Rural Study into Ammonia-Hydrogen Production: Final Report:

P13-0163

Report for Scottish Enterprise

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Executive Summary

Fossil-based ammonia production is increasing globally to meet the demand of rising population and food production: recent trends to 2013 have subsequently seen ammonia and fertiliser prices rising rapidly across the world.

In Asia there has been a move towards using cheaper coal (in place of natural gas) for ammonia production, and in USA shale gas is being employed: this may bring down unit ammonia cost in the medium term – however this will increase GHG (greenhouse gas) emissions as a result. Fossil-ammonia production already accounts for some 1.2 % of global GHG emissions at present and is set to rise rapidly[1].

Given the expansion of renewable energy taking place across the world – and given the issue of supply/demand matching which renewable energy faces (in the case of wind and solar) – there is a logical argument for producing ammonia more sustainably from these sources. This was the case pre-1920 when most ammonia in Europe was produced via hydro-electric power and electrolysis. Such practices died out due to the emergence of the lower-cost fossil-fuelled Haber-Bosch process – however this cycle may have now come full circle.

Scottish Context

In Scotland, the past 10-15 years has seen a dramatic rise in wind power developments: Scottish wind farms account for 50% of all UK wind-energy production. This market is now facing new challenges however, with expensive grid upgrades largely holding back further development. Many Scottish on-shore wind farms are located on agricultural land – and in this case the generation of ammonia from wind has an even more pressing case for uptake - since ammonia is the key ingredient for fertiliser production - and can be used as fertiliser in its own right.

This study has analysed the technical, economic and practicality issues surrounding generation of renewable ammonia and has reached the following conclusions:

Conclusions

- Ammonia from wind is technically feasible using electrolytic hydrogen and nitrogen produced from wind – and a high-temperature ammonia synthesis route via Haber-Bosch type process.

- Other low-temperature ammonia processes are under research - however not commercially available at present.

- Some regions of Scotland would prove ideal testing grounds for such a concept – given the high wind facility and requirement for fertiliser on mixed / arable farms

- System developers for hydrogen and nitrogen systems are fairly numerous in UK – and with good Scotland-based equipment supply possible.

[1] International Fertilizer Industry Association (IFA) 2009

- Ammonia synthesis at a ‘mini’ scale (sub 500 tonnes per annum) is novel and no commercial systems exist – however some systems are in development and are technically feasible.

- Application of anhydrous ammonia to land can be done directly by ground injection (used for 27% of all fertiliser applied in the USA): however other solid processing forms are possible.

- Farm-based ammonia production can allow a saving on purchase of traditional fertiliser. For example, ammonium nitrate – which costs in the region of £330 per tonne and represents an annual cost of around £40k-£50k per annum for medium scale farms.

- An additional revenue stream for farms can be demonstrated –based on the potential to sell ammonia to 3rd parties as fertiliser (if sufficient quantity is produced). Approximate market value is £650 per tonne.

- A key additional cost-benefit to farmers in Scotland can be achieved by installation of new-wind (with additional feed-in-tariff) facilitated by ammonia production. As the energy is used on-site and not exported to grid - this can offset the potentially expensive grid connection cost - which can be as high as 50% of the turbine cost in some cases.

- Initial systems capital cost will be high and payback limited to greater than 15 years (unless a significantly large grid-connection cost saving for new turbines can be realised): however system capital costs will fall in future if this technology were to be taken up in large scale.

- A large scale uptake of the technology could see a good potential return for Scotland in terms of new jobs, and investment – and critically, could see Scotland move to the fore in the emerging ‘hydrogen economy’ which could have implications outside of the renewables sector.

- Other uses for ammonia can also be envisaged such as NO_x reduction in HGV via SCR (selective catalytic reduction) – however fertiliser remains the primary application initially.

Recommendations

- A small-scale device (100-300 kW hydrogen facility) should be taken forward as a prototype unit to firmly establish the practicality of this concept. Such a unit would have a total capital cost in the region of £2m.

- The device could initially be housed within an academic institution (St Andrews have suggested their Gaurdbridge Energy Campus) – with the unit being moved to a ‘real-world’ farming site subsequently. Mackie’s farm in Aberdeenshire has been assessed and is an ideal location.

- An initial study-party should carry out a field-visit to the present technology developers - in advance of any design work: sites recommended for visit include:

    - University of Minnesota (prototype wind-ammonia research facility completed in 2013),
    - NH3Canada (mini ammonia system developer in Canada),
    - Proton Ventures/Casale (mini ammonia system developers in EU)
    - Farming sites in USA where ammonia ground injection is currently practised.

- A number of potential funding routes exist – however given the international context of potential partners and significant capital cost involved, the Horizon 2020 route (next stage of FP7) may be a feasible route to explore academic-industry collaboration.

- Whilst some of the design work for such a unit may take place outside of the UK, it would be recommended to see all component building, assembly and testing taking place within Scotland: thus maximising the economic and employment potential – and locking in the science and engineering expertise for the future. This should be considered as a contractual obligation for any engineering partners building the facility in future.

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1 Introduction

1.1 Aim of the Study

This project was initiated by Scottish Enterprise to investigate the feasibility of storing renewable energy as either hydrogen or ammonia in the context of Scotland. The need for renewable energy storage solutions is well known, as is the fact that some parts of the power grid in Scotland are nearing saturation point for new wind applications – many of these are situated in remote rural locations, far from the centres of population.

