yet been proven in practice at the scale required in the Groningen 2.0 project. These alternatives are often more complex than the suggested base case solutions due to the fact that different systems and/or technologies are combined to provide a solution. Although specific combined concepts appear promising, the fact that the complexity increases may inherit additional technical and financial risks that companies are not willing to accept in reality. The conclusions described in this chapter do not explicitly take this consideration into account.

Generally it can be stated that the base case system has such huge investments and is so enormous in size, that it will be difficult to combine in a substantial way all components of the project with other (possible) developments and activities in the region. Options to significantly reduce base case investment and operational costs by applying alternative technologies to produce or reject nitrogen have not been found. The only option to reduce costs substantially can be achieved by changing the injection strategy, for example from the dispersed approach presented by NAM in the base case approach to a North-South sweep approach. However, an investigation of the pros and cons of alternative nitrogen injection strategies was outside the scope of the Groningen 2.0 Screening Study reported here.

Nevertheless, a number of options were identified to reduce costs and improve the performance of the base case approach, to challenge innovations in the region, to strengthen already existing activities in the region, and to contribute to the economic development of the region.
Some of the most interesting options were selected for a more detailed assessment focusing on costs and environmental performance. The calculations show that the investment costs and the investigated environmental impacts are well within a 10% range of the base case figures. Looking at the economics this could mean an increase or decrease of the total costs up to hundreds of millions to more than a billion euro. However, the uncertainty in these calculations is huge, estimated at 30% and maybe even more. Consequently, it is difficult to draw solid conclusions based on these calculations at this stage.

4.1. Alternatives that appear to be interesting to investigate further

The following alternative options seem to have medium to high potential to optimize the Groningen 2.0 initiative and deserve further assessment in order to determine their value as well as their benefits for the region when developing a Groningen 2.0 implementation plan. It is also indicated which follow-up actions are advised.

Nitrogen injection strategy:

- Indicative calculations have shown that an injection strategy with lower maximum nitrogen volumes could lead to considerably lower costs and energy consumption. For example, starting with (much) lower injection volumes would (strongly) reduce the required installed capacity of the air separation units. Another alternative would be the injection of nitrogen in certain geographical parts of the Groningen field (e.g. starting in the North) or at specific clusters.

However, starting with a lower injection rate while maintaining field pressure will reduce the production of natural gas in the first years of the project. It should be noted that both options mentioned have not been investigated in detail in this screening study. Nevertheless the Steering Committee feels the need to mention these options because indications are that they could reduce cost, energy consumption and environmental impacts considerably. It may also reduce the amount of 'lost reserves' caused by nitrogen injection. However these options are only worth considering if they meet the original purpose of reducing the strengths and frequency of tremors and earthquakes due to the extraction of natural gas in the coming years.

Nitrogen production:

- Production of nitrogen from flue gases of power plants (and possibly from industry) seems interesting, especially in combination with CO_2 capture because CO_2 is a by-product of this nitrogen production process so it may come available at very low costs. The lack of public support for on-shore CO_2 storage necessitates off-shore storage.[9] A benefit for the region would be that off-shore storage of the by-product CO_2 would help to start off CCS seriously to reduce CO_2 emissions from human activities.

- Flexible nitrogen production using ASUs may be feasible to respond to strong variations in electricity prices. A more flexible power demand will help facilitate the full accommodation of electricity from renewable sources (wind and solar). However, given the high power demand for nitrogen production, there is good potential in the base case approach to negotiate a competitive power deal with suppliers. A more detailed technical and economic assessment based on real cases is necessary to understand how realistic the indicated alternative nitrogen production strategy could be. Commercial information about power purchase is confidential so this alternative should be assessed within Shell/NAM.

- Nitrogen production by using G-gas in a dedicated conversion unit may be interesting because oxygen removal may not be necessary anymore. This option has only been touched briefly in this study so a more detailed technical and economic screening is necessary.

Using by-products:

- Another option is the use of by-products from nitrogen production using ASUs. Only the use of oxygen seems promising. The separated oxygen could be made available at relatively low costs. The oxygen could be used for different processes such as the combustion of fuel in an oxyfuel power plant in combination with CCS. Another promising option is the use of oxygen in (biomass) gasification processes to produce for example syngas as a chemical feed stock or a fuel. Some oxygen may also be used in other applications, especially waste water treatment. Applying these options could help to enhance the environmental performance of the region. It would also contribute to a cleaner fossil fuel use. Moreover it could support the transition to a bio-based

[9] It may be interesting to combine such a CCS project with other CO_2 transport and storage needs, such as transport and storage of CO_2 as part of a potential Tulip Oil project at Terschelling.

economy in the region by applying biomass gasification technologies stimulated by the availability of oxygen in large quantities at relatively low prices.

Nitrogen rejection:

- Membrane technology may be a competitive alternative to, or combined with, cryogenic nitrogen rejection. More information is needed to be able to assess the economics and technical issues of appropriate membranes and membrane systems. This information is difficult to retain because manufacturers are not very keen to provide detailed information for feasibility purposes.

- Purchasing power for the NRUs and the production sites from the public grid may not be needed when the power is produced on-site, by gas engines or downstream steam cycles. The engines could be shut-down partially when cheap grid-electricity comes available from intermittent sources (wind and solar).

- NRUs can also be used to convert G-gas to H-gas. This option could be interesting to adjust the produced G-gas to developments in H- and G-gas markets in the Netherlands and abroad.

Use of nitrogen-rich methane:

- H to G-gas conversion using nitrogen-rich G-gas looks interesting as it saves cost on two sides: less nitrogen rejection is needed and Gasunie/GTS has lower cost for H- to G-gas conversion. Timing is an important issue here as well as determining the exact market demand. The overall potential of this option is limited due to decreasing market demand of G-gas. However, till at least 2031 it may reduce the need for N_2 rejection with 1 to 1.5 BCM per year in comparison with the base case.