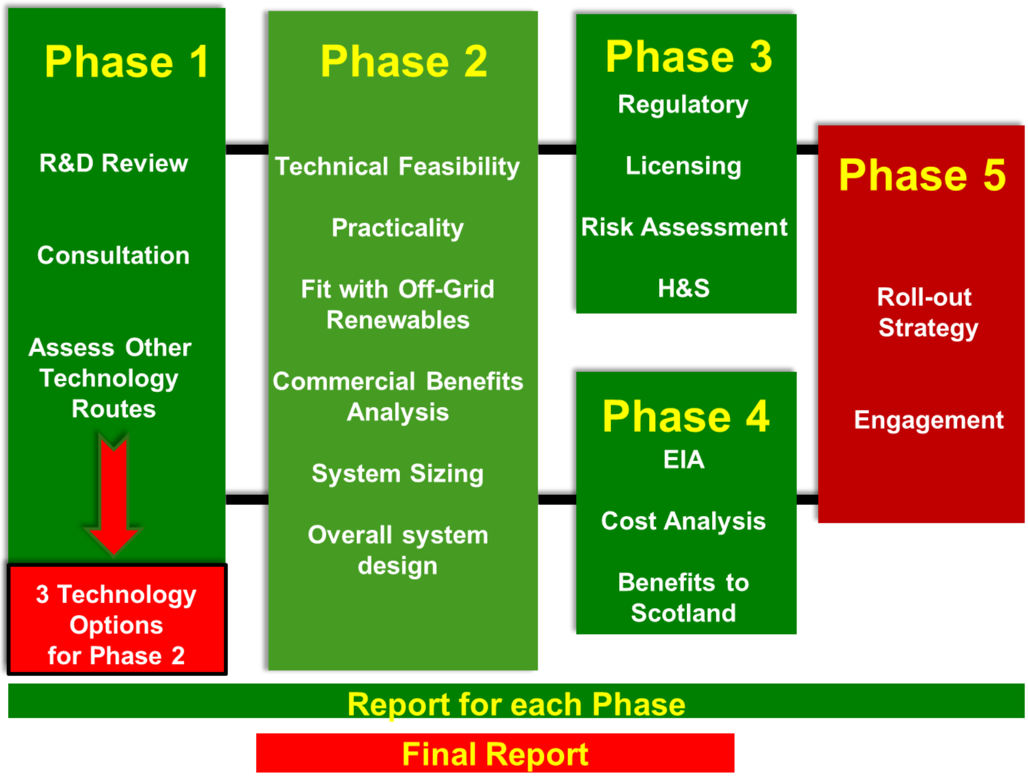
The challenge was therefore to assess the feasibility of storing renewable energy – and in using the renewable products in a practical way given the rural context.

A key element of the study was to investigate whether renewably-produced ammonia could have application potential in Scotland – either as crop fertiliser or for other purposes: the application of hydrogen by-product for transport, heat and energy storage was also an important aspect of the study.

This report summarises the conclusions of the five phase-studies carried out in 2013 – and reports on the implications that such a development might have longer term on the farming community, expansion in renewables generation, and the Scottish economy in general.

The five project phases are detailed below:

Figure 1: Project Phases (project timescale May-Dec 2013)



1.2 Phase 1: Background research and assessment of suitability of differing technology routes

Phase 1 of this study examined the various energy storage options available for storage of renewable energy – with an assessment of suitability at the small-medium scale in question. Suitability was found to be dependent on several factors – cost, efficiency, and practicality. Details of this study can be found in the Phase 1 report – a summary is shown the table below:

Table 1: Energy storage 'Pros and Cons' for small-medium wind-farm on farm / rural application

Energy Storage Method	Pros	Cons
Solid State Battery	• Compact, good efficiency, • Very mature technology	• High cost, low system life
Flow battery	• Good efficiency	• Large footprint • Complex • Costly • Environmental risk from chemical spill.
Compressed Air	• Efficiency good (if compression heat captured and then re-used on expansion))	• Only practical on large scale • Requires large geological features underground • Not commercially available
Liquid Air (cooled & liquefied and re-expanded over turbine)	• Good efficiency (if external heat source available for expansion phase)	• Larger scale is more practical • Very costly at small scale • Not commercially available
Pumped Hydro	• Efficiency good • Cost effective	• Specific geological features required (large head) • Larger scale only is practical
Hydrogen	• **Compact** • **Cost is reducing with time and scale**	• **Capital cost still high,** • **Round trip efficiency medium (35-45%)**

From the above it was clear that all current energy-storage techniques have short-comings. Given the current states of development and cost for the differing techniques, hydrogen was found to be the best option for farm-scale operation.

1.3 Ammonia suitability and rationale for small-scale renewables

In Phase 1 ammonia was assessed for its suitability to be produced by small-scale renewable means and for the commercial viability of doing so.

Global ammonia demand is forecast to grow at an average annual rate of approximately 3 % over the next 10 years, well above the historical growth rate of closer to 2 %. Strong agricultural fundamentals are expected to drive this growth and fertiliser use accounts for approximately 80 % of global ammonia demand.

The impact of growing demand for ammonia on production rates and cost can be seen in the figures below: consequently farm-fertiliser costs are rising rapidly also:

Figure 2: Rising global production of fossil-based ammonia products over past 10 years[2]

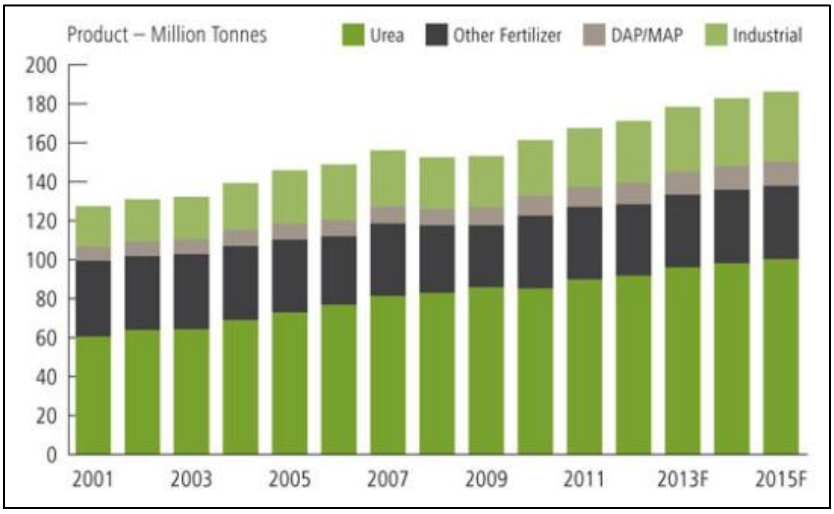
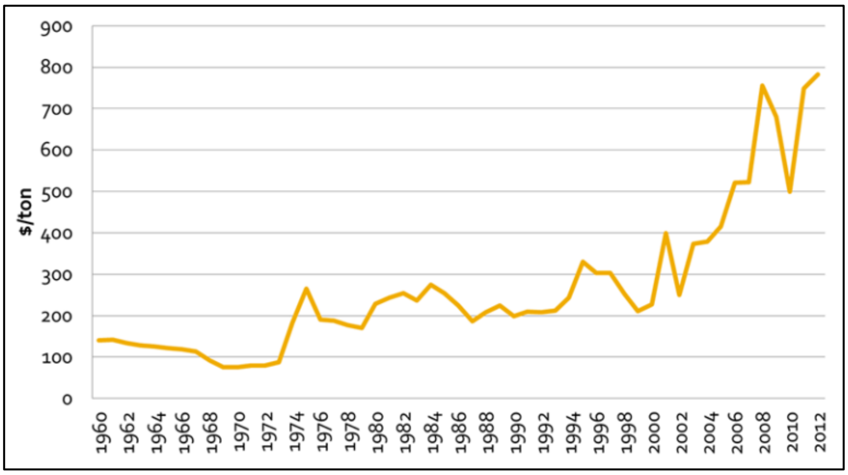


Figure 3: Anhydrous ammonia price $ per US ton 1960-2012[3]



[2] http://www.potashcorp.com/overview/nutrients/nitrogen/market-overview/world-ammonia-and-urea-consumption-by-region
[3] USDA ERS / http://crops.missouri.edu/fertility/prices.htm

1.4 Phase 1 Conclusions

The Phase 1 study into the general applicability and suitability of hydrogen/ammonia in Scotland reached the following conclusions:

- The required technology to produce renewable ammonia is technically available; however commercial 'off-the-shelf' solutions are not yet ready for market.
- The potential £/kg production cost of renewable ammonia on small-scale looks promising when contrasted with existing traditional fertiliser sale-price – however small-system capital cost will be high - as this is a new technology development.
- Ammonia market value in 2013 at time of writing was in the region of £550-£650 per tonne. This price fluctuates with changing energy costs and varies geographically.
- The GHG (green-house gas) impact of fossil-ammonia production is extremely high and growing. Growth in Asian production from cheap coal will worsen this situation: the outlook for renewable ammonia therefore looks strong.
- The optimised case for 'ammonia from wind' in UK will be where grid connection for (power export) is a highly expensive option and can be negated – and where FIT/ROC tariffs for new wind can be maximised.
- Ammonia application to agricultural land in liquid anhydrous (without water) form is possible – this was practised previously in the UK before 1980 – and is still presently practised in the USA where 27% of all fertiliser is applied in this manner.
- Other energy storage options are either impractical or presently too costly for small-scale farm systems.
- **3 options were recommended for more in-depth study in Phase 2:**
    - Ammonia synthesis for crop fertiliser and application to land
    - Hydrogen-fuelled farm vehicle applications
    - Hydrogen / Ammonia - engine based CHP for on-farm use at times of low wind.

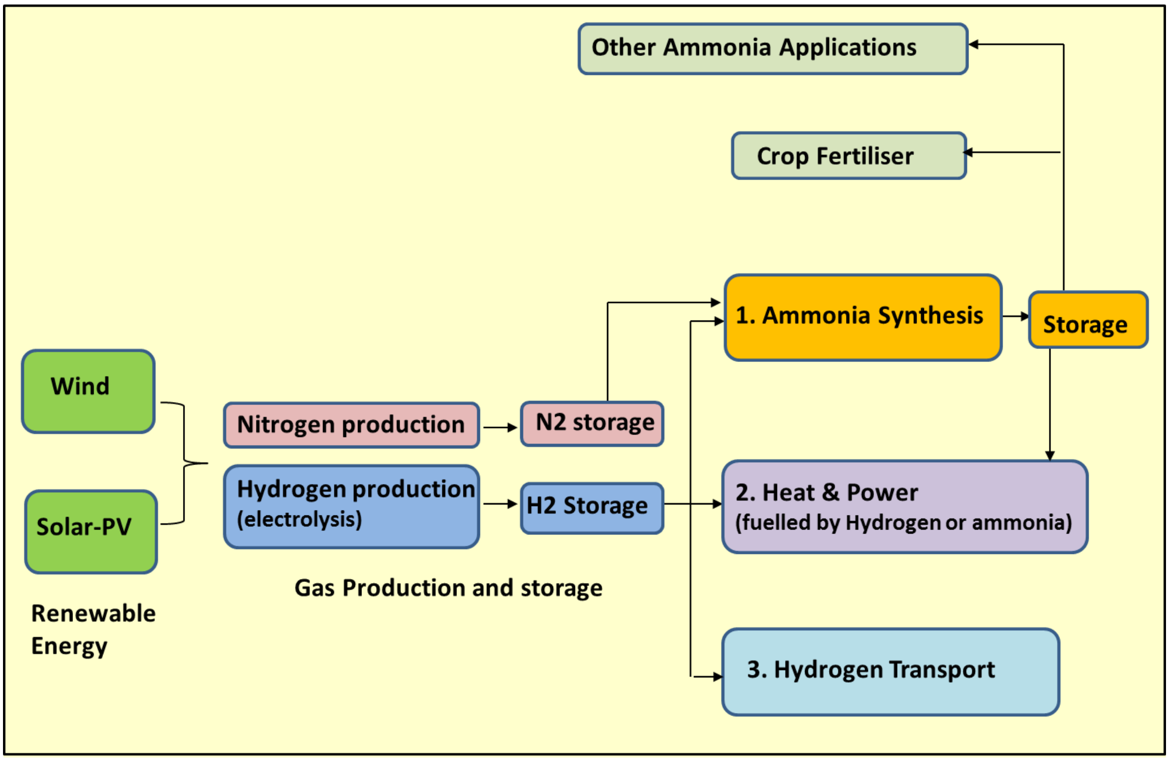
2 Phase 2: Detailed technological assessment of options.

In Phase 2, the following options were assessed in detail for suitability:

- Ammonia synthesis for crop fertiliser
- Hydrogen / Ammonia - for heat and power for on-farm use / export (CHP)
- Hydrogen or ammonia-fuelled farm vehicle applications

The graphic below shows the interaction between the 3 technology options:

Figure 4: Technology options for analysis in Phase 2



Note: *Nitrogen is also required for ammonia synthesis – this can also be produced from renewable energy.*

2.1 Options analysis

All of the above options were looked at in detail in Phase 2: (see Phase 2 report)

The conclusion was that the generation of hydrogen to be used for transport or heat & power are both possibilities and interesting research options – however there is no financial imperative or benefit from the perspective of the farmer.