- Use of (very) nitrogen-rich natural gas in the chemical industry for e.g. ammonia production may also be an interesting alternative. Regional market developments and economics need to be assessed to assure that this demand will exist in practice. Also the final price at which the nitrogen methane mixture is to be sold as well as the possibility of long-term contracts (to enable serious investments) are key factors for this option.

- Another option is the use of nitrogen-rich methane in a dedicated (self-owned) power plant that also produces the nitrogen. Market developments, economics and profitability need to be assessed.

- Detailed studies should show whether gains in revenues exceed extra costs for pipelines and the costs to produce nitrogen to compensate for the pressure loss in the Groningen reservoir. Alternatively however, this pressure may also be maintained by injecting cheaper N_2 from NRUs using membranes or N_2 that is obtained from NRUs when they are used to produce H-gas out of

G-gas. An additional option to maintain field pressure maybe to use captured CO_2 when opportune, feasible and acceptable.

- For the region additional benefits of the use of nitrogen-rich methane are that new business opportunities may arise in the chemical industry to transform nitrogen-rich methane into valuable products.

Heat integration:

- There are interesting combinations possible regarding heat integration between especially the ASUs, power plants, the regional industry, and horticulture. The technical and economic feasibility of heat integration needs to be assessed in relation to the regional Flexiheat Initiative and based on a realistic case to understand the full potential. The benefits for the region are that heat integration may reduce production and energy cost for regional industry. It would help to become more cost competitive and of course to reduce environmental emissions.

4.2. Alternatives that appear interesting but are probably not feasible

Options that have a reasonable potential but are probably not feasible as an alternative to the Groningen 2.0 base case approach are listed below.

- *Membrane or PSA nitrogen production:* Membrane and PSA technology may be interesting alternatives to reduce the costs of nitrogen production but most probably these technologies can't meet the oxygen specifications of the nitrogen gas. There is, however, some uncertainty about what the exact oxygen specifications are. Therefore it may be worthwhile to investigate and define these specifications more exactly before definitely ruling out these technologies.

- *Nitrogen rejection flexibility:* It may be interesting to investigate the possibility of a more flexible operation of the NRU which could save on power cost. Basically the NRU will be fully utilised (at least during the winter season) but a more detailed technical and economic assessment helps to determine the possibilities and advantages of flexibility.

4.3. Alternatives that appear not to be feasible

Some of the options that have been assessed appear not to be feasible when compared with the base case approach. These options are:

- *Decentralised configuration of nitrogen production:* This option may facilitate the use of local heat integration but opportunities are very limited (no large local heat demand, only for housing and SMEs). The main showstopper is the fact that there are no scaling benefits (economy of scale). A decentralised set-up appears to be much more expensive with no real benefits.

- *Transporting nitrogen by ship or pipeline from elsewhere (Tata Steel of Ruhr area):* The nitrogen demand is on such a large scale that the share of nitrogen that could be delivered from elsewhere is only a small part of total demand, implying that production in the region is always necessary. The small share of nitrogen that could come from elsewhere can easily be covered by regional production at much lower cost.

- *Use of (nitrogen) infrastructure for biogas:* The main issues is the timing effect because the nitrogen pipelines may only come available for biogas after 2050 unless the base case injection would be changed taking note of this option. The injection of biogas in the nitrogen-rich methane is not an option as both nitrogen and CO_2 in the biogas lower the Wobbe index meaning that the gas mixture becomes more off-spec.

- *Use of the by-product helium:* The helium recovery costs are substantial. It seems unlikely that further studies towards selling helium will result in a positive outlook on a solid business case.

4.4. Potential options not yet analysed or not analysed in enough detail

Some potential optimization options were identified during the course of the study but were not yet evaluated in such detail that the full potential becomes clear, for example because it would require detailed engineering or financial analyses. It might be interested to make an assessment of these options:

- *Short term lease of air separation units;*
- *Alternative use of ASUs when no longer needed to produce nitrogen;*
- *Production of natural gas liquids at cryogenic NRUs;*
- *Co-production of LNG for local use by cryogenic NRUs (as already applied in e.g. Poland);*
- *Using gas generators to produce N2 by combusting G-gas (as already mentioned in 4.1).*

List of appendices:

A: Governance and organization

B: Detailed description of the work packages

C: Summary of all expert reports

Attachments to this report

I: Wytze Sloterdijk & Robert Mellema (DNV GL): NAM Groningen 2.0 WP1 Final report, August 2014.

II: Cindy Visser (IVEM/RUG): Final report Groningen 2.0 Pressure maintenance Work package 2, September 2014.

III: Chris Hendriks & Wouter Meindertsma (Ecofys): Groningen 2.0 Energy and Infrastructure Improvement Options for Nitrogen Injection, November 2014.

IV: Harry Croezen & Martijn Blom (CE): Overarching Impact Analysis for the Groningen 2.0 initiative, December 2014.