Fuel-cell technologies for CHP or transport both exist and have been installed commercially – however from a farming perspective there would be little economic logic in doing this whilst capital costs are so high and the potential benefits questionable.

Power generation via internal combustion engines units is a cheaper option – however system inefficiencies make this another illogical approach from the perspective of wind-derived hydrogen.

Using ammonia as a fuel for power/heat production was found to financially unviable and as a transport fuel somewhat impractical due the H&S concerns during vehicle filling.

The focus of this project therefore should be purely:

- Production of hydrogen by means of electrolysis from renewables
- Production of nitrogen by means of pressure-swing adsorption from renewables
- Production of ammonia from H_2 + N_2 by small scale ammonia reactor
- Application of ammonia for crop fertilisation
- Application of ammonia for other purposes (to be researched)

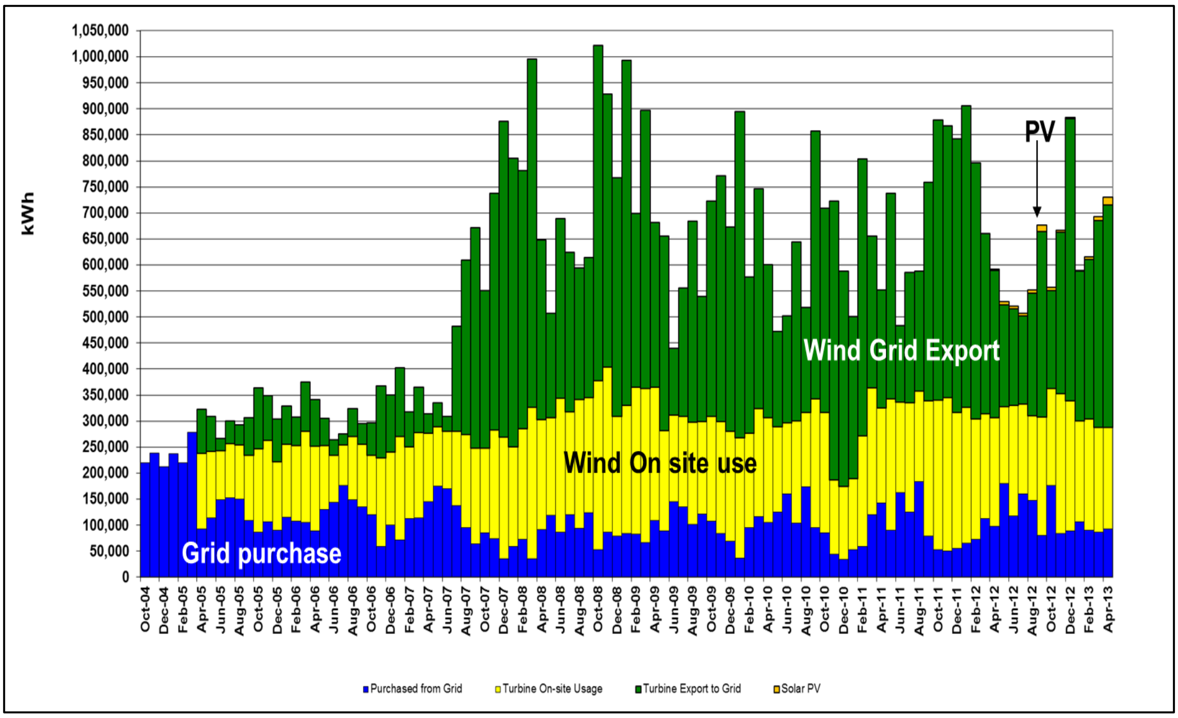
2.2 System Overview: ammonia production unit to satisfy a medium scale farm facility

Various farm units were analysed in terms of total renewable output and total fertiliser use. Mackie's in Aberdeenshire has been identified as a good case study for application – the total amount of ammonia required to satisfy a farm of this scale is approximately 50 tonnes per annum. (See Phase 2 study)

Mackie's farm currently has three 850 kW wind-turbines at this site with a further similar turbine with planning approval.

The graphic below shows the total wind energy produced, grid import – and shows how the wind energy is generated, used onsite, and exported on a month to month basis. Also shown here is the 150 kW solar-photovoltaic output – which came on stream in mid 2012. Essentially the green exportable portion is all avaialable for hydrogen and ammonia production.

Figure: Renewable energy geneartion and energy consumption (Mackie's– 2004-2013)



2.2.1 Availability of wind for hydrogen production

2 possible scenarios were studied - which were simply designed to illustrate the potential scale of hydrogen / ammonia production capacity at a farm / wind-farm on the scale of Mackie's:

- **Scenario 1**: Divert **850 kW** of current output to produce H_2
- **Scenario 2**: Divert **230 kW** of current output to produce H_2

Table 2 shows the total hydrogen systems size which would be required in each case and the estimated hydrogen production per month / annum based on a (**conservative**) 25% capacity factor. *This is an initial ranging shot to illustrate the relative size of the systems – not a precise assessment.*

Hydrogen production via wind is intermittent – and based upon the rising and falling wind turbine output – hence the conservative **25% capacity factor** has been used for the hydrogen generation systems.

Table 2: Hydrogen production availability and required system size for two scenarios based upon a conservative hydrogen system capacity and efficiency

Scenario	Potential wind output to H_2 (kW)	Electrolyser system size required	Average turbine output to H_2 per annum (based on 25% capacity factor) (kWh)	Average hydrogen produced per annum** (kg)	Hydrogen storage capacity required (est. 3 days maximised production)++ (kg)
1	**850**	1 MW	1,861,500	34,860	1,150
2	**230**	250 kW+	503,700	9432	310

***Hydrogen production based on 1 kg per 53.4 kWh (64% efficiency)*[4]
++*Based on maximum wind power output to electrolyser for 72 hours*

2.2.2 Ammonia production potential based on Scenarios 1 & 2

Based on the Scenarios 1 and 2 above – the total *potential* ammonia production is shown below:

- **Scenario 1** (based on 34,860 kg H_2 per annum) : **198 tonnes ammonia pa**
- **Scenario 2** (based on 9,432 kg H_2 per annum) : **53 tonnes ammonia pa**

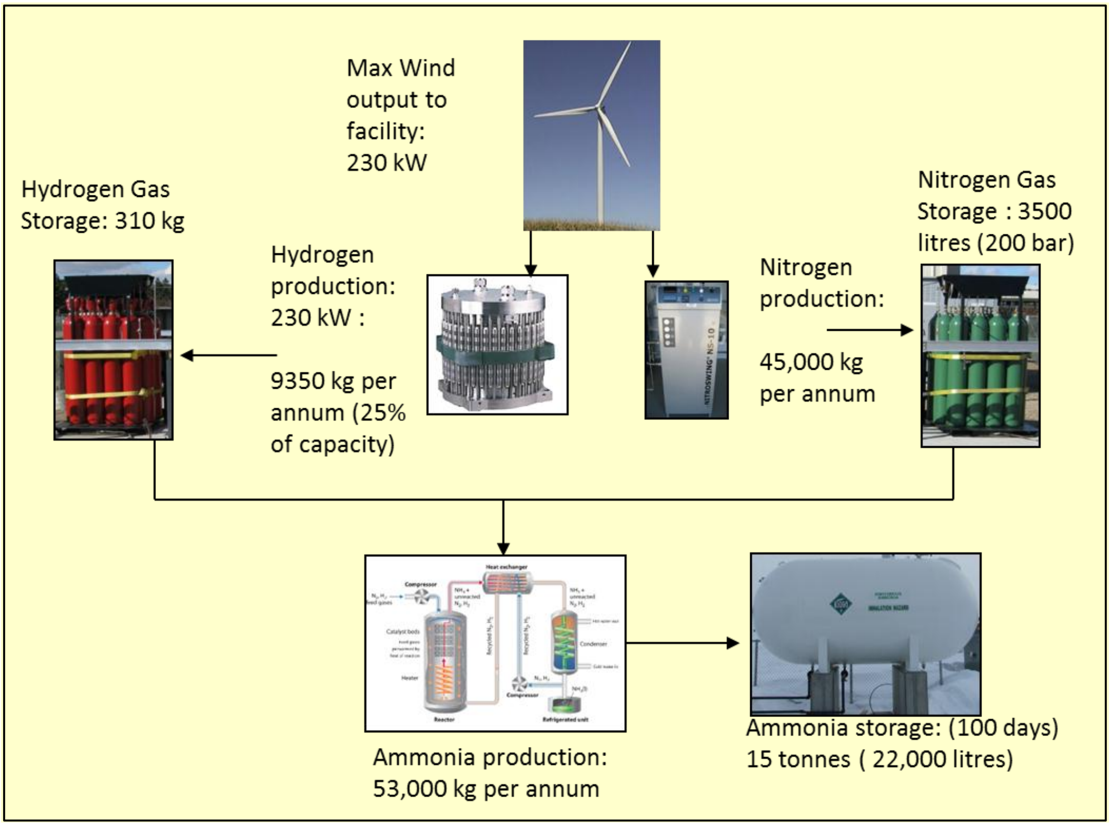
Note: The actual present fertiliser use at the case study farm is 130 tonnes Ammonium Nitrate (corresponds to **53 tonnes ammonia**): therefore Scenario 2 would satisfy this requirement.

[4] http://www.hydrogen.energy.gov/docs/cs_distr_wind.doc (US DoE hydrogen from wind)

A renewable ammonia system would constitute an electrolytic hydrogen generation unit (and hydrogen gas storage), a nitrogen generation unit (with nitrogen gas storage), and ammonia synthesis plant, and an ammonia storage facility.

The proposed system with an approximate scale suitable for a medium sized farm in Scotland is shown below: capable of producing 50 tonnes ammonia per annum.

Figure 5: Optimum system size for case study farm



- Ammonia application is only attempted at specific times of year – hence the requirement for a large ammonia storage tank (100 days of use).
- The Hydrogen and Nitrogen production systems would be 100% wind-powered. In the case of Hydrogen this is significant since it is the most energy-intensive step.
- Ammonia production could in theory be entirely wind-powered: however a sensible option initially would facilitate the use of some grid power in times of low wind - to maintain production consistency). This would enable the high-temperature ammonia process to be more efficient. (see Phase 2 report).

2.3 Conclusions on technological assessment

- The focus of this project should be on the renewable production of hydrogen and nitrogen – and subsequent production of ammonia by the high-temperature Haber Bosch process.
- The production of excess hydrogen for the purposes of heat and power has no financial benefit to the farmer and would not add significantly to the scientific element of the project.
- Ammonia for vehicles is a possibility however there are H&S concerns regarding vehicle filling.

- A 230 kW hydrogen system would produce enough hydrogen to facilitate ammonia production to satisfy the case study farm (53 tonnes pa)
- A larger 850 kW unit could produce 3x ammonia needs and allow onward sale to other farmers.
- The ammonia synthesis unit would be a traditional high-temperature catalysis unit (Haber Bosch). Other low-temperature means of producing ammonia are not commercially viable yet.
- The ammonia facility could in principle be entirely wind-powered – however we recommend a grid-power facility to enable consistent production. Hydrogen production is the most energy intensive step and should be 100% wind powered.
- Ammonia storage would need to be great enough to facilitate the sporadic fertilization periods throughout the year.