Appendix A: Governance and organization

The Steering Committee consisted of the following members:

- Prof. Wim Turkenburg, chairman of the Steering Committee
- Margriet Kuijper (NAM), project owner
- Frank Geuzenbroek (Shell), until Jan 2014
- Rob Moene (Shell), technology opportunity manager CO2 abatement (joined Jan 2014)
- Jan van Elk (NAM), subsurface expert
- Bart Jan Hoevers (Gasunie GTS), infrastructure expert (joined April 2014)
- Jörg Gigler (Gigler Energy Support), secretary of the Steering Committee / manager of the Groningen 2.0 study

To support the work of the Steering Committee, a group of experts was asked to perform screening studies on alternatives to the base case of nitrogen injection that appeared to be worthwhile to investigate. The Expert Group reported directly to the Steering Committee. All investigative work was performed by or under the responsibility of these experts. The Expert Group consisted of the following members (these persons were most frequently involved and participated in meetings, several other experts where consulted by these representatives):

- WP1: Wytze Sloterdijk & Martin Hommes, DNV GL
- WP2: Cindy Visser & Ton Schoot Uiterkamp, RUG/IVEM
- WP3&4: Chris Hendriks, Wouter Meindertsma & Kornelis Blok, Ecofys
- WP5: Harry Croezen & Martijn Blom, CE Delft

Preparation of the project started in October 2013. In the first three months the objectives and scope of the project, the division of the work into logical work packages and the selection of potential experts to conduct the screening studies were determined. The Steering Committee met about one to two times per month to discuss contents, progress and planning (apart from the summer period).

In February 2014 the project was kicked-off in a meeting of the Steering Committee together with the Expert Group. All work packages and their interrelations were explained and experts gave their view on the work. Project execution started March 1st 2014 and in July draft reports from WP1-4 were available. The reports were finalized in the period September-December 2014. WP5, which needed the results of the other work packages WP1-4 for their analysis, delivered a first draft in September 2014 and a final draft at the end of December 2014.

Early January 2015 the Steering Committee delivered their final draft report which was sent for comments to all experts, all members of the Steering Committee and several NAM/Shell persons who are involved in the Groningen 2.0 Project. On January 19, 2015 the final draft report was presented by the chairman of the Steering Committee to NAM at their office in Assen, followed by discussions. All participants were given a one week notice for comments. In February 2015 the Steering Committee delivered the final report.

During project execution four meetings with the Expert Group took place:

- Kick off meeting (February 5, 2014) to mark the official start of the project;
- Intermediate progress meeting (March 31, 2014 and May 14, 2014);
- Final meeting to present and discuss the results and conclusions of the work packages and a preliminary draft of the summary report of the Steering Committee on the outcomes of phase 1 (September 11, 2014).

Most Steering Committee and Experts Group members were present at the meetings. In addition experts of Shell/NAM joined to share knowledge and ideas. Besides this, bilateral meetings took place between the secretary of the Steering Committee and the Work Packages leaders, and between these leaders and experts from Shell/NAM.

After the September 11 meeting, additional questions from the Steering Committee were formulated and addressed by Ecofys as well as CE Delft. The results of this work were added to (Ecofys) or integrated in (CE Delft) the final reports of WP3, WP4 and WP5.

Appendix B: Detailed description of the work packages

WP1: Alternatives for the conventional base case of nitrogen production & rejection

Background: In the preliminary base case in the 'Technical addendum to the Winningsplan Groningen 2013' (here referred to as conventional nitrogen production) it is envisaged that nitrogen is produced at a central location and it is distributed to a number (20+) of injection wells of the Groningen gas field. Rejection of nitrogen from the produced gas that may contain varying and gradually increasing concentrations of nitrogen is assumed to take place at the production clusters (about 20 locations). The investments and energy consumption of this option will be considerable (energy consumption: max 1.3 GW for production, max 0.4 GW for rejection).

Objectives: To assess alternative nitrogen process chains, relative to the base case nitrogen production and rejection that are cost effective, have a lower energy consumption and lower GHG emissions, and may enable integration with specific regional or local processes and developments.

Results: The results should include a description of the technical systems of the alternatives, a rough indication of the key figures and benefits, such as investment and operational cost, infrastructural needs, impact on landscapes. energy use, GHG emissions, safety, other relevant emissions, to allow for a first estimate of the feasibility. Results should also indicate what/where the risks and uncertainties are of alternative production processes and how they can be mitigated. Key figures will be used as input for WP5 that focuses on an integral assessment and evaluation of environmental and economic impacts.

Relevant questions:

- What kind of alternative processes are available to produce/reject nitrogen that have a better performance than the base case in terms of cost, infrastructural needs and environmental performance?
- What kind of combinations are feasible with local/regional developments, such as the combination with LNG production (using cold for nitrogen separation from air) and other processes?
- Is it feasible to produce nitrogen in a decentralised set-up through standard size units thus creating opportunities to utilise waste heat from nitrogen separation locally in, for example, the built environment and industry? What are other advantages and disadvantages to this decentralised scenario?
- What are the cost, infrastructural needs and the environmental implications of a decentralised set-up? What are local implications (e.g. landscaping) of this kind of plant? What are the potential local benefits of such a set-up?
- Is it possible to reject nitrogen from the produced gas in a central location? What are the benefits?

- Is it possible to operate processes in a variable/fluctuating mode, e.g. to use surpluses of cheap electricity from renewable sources (wind/solar) in case there is an oversupply or to shut down at high electricity prices? What is the downstream effect, e.g. on the nitrogen injection and/or rejection part? Are there any bottlenecks that could hinder a variable production mode (e.g. expected subsurface problems)? Would there be a need for storage of nitrogen in order to guarantee a continuous injection flow of Nitrogen?
- How to deal with changing quantities of nitrogen to be produced (i.e. increasing quantities from the start but if rejected quantities of nitrogen increase it could be re-injected)? What is an optimal configuration of the whole system to deal with this variability over time?
- Are modular/mobile nitrogen production or rejection units feasible?