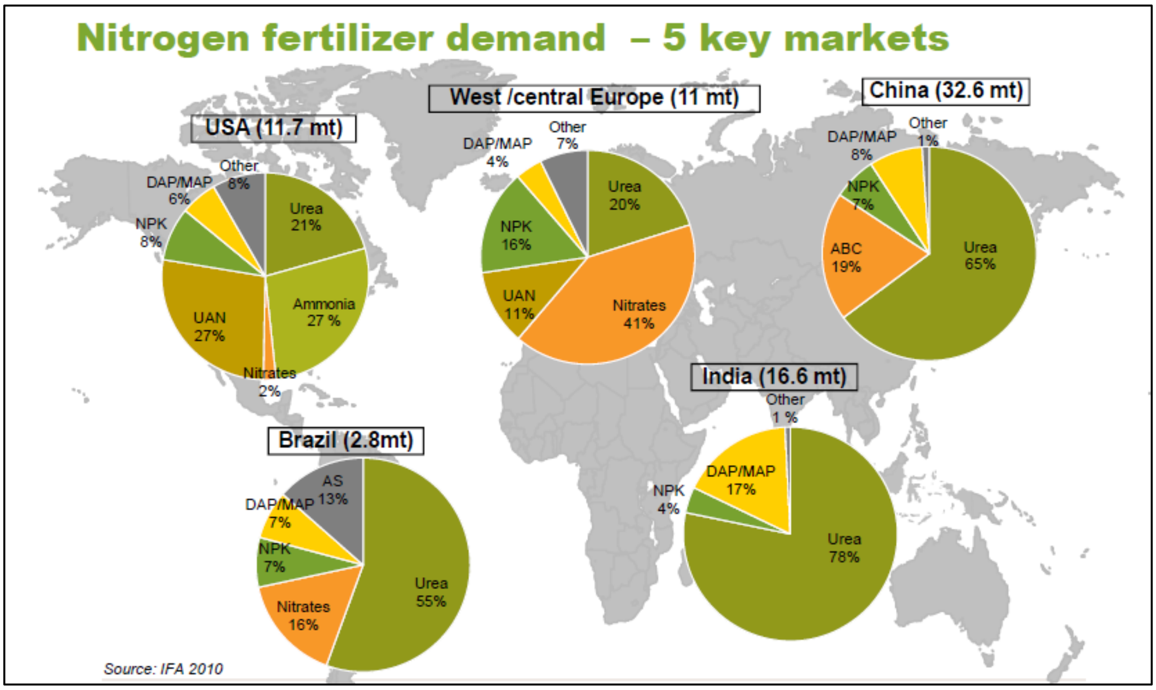
3 Ammonia application and feasibility of ground injection

The purpose of this section is to explore the application methods of anhydrous ammonia and assess practicality and usefulness

3.1 Global application of anhydrous ammonia

Anhydrous NH_3 can be applied to land and provide a satisfactory N-fertiliser. However, it is not widely used in the UK. The USA applies approximately 27% of its fertiliser in liquid anhydrous NH_3 form – however it is the only global region presently to do so due to the commercial availability of solid forms and urea.

Figure 6 : Nitrogen demand and application type-global (2010)[5]



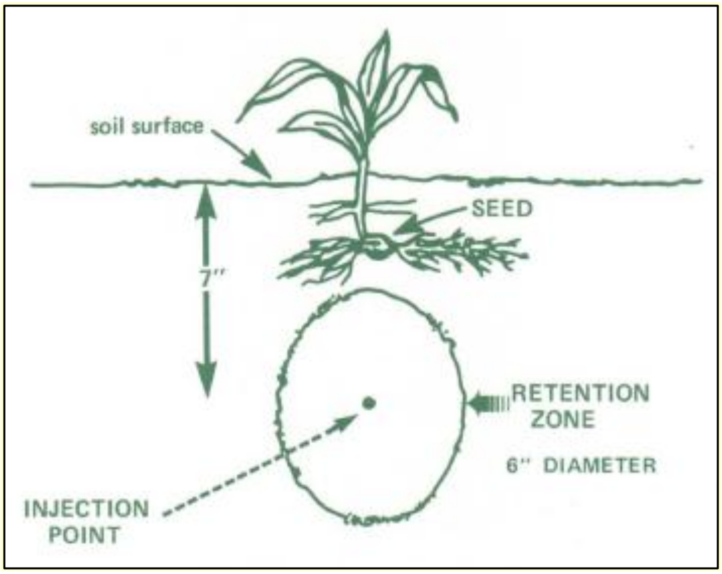
Stored as a liquid under pressure (8 bar) or refrigerated (-33.3°C)[6] NH_3 (ammonia) becomes a gas when exposed to air and needs to be injected into the soil to prevent loss to the atmosphere which can greatly reduce its effectiveness as a fertiliser. Hence injection is a technique that has been successfully used in the USA and used previously in the UK.

3.2 Ground injection of liquid ammonia

Liquid ammonia is applied to land by means of deep injection to 15-20 cm. Soil application takes advantage of the rapid expansion of liquid ammonia into the gaseous form and its tremendous affinity for water. When the liquid is released in the soil, it quickly spreads out to a diameter of about 6 inches depending on the rate applied, soil moisture, and soil texture. All parts of the injection machinery and contact surfaces must withstand a minimum working pressure of 250 psi (17.2 barg). Providing the depth of injection is adequate, little or none of the NH_3 is lost to the atmosphere.

[5] http://www.yara.com/doc/57957_2012%20FIH%20Dec%20slides%20only.pdf
[6] (Lan et al., 2012),

Figure 7: Ammonia injection and retention zone[7]



In the USA anhydrous ammonia has typically been applied in autumn, mainly to spread the farm workload, but also to reduce the risk of high concentrations of NH_3 inhibiting germination of spring-sown crops. However, this approach relies upon temperatures below 0°C during the winter thus inhibiting nitrification of the NH_4^+ ion and minimising the risk of nitrate leaching over winter. In milder climates or seasons crop recovery has been shown to be greater following application in spring[8] and this approach may be more appropriate for Scotland.

Figure 8: Ammonia application in the USA

3.3 Applying anhydrous ammonia in aqueous form.

Since the handling of anhydrous NH_3 is not common in the UK, the most practical means of applying NH_3 to land near sites of production may be as a solution dissolved in water. Since anhydrous ammonia needs to react with water to form ammonium in soils – there may be a good case for using aqueous ammonia in the case of very dry soils.

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[7] C.J. Overdahl and G.W. Rehm, University of Minnesota
[8] Vetsch and Randall, 2004

The limitation with this option is that while NH_3 is very soluble in water, a solution of NH_3 contains only between 20 and 24% N, compared with the 82% N in anhydrous NH_3. This lesser concentration will greatly increase the costs of transport.

If the ammonia is to be used on a single farm (case-study proposal) – then this may not be such an impediment since the transport distance from tank to field is low. It will require additional man-hours for application however. If the proposal was to produce and distribute ammonia to nearby farms – then using aqueous form would have a significant disadvantage in terms of transport cost.

Despite the greater bulk, an aqueous solution of NH_3 has some advantages. It does not have to be stored under pressure and therefore poses less of a risk to the operator (although care should still be taken in handling a solution of NH_3).

3.4 Local providers / applicators of anhydrous ammonia

Anhydrous NH_3 injection is offered in Scotland by:
D Watson & Co, Agri Services. Byeloch, Mouswald, Dumfries DG1 4JU
http://www.drewwatson.co.uk/inorganic-manure.html

D Watson & Co have offered their services to assist in any practical demonstration of ammonia application as part of a demonstration project.

3.5 Possibility for solid-state fertiliser production at farm-scale

- On a small farm-scale it is very unlikely that either Urea or Ammonium Nitrate (AN) could be produced from electrolytic ammonia. The principal reason for this is that AN production is a volatile industrial process which requires nitric acid manufacture. This would not be particularly feasible within a farm environment.

- For Urea, the production process is more straightforward – however it requires a CO_2 gas-stream to be viable. In a typical Natural Gas / Haber Bosch production process, this CO_2 gas is produced via the steam reformation process as a by-product.

- NH_3 (ammonia) can be reacted directly with potash and phosphoric acid to yield **ammonium potassium phosphate**. This option would need to be fully researched in combination with chemical processing experts – the equipment required may be feasible at farm scale – however this would need to be proven by bench-scale tests initially.

Were the electrolytic ammonia production to be taking place on a more industrial scale (i.e.: millions of litres per annum and utilising the entire wind resource of a region or island for example) - then such industrial scenarios could be envisaged in a more industrially compatible environment.

3.6 Conclusions on feasibility of ground injection of renewable ammonia

- Only the USA currently uses straight ammonia as fertiliser and this is currently all ground injected (27% of USA total fertiliser application in 2010).

- There are significant health and safety risks in dealing with anhydrous ammonia and strict protocols need to be observed.

- Application of anhydrous ammonia needs to be performed carefully to ensure correct application and effectiveness.

- Ammonia injection was previously used in UK however the practice died out due to the simpler AN application.

- The availability of a cost-effective renewable ammonia produced at point of use would be an attractive option and could result in a return to ammonia injection.

- Solid fertiliser products could be developed from renewable ammonia depending on the scale / location of the systems. St Andrews University are well-placed to further investigate these options.

4 Potential System Suppliers

4.1 Ammonia systems

At the time of writing (July 2013) there were only two commercial organisations involved in producing small bespoke wind-ammonia production units. These were **NH3 Canada** based in Nova Scotia, Canada, and **Proton Ventures** – a Netherlands based developer who is developing a 'mini' wind-ammonia unit (1000 tpa) in conjunction with Casale in Switzerland.

4.1.1 NH3 Canada

NH3 Canada is developing a modular product (NH500) which is capable of producing 500 litres of liquid ammonia per day (equates to 430 kg per day or 150 tpa).

http://www.nh3canada.com/Products.html

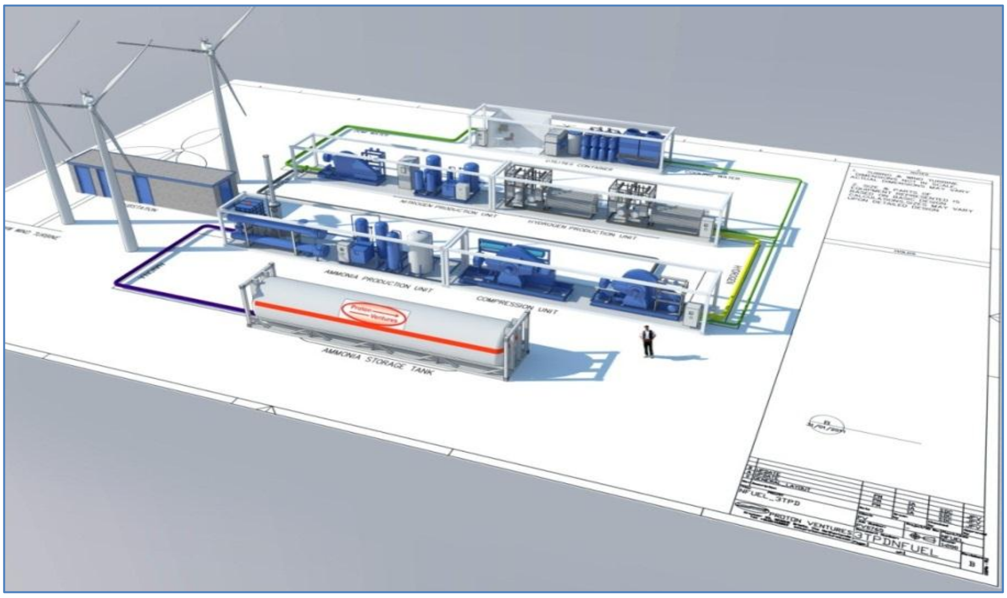
4.1.2 Proton Ventures BV

Proton Ventures BV is a Netherlands-based technology developer focussed on small-scale ammonia and nitric acid markets. Through a partnership with Casale (Swiss) Proton are developing 1000 tonnes/year mini-ammonia plants (equates to 2740 kg per day). For application with wind-ammonia this figure would be closer to 250 tonnes per annum – based on fluctuating wind power input.
http://www.protonventures.com/NFUEL.html)

Proton BV Available System details

System Size: The present system under development produces 1000/250 tpa (considerably larger than required for a small-scale farm production unit). This unit can be run at lower capacity using smaller H2 and N2 systems. The system would thereby be scalable for expansion in future by the addition of more H2/N2 capacity. Redesigning the ammonia synthesis unit at a smaller capacity would incur an additional development cost-cycle.
Estimated System efficiency: **13 kWh per kg ammonia.**

Figure 9: Proton Ventures wind-ammonia concept (1000 tpa) (250 tpa if wind powered)



4.1.3 Other ammonia system builders

There are several companies in Europe specialising in ammonia plant: the plant in these cases is very large and dedicated to large scale Haber Bosch process. Such companies may be interested in design / construction of 'mini' systems.