Experts: Wytze Sloterdijk & Martin Hommes (DNV GL)

WP2: Valorisation of by/waste products of nitrogen production & rejection and alternative commercialisation of nitrogen rich gas

Background: During production of nitrogen several by and waste products become available. Examples of such products are oxygen (expected purity 60-70 percent), chemical components and products (e.g. Argon), and waste heat. These products might be used in new processes or products or they could be used to facilitate certain industrial and/or energy developments in the region. After nitrogen injection into the Groningen field it is likely that at a certain moment the produced natural gas will contain increasing quantities of nitrogen. In general it is not possible to use this mix of nitrogen and natural gas which makes nitrogen rejection a necessity. However it may also be worthwhile to use the nitrogen rich natural gas in processes that are not critical to nitrogen or to mix this gas with other products to make it suitable for specific industrial purposes.

Objectives: To assess what kind of by/waste products are produced in different nitrogen production and rejection processes (base case and alternatives), how these by/waste products can be used in other processes, products and markets, and how they could fit in or promote relevant regional developments. Another objective is to investigate what possibilities exist for utilisation of nitrogen rich natural gas in e.g. (new) industrial processes.

Results: The results should present an overview of potential by/waste products as well as possibilities to use these products for creating new products, processes and markets. It should also include an estimation of the cost/market value and any potential market disturbing effects. It should indicate in which applications nitrogen rich gas could be used, what the size of these markets are, what the economics look like, and what the infrastructural needs are. Key figures will be used as input for WP5 that focuses on an integral assessment of environmental and economic impacts of options investigated in the Groningen 2.0 Screening Study.

Relevant questions:

- Which by/waste products are produced in different processes and what are traditional target markets? Examples are the use of argon in the (medical) industry, and the use of oxygen for oxyfuel combustion processes with possibility of CO_2 storage.

- What kind of local/regional developments could be supported by these products: use of waste heat for heating buildings or supplying heat to industrial processes, heat for industrial drying processes, e.g. Avebe and sugar plants, interactions with regional industrial and innovation platforms such as NOM, Wetsus, and Energy Valley to connect with innovation and new business development?
- What is the effect of these products on the costs, safety and environmental performance of both nitrogen production and local/regional markets? How can both developments benefit from each other?
- Will these products have negative effects, such as local/regional and (inter)national market disturbance? E.g. large scale production of argon could have a significant effect on world market prices.
- Does the energy transition create opportunities for new combinations, e.g. how can the production of biogas in the region be used to create new processes and products, how can power-to-gas processes (based on hydrogen production from renewable energy sources) create new possibilities for a sustainable development of our economy and energy system?
- What options exist to utilise nitrogen rich gas, e.g. electricity production, feedstock in the (chemical) industry, steam production/CHP, biomass/coal gasification, BTL/GTL processes (multi input/multi output), mixing with high caloric gas?
- Is it feasible to use the gas nitrogen mixture in fuel cells for production of electricity and heat? What type of fuel cells are suitable for this process and how susceptible are fuel cells to changing concentrations of nitrogen?
- Which options exist to change the composition of the nitrogen rich natural gas, such as blending with biogas (components), hydrogen, oxygen or other components in order to 'construct' a gas that can be used in a range of (end use) applications or in industry?
- How would the technical system of using Nitrogen rich gas look like (what kind of installations, sizes, locations, costs, benefits)?
- Are the opportunities for oxy-processes in the region to create nitrogen surpluses?

Experts: Cindy Visser & Ton Schoot Uiterkamp (RUG/IVEM)

WP3: Covering the energy demand of nitrogen production & rejection (incl. energy storage)

Background: The production and rejection of nitrogen is very energy intensive with associated cost and GHG emissions. One option is to build a dedicated energy plant for these processes. Another option is to combine the energy production for nitrogen production and rejection with other energy production processes in the region or to use surpluses of sustainable energy. Given the increasing need of energy storage in the future, it might also be an option to combine nitrogen production and injection with some kind of energy storage.

Objectives: To investigate what kind of alternatives exist to a conventional (additional) power plant to provide the energy necessary for nitrogen production and rejection, how the energy demand could be used to promote sustainable local/regional energy developments, and what opportunities exist to combine these processes with energy storage.

Results: The results should indicate how the energy demand of nitrogen production and rejection can be covered by alternatives to a dedicated power plant or by the use of existing power capacity. It should address cost, indication of the scale, layout of such an alternative etc. It should also address possibilities for energy storage, such as CAES (Compressed Air Energy Storage) and other options. Key figures will be used as input for WP5 that focuses on an integral assessment of environmental and economic impacts of options investigated in the Groningen 2.0 Screening Study.

Relevant questions:

- Which alternatives exist for power production for nitrogen production and rejection compared to the base case (central production)?
- Is it feasible, given wind and solar energy production scenarios, to use surpluses of electricity to produce and reject nitrogen? What are operational effects of such a set-up (fluctuating operation)? Is it feasible to introduce a base load scenario, combined with flexible peak production during periods of low electricity prices?
- How could the energy demand help to promote/stimulate local and regional developments regarding (sustainable) energy production? Examples are the use of biogas for nitrogen production or the use of available wind and solar surpluses.
- What are the possibilities to combine all processes for nitrogen production and rejection with energy storage (i.e. capture of energy when surpluses of electricity occur)? Examples are to use CAES (Compressed Air Energy Storage) as a way of storing nitrogen to create a buffer for the process as well as a means of creating an electricity demand during periods with surpluses of electricity.
- It is feasible to use the oxygen from nitrogen production to operate an oxyfuel plant to cover the energy demand? This question related to WP2 where it will be investigated if oxygen can be used for oxyfuel processes.
- What are the possibilities to use regional power generation capacity, such as the NUON Magnum plant, for power generation and what are potential benefits?

Experts: Chris Hendriks, Wouter Meindertsma & Cornelis Blok (Ecofys)

WP4: Alternative use of infrastructure (networks, wells, equipment)

Background: The energy intensive process of nitrogen production and rejection could offer new possibilities when combined with developments regarding the alternative use of infrastructure, such as wells, gas networks and equipment (e.g. compressors). An interesting option could be the use of wells and gas networks for geothermal activities, or the use of infrastructure for biogases.