4.1.4 Bespoke built systems

Only one actual functioning small-scale ammonia plant has been constructed. This was built as a demonstration/ research unit at the University of Minnesota. The unit was funded by a research program and designed and built under sub-contract. In mid-2013 the unit was in process of early running trials and fine-tuning.

http://nh3fuel.files.wordpress.com/2013/01/2011-tiffany-reese.pdf

4.2 Hydrogen electrolyser system suppliers

Hydrogen system suppliers are now quite numerous – as this technology continues to grow in interest – the recent interest being from energy storage / 'power to gas' applications.

Some prime candidates active in UK would be:

- **ITM Power** (PEM systems)
- **Hydrogenics** (PEM and Alkaline systems)

The advantage of ITM Power is that they are UK-based (with an office in Aberdeen) and therefore production in Scotland is a distinct possibility.

4.3 Nitrogen production systems

PSA (pressure swing adsorption) systems for Nitrogen production is well established and there are several manufacturers in UK. Two examples of local Scotland-based manufacturers shown below:

- **Dundee Nitrogen Company**, Unit 8 Riverside Court, Mayo Avenue, Riverside Drive, Tayside, Dundee DD2 1XD
  http://www.dundeenitrogen.co.uk/Home.php

- **In House Gas (Manufacturing) Ltd**, 2, Railway Court, Lennoxtown, G66 7LL., Scotland
  http://inhousegas.com/product.php?productID=5

4.4 Conclusions on system suppliers

- Hydrogen production is a key element in the process. A UK-based supplier such as ITM Power might be best placed to supply – and could potentially manufacture in Scotland.
- Nitrogen system suppliers exist in Scotland
- Very few ammonia systems manufacturers exist who are focused on mini-systems. Proton Ventures appear to be a good candidate for system design- a Scottish manufacturer could be located to assemble the various plant elements
- An overall 'systems engineer' should be employed to oversee the full systems design & build (including civils, system integration, control systems etc.)
- For ammonia ground injection – USA based suppliers should be approached.

5 Business case and economic benefits

5.1 Economic benefits for farmer: business case analysis from Phase2

In Phase 2 a business case analysis was carried out (using an excel model) to assess the best options for a farmer producing hydrogen and ammonia via an on-site wind farm:

Options modelled included:

- Using an existing wind turbine to produce only the required ammonia quantity for 1 farm - and thereby saving on fertiliser cost (up to £50k per annum for a medium sized farm).
- Using existing wind to produce excess ammonia for sale to 3rd parties (other farmers)
- Using existing wind to producing excess hydrogen to use as ‘stand-by’ fuel for CHP.
- Install a new wind turbine and produce ammonia.

The best case-options for increased farmer revenue were found to be:

- Those where excess ammonia can be produced and sold on to 3rd parties. This was calculated on the basis of a 2013 market value for ammonia in the region of £650 per tonne.
- New wind installations facilitated by the ammonia system – whereby the existence of the ammonia unit may reduce the potentially large cost of grid-upgrade for power export (grid cost can be greater than 50% of turbine costs in some cases). Since with ammonia production the wind energy produced is used on-site (less export requirement), the grid upgrade cost can be avoided or reduced. Thus the farmer can benefit from ammonia production, increased Feed-In-Tariff, and lower grid installation costs.

The worst case-options for increased farmer revenue were found to be:

- Production of excess hydrogen for onsite use. This option was looked at from an engine-based CHP perspective (fuel cells remain expensive options). The loss of wind-energy export tariff, coupled with low ‘round-trip’ electrical efficiency of hydrogen-engine systems made this option unattractive. Full heat capture via CHP could improve this however the business case was still weak.

Details of the above analysis can be found in the Phase 2 study.

5.2 Indirect Economic Benefits to Scotland

There are additional economic benefits potentially to be derived from using renewable fertiliser – which are less tangible and harder to quantify:-

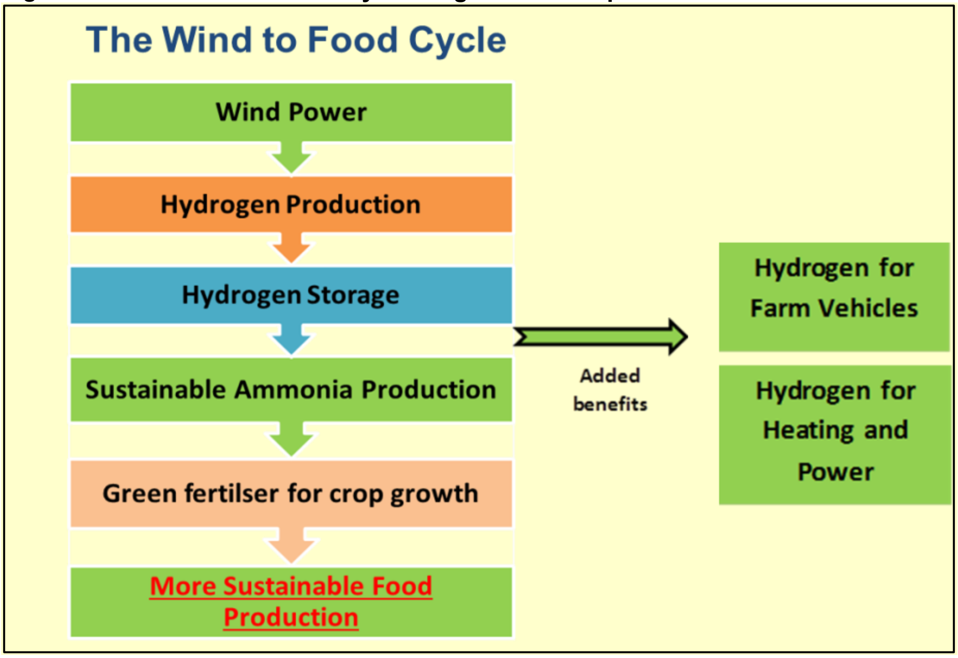
5.2.1 Sustainable food production

The food production industry