Objectives: To investigate what the options are to use the existing and new infrastructure (networks, wells, equipment) for other purposes than nitrogen production and rejection.

Results: The results should indicate how the nitrogen production, rejection and infrastructural systems could be used for alternatives and how these alternatives can support regional developments. Key figures will be used as input for WP5 that focuses on an integral assessment of environmental and economic impacts of options investigated in the Groningen 2.0 Screening Study.

Relevant questions:

- What are potentially interesting options for using the dedicated nitrogen production and rejection infrastructure, such as the pipelines, compressors, injection wells and other equipment (such as facilitating biogas injection, promoting geothermal and waste heat projects, developing energy storage options, storing CO_2 on longer terms)?
- What aspects should be taken into account during the design to make the infrastructure suitable for other purposes?
- Are these alternatives feasible (what are economic and environmental key figures)?
- How do these alternatives fit with local/regional developments? Could these alternatives be used to spark local/regional developments and in what way?

Experts: Chris Hendriks, Wouter Meindertsma & Kornelis Blok

WP5: Environmental, economic, energy, risk and impact assessments: this is a cross-sectional topic which is relevant to all topics listed in WP1-4

Background: Work packages 1-4 will assess alternatives to the base case, being conventional nitrogen production and rejection. These studies will be conducted by different experts from different organisations which means that their approaches and calculation methods may differ. In order to be able to judge and compare the environmental and economic performance of these alternatives as well as potential risks and impacts of these alternatives it is necessary to use one common technology assessment methodology that is consistent for all studies.

Objectives: To assess the environmental and economic values and key figures of all (surface) alternatives to conventional nitrogen production and rejection as well as potential impacts and risks, in order to be able to compare all options on the same basis. The assessment should focus on energy, risk, and impact analyses, taking into account mass/material and energy balances, space requirements and impacts, GHG emissions and other environmental impacts (as required when providing an Environmental Impact Statement. The assessment will be executed using elements of a LCA approach.

Results: The results should give a first order estimation of the environmental and economic performance of conventional nitrogen production and rejection as well as all alternatives assessed in the studies 1 to 4. It should contain a clear overview including all relevant key parameters.

Relevant questions:

- What is the environmental performance of the base case (conventional nitrogen production and rejection) and the alternatives? This should be assessed with first order estimations of the environmental and economic performance as well as potential risks and impacts to the surroundings, land use, spatial effects etc. Necessary data will partly be delivered by the experts of WP1-4.
- What is the economic performance of the alternatives?
- How do the alternatives score on environmental issues and cost compared to the base case?
- What are the potential risks and impact of the alternatives (focusing on data necessary for scoping of an Environmental Impact Statement - MER)?

Experts: Harry Croezen & Martijn Blom (CE Delft)

Additional requests

After the WPs delivered their final reports the steering committee had additional requests regarding options that seemed worthwhile to explore in more detail as it had not been covered extensively at the time. Ecofys was asked to explore these options, CE was asked to include the impact of some of these options in their analysis. The additional options explored by Ecofys were:

1. Potential uses of oxygen in Delfzijl and Eemshaven
2. Membranes as alternative for cryogenic separation (at the NRUs)
3. Opportunities to produce ammonia from nitrogen-rich natural gas
4. Opportunities to integrate LNG production and distribution in the Northern Netherlands

Appendix C: Summary of all expert reports

In this appendix the conclusions of all expert reports (including the additional work) are summarised for each work package. The essence of these conclusions have not been altered, only text changes have been made which are deemed necessary to understand these conclusions without reading the whole expert report.

WP1: Alternatives for the conventional base case of nitrogen production & rejection (report by DNV GL)

Nitrogen production technology:

The volume of 42 BCM produced natural gas can be replaced by 37.4 BCM of nitrogen. Oxygen specifications in the produced nitrogen must be in the ppm range, so there is no realistic alternative for cryogenic production of nitrogen that meets these specifications (as suggested in the base case). Alternative production of nitrogen by PSA (with an oxygen concentration of 150 ppm at 60 bar) was calculated to have lower capex and slightly higher opex than cryogenic technology but due to the required oxygen specifications this is not an option.

Location/siting of nitrogen production and nitrogen supply:

Economy of scale promotes a central production location as suggested in the base case. Local production of nitrogen is possible but with higher cost and attention is needed to deal with technical and permitting complexity.

Shipping of nitrogen to the region requires about the size of one large LNG tanker per day. This has large environmental implications in the area (Wadden Sea) and the required volumes are not likely to be met, so additional regional production capacity is always necessary.

Membrane separation technology for nitrogen rejection:

For nitrogen rejection from the produced nitrogen-rich methane membrane separation is an option worth further exploration. In this stage cost estimates could be made based on the assumption that for a 100,000 (n)m^3 gas flow per day a unit price of around k€ 600can be assumed with an annual opex of around k€ 400. This should certainly be verified by contacting potential producers of membrane separation technologies which was not possible within the scope of this screening stage. Information on pressure loss in the unit should also be gained in order to calculate the required compression power for reinjection of nitrogen in the field and gas into the grid. A gas blending station very likely needs to be an integral part in the gas production.

WP2: Valorisation of by/waste products of nitrogen production & rejection and alternative commercialisation of Nitrogen rich gas (report by RUG/IVEM)

Use of nitrogen rich methane:

The bandwidth for nitrogen in Slochteren gas is small, 14.29%-14.73%, so excess nitrogen (added for pressure maintenance reasons) needs to be removed before entering the gas grid or dedicated applications need to be found. In the chemical industry this nitrogen-rich natural gas can be utilized as feedstock in the production of fertilizers or synthesis gas and its derivatives. Another utilization of the mixture is by providing heat and/or electricity by combustion in a power plant, CHP or by reforming in a fuel cell. In all cases this is technically feasible, but the question is whether it is economically feasible as large investments are needed and the immense scale is questionable (30-40 BCM). Especially in the case of providing heat a further analysis is needed to check how much can be delivered and to which demand this would match.

Use of by products from nitrogen production/rejection:

If nitrogen is extracted from air several by-products could be obtained, e.g. oxygen, argon and helium. Oxygen is mainly used in the steel and chemical industry. Because the ASUs will produce a lot of oxygen (~300% of the Dutch market) new potential markets have to be sought. Three possibilities are the utilization of oxygen for oxy-fuelled power plants, for supercritical oxidation in waste water treatment plants, and for gasification of e.g. biomass.

Argon is used for the carbon reduction of steel with oxygen, as blanket gas to prevent oxidation, and for aluminium welding. Because the theoretical argon production amount as a result of nitrogen production can be large (63% of the world market), commercial co-production of this gas might only be attractive if new markets can be found.

Helium is used as coolant in cryogenic engineering (e.g. for cooling of MRI-scanners and NMR-devices), welding, heat transfer, or for its lifting properties. In the project enough helium could be obtained to provide 0.1% of the current world production. Also, a significant value stream could be obtained from the nitrogen rejection unit (NRU) as some helium is present in the Groningen gas field (0.04%). The major problem, however, is that helium recover cost are substantial. A further analysis is needed to assess whether selling helium provides a solid business case or not.

Alternative production of nitrogen:

Major oxygen consumers (as these are nitrogen producers) are coal- or gas-fired power plants through the use of flue gases. Another option is production of nitrogen by using G-gas as fuel in e.g. gas generators; G-gas already contains 14% nitrogen and when air is used for combustion it makes sense to capture the nitrogen from the flue gas. Although the idea is the same as obtaining nitrogen from flue gas, the difference is that in the case of flue gas from a power plant nitrogen is a by-product, whereas in this case nitrogen would be the main product. This probably means that a different system is needed to capture the nitrogen and this could potentially be cheaper than capturing and purifying nitrogen from the flue gas of power plants.

Potential of biogas / green gas:

Another issue was to calculate the potential of biogas / green gas and synthetic natural gas as replacement of a part of the natural gas from the Groningen gas field, for which extraction can be avoided. However, it turns out that the potential is very small (green gas could provide 0.8% of Groningen gas production; synthetic natural gas 0.4%).

WP3: Covering the energy demand of Nitrogen production & rejection (incl. energy storage, report by Ecofys)

In the assessment of WP3 one alternative to the NAM base case and six options on energy and infrastructure have been included. An alternative is defined as a variant of the nitrogen injection scenario that fundamentally differs from the base case. Options consist of different solutions for meeting the energy requirements and possibilities for infrastructure of the base case. Also possibilities for adapting the injection strategy were identified, which may affect the alternative and the options.

Adaptation of injection strategy:

In the base case approximately 37.5 BCM of nitrogen per year is injected into the Groningen gas field from 2020 onwards, gradually reducing to 3 BCM in 2048. At the start of the project the full amount of nitrogen is delivered by air separation units, but gradually more and more is coming from the recycled nitrogen which is rejected from the produced gas. This will lead to increasing overcapacity of the air separation units. Adaptation of the injection strategy by starting with lower injection volumes will reduce the required installed air separation units capacity. When a constant rate (flat rate) of nitrogen production is maintained, the air separation units capacity needs to be only 13 BCM per year, reducing N_2 production investment costs. Starting with a lower injection rate will lead to lower production of natural gas in the first years of the project and reduced revenues. The production is compensated in the later years of the project, leading to a similar total production of natural gas as in the base case.

Alternative sources of nitrogen:

In the base case the nitrogen is supplied by air separation units located at the Eemshaven. The flue gases of the nearby situated RWE coal-fired power plant can be an alternative source of nitrogen. The nitrogen production capacity of the RWE plant can be up to 25 BCM per year. This is about two-third of the maximum capacity required in the base case (37.5 BCM). To separate the nitrogen from flue gases, components like oxygen, carbon dioxide and impurities like sulphur dioxide (SO2) and nitrogen oxides (NO_x) need to be removed. The tolerated level of oxygen is 5 to 10 ppm or lower. The oxygen can be removed by a cascade of techniques but these methods need to be proven at the scale required. To remove carbon dioxide from the flue gases, post-combustion carbon capture and storage technologies can be used. Such technology, however, has not yet been proven at such large scale integrated in a power production process, but widely research and demonstrations are taking place. At the moment a large integrated demonstration project has been started in Canada (Boundary Dam, started Oct 2014), Shell being involved, which is interesting to follow. A first indication shows that the costs of nitrogen production from flue gases are comparable to the nitrogen production cost from air separation units. The carbon dioxide (CO2) emissions associated with the energy required to recover nitrogen from the flue gas case in that case are practically zero.

Energy options:

Three options for improvement with respect to energy were assessed: 1) Power load management, 2) Use of waste heat, and 3) Oxyfuel combustion.

1) Power load management: The total power use for the air separation units in the base case is estimated at 104 TWh. In the first year, the power demand is 10.7 TWh, gradually decreasing to 0.7 TWh in 2048. At the same pace, overcapacity of air separation units will be created. This gives the flexibility to operate air separation units when prices of electricity are low and reduce or stop production when prices are high. In the coming years the variation in prices is expected to grow because of the increasing share of renewables on the grid. Assuming modelled prices for 2030 this saving could increase to about € 2 billion; from € 6.2 billion in the base case down to € 4.2 billion. This calculation assumes full flexibility of the air separation units. Current technology has limited flexibility, which may reduce the savings to about € 0.8 billion a year.

2) Use of waste heat: The operation of air separation units could potentially lead to generation of low-temperature waste heat of up to about 110 degrees Celsius. First order calculation indicates that about 150 to 300 MW_{th} of heat could come available. A main use for this heat could be the heating of the boiler feed water of the power plants nearby the air separation units in the Eemshaven. Using waste heat instead of low-pressure steam from the power plant's steam cycles increases the efficiency of the plant. The estimated demand is in the order of 150 MW_{th} matching quite well with expected availability.

Other potential use of waste heat is in the industrial site of Delfzijl. The estimated potential demand for low-temperature heat in large industrial plants is estimated at 40 MW_{th}. The presence of waste heat could also stimulate industries with high demand for low temperature heat to settle in the area, e.g. horticulture. Currently within the Flexiheat project an assessment is done on infrastructure to exchange heat between industries.

3) Oxyfuel combustion: A main by-product of the air separation units is oxygen. For each cubic metre of nitrogen approximately 0.25 cubic metre of oxygen is produced. The oxygen could be used in oxyfuel combustion to capture carbon dioxide from power plants. Oxyfuel combustion typically reduces plant efficiency by 8 to 10%. When oxygen is delivered for 'free', the plant efficiency drop is substantially less: 2 to 4%. The avoided costs are estimated at about € 20 per tonne of carbon dioxide and avoided emissions (because no energy use is allocated to oxygen production) are about 0.2 tonne of carbon dioxide per tonne of carbon dioxide captured. A potential candidate for oxyfuel combustion is the nearby situated RWE coal-fired power plant. When the whole plant is converted to an oxyfuel combustion plant about 6.5 to 7 BCM of oxygen per year will be required.

WP4: Alternative use of infrastructure (networks, wells, equipment; report by Ecofys)

Infrastructure options:

Three improvement options with respect to infrastructure were assessed: 1) Application of nitrogen-rich natural gas: adaptation of the injection strategy, 2) Using the nitrogen injection wells for producing geothermal energy, and 3) Using the nitrogen pipeline network for biogas collection and transport.

1) Application of nitrogen-rich natural gas: The injection of nitrogen into the Groningen reservoir will lead to natural gas production diluted with nitrogen. When concentrations of nitrogen are too high, the production of the gas will be ceased as it is not economical anymore to reject the nitrogen: roughly at the time that the revenues of the natural gas are lower than the costs to reject nitrogen. Instead of leaving the gas in the reservoir, the nitrogen-rich gas can be used for dedicated purposes, e.g. as fuel for the RWE coal-fired power plant. To have the supply of this gas gradually available (and not all at once), the injection strategy of the base case needs to be adapted. Injection should start at a limited amount of wells and gradually shift to other wells. Detailed study should be performed whether this option is economically attractive, i.e. does the expected gain in natural gas revenues exceed the extra infrastructure cost.

2) Using the nitrogen injection wells for producing geothermal energy: For the injection of nitrogen in the base case, approximately 23 additional wells are required. These wells could be multifunctional, i.e. be used at the same time as geothermal wells. The only feasible geological formation to extract geothermal energy is the Bunter sandstone layer above the Groningen field. A first estimate concludes that such a well could have a capacity of 5 to 6 MW_{th} for water with a temperature of about 65 degrees Celsius. The demand for low-temperature heat in Groningen – not too far from the wells – is mainly from residential areas and horticulture. The heat demand of the residential areas is estimated at 115 to 175 MW_{th}. Heat demand of existing horticulture is about 16 MW_{th}. In principle there is sufficient heat available to cover heat demand in the area but the technology needs to be tested. Whether it will be economically attractive depends very much on the local situation. Important factors are the availability of existing heat infrastructure and the distance from the well to the demand.

3) Using the nitrogen pipeline network for biogas collection and transport: The nitrogen pipeline infrastructure could be reused when the pipes are not used for natural gas anymore, e.g. to transport biogas from local producers to a central location. This will save cost and improve the use of the gas. At a central collection location, the biogas gas can be upgraded and, for instance, be injected into the natural gas pipeline system. The potential supply of biogas in the region is estimated in the order of 0.1 to 0.3 BCM per year. The pipeline capacity will be (more than) sufficient to handle this amount. As it is not expected that the pipelines will be available before 2040-2050 it is not likely that this potential use will have a large impact on the nitrogen project.

WP5: Environmental impact assessments (report by CE Delft)

Based on a discussion with the Steering Committee as well as the results of the other work packages, the assessment was focussed on the following alternatives:

1. Base case of nitrogen production, injection and rejection, as originally proposed by NAM;
2. Partial production of the nitrogen needed from flue gases of a coal-fired power plant using MEA for flue gas treatment (excluding cost for CCS);
3. Partial production of nitrogen from flue gases of a coal-fired power plant using a physical absorbent (Selexol) for flue gas treatment (excluding cost for CCS);
4. Option 2. combined with ASU waste heat supply to the coal-fired power station (used for heating condensate in a steam cycle)[10];
5. On site generation of power for NRU's using gas engines and downstream steam cycles where power is produced from natural gas delivered by the NRU in periods of high power prices and use of electricity from the grid during low power prices;
6. Oxygen supply to a gasification plant (e.g. Magnum Power Plant Eemshaven) that saves on local oxygen production cost.

The next table summarises the main results of the assessment for the alternatives.

	1. Groningen 2.0 project as designed	2. Nitrogen from flue gases: MEA applied	3. Nitrogen from flue gases: Selexol applied	4. Nitrogen from flue gases, MEA + waste heat utilization	5. On-site power production	6. Oxygen supply to gasification
Investment costs (M€)	8,360	8,530	8,330	8,540	8,880	8,340
Difference with Groningen 2.0 (M€)		170	-30	180	520	-20
Reason for difference		Part N_2 from flue gas instead of ASU	Part N_2 from flue gas instead of ASU	Part N_2 from flue gas instead of ASU, hot water pipeline from ASU	Additional investments for gas engines	Reduced investment in ASU for Magnum project
Aggregated annual economic costs (M€ net present value)	14.,50	15,340	14,739	15,242	14,022	14,088
Aggregated environmental damage costs (M€ net present value)	2,290	2,380	2,287	2,347	1,848	2,236
Aggregated power consumption (PJe)	868	901	865	888	849	839
Aggregated CO_2-emissions (Mtonnes)	126	131	126	129	105	123
Aggregated NO_x-emissions (ktonnes)	34	35	34	35	42	33
Ratio economic costs ÷ power consumption	16.5	17.0	17.0	17.2	16.5	16.8

Note: 'N_2 from flue gases' refers to partial production of N_2 from flue gases of a pulverized coal fired power plant (without CCS).

[10] Waste heat utilization is combined with the use of N_2 from flue gases to match potential heat supply and demand

The following conclusions can be drawn:

- Compared with the entire Groningen 2.0 project – including investments in new wells, pipelines and other infrastructure – the various alternatives explored in WP5 have little influence on total investments as the investments in N_2 infrastructure, ASU's and NRU's of the base case are very high.
- On the level of individual processes differences can be quite substantial, for example: investments for nitrogen production of 11.4 BCM from flue gases are 30% higher compared to ASU's when using a gas treatment system based on MEA and costs are 5% lower when flue gas treatment is based on a physical absorbent (Selexol).
- Investments in an ASU for the Magnum gasification project would be reduced by an estimated 30% if the oxygen enriched vent of the ASU's would be used as oxygen source.
- Utilization of gas engines will require significant additional investments, but this is compensated by reduced annual operational costs (illustrated by lower aggregated costs).
- The aggregated economic costs are determined primarily by electricity purchases which isa , illustrated by the almost uniform economic costs ÷ power consumption ratio's. The aggregated economic costs illustrate that economically attractive alternatives are:
    - N_2-production from flue gases using a gas treatment system based on a physical absorbent;
    - waste heat supply;
    - O_2-supply;
    - on-site power generation in combination with purchases from the public grid of cheap electricity.
- The first three options lead to reduction of power consumption, while the combination of on-site power generation and cheap power purchases results in both electricity savings (due to absorption cooling) and a reduction in the costs per unit of power. The same accounts for the emissions. For on-site power generation in combination with purchases of cheap electricity from the public grid, CO_2 emissions are reduced not only by reduction of power consumption relative to the Groningen 2.0 project, but also because of the utilization of renewable power and gas based power. Total NO_x emissions are estimated to be somewhat higher for this last option because of the higher emissions per GJ from gas engines.

Uncertainties in outcomes and relevance of comparing alternatives:

The assessment of optimization options was based on rough first order estimates for investment costs and future prices for fuels, power and CO2. For environmental impacts it was assumed that power for the different alternatives is produced by a coal fired power plant. As a consequence the uncertainty in the calculated environmental impacts and total costs per alternative are very significant and are estimated at 30% at least. Given these significant uncertainties and given the comparability of the estimated costs and environmental impacts, it can only be concluded that the different optimization options give little or marginal differences in the total costs and impacts associated with the considered variant of the Groningen 2.0 project.

Additional requests: conclusions for options explored by Ecofys[11]

1. *Potential uses of oxygen in Delfzijl and Eemshaven*

Although low cost oxygen could create good economic conditions for oxygen demanding processes, it was concluded that the market for oxygen in the Groningen are is currently small and industry demand is limited. A potentially large market is the use of oxygen for oxyfuel processes but no such initiatives exist yet. There is a large demand for oxygen in steel manufacturing but because these activities are not present in the region, it may be interesting to assess the possibilities of long distance transport to areas where steel manufacturers are located (such as Ijmuiden).

2. *Membranes as alternative for cryogenic separation (at the NRUs)*

Given the fact that methane as well as nitrogen are useful products, it may be interesting to combine different types of membranes at the NRUs that are selective for these gases. When constructed modularly these membrane separation systems can be adapted to changing conditions regarding gas composition and flow rates. Also multiple stages in membrane separation with internal recycling are an option to prevent the loss of methane that could otherwise be lost as a result of methane slip. Membrane systems with nitrogen reductions up to 60% may be cost competitive with cryogenic technology. Membrane systems that can cope with the scale required in the Groningen project are currently under development.

3. *Opportunities to produce ammonia from nitrogen-rich natural gas*

Producing ammonia from nitrogen-rich natural gas requires new facilities with larger reactors and catalysts causing increased CAPEX. To be cost competitive the nitrogen-rich natural gas would need to be made available at low(er) prices to compensate for the higher cost. Literature suggests that the optimal nitrogen concentration for ammonia production is about 30%. Membrane separation could be an option to reduce or stabilize the nitrogen content of the feed gas. Detailed analysis and further assessment is necessary to assess the economic feasibility as well as the real impact of this nitrogen gas mixture on the ammonia production process. Rejected nitrogen could be used to replace nitrogen production from an ASU.

4. *Opportunities to integrate LNG production and distribution in the Northern Netherlands*

This option has been assessed briefly because in the region there are plans for LNG production to be used as transport fuel for trucks, trains and ships. The NRUs could be redesigned to deliver LNG. Detailed engineering is necessary to confirm technical and economic feasibility.

[11] Conclusions regarding additional studies are summarized here by the steering committee based on the separate notes written by Ecofys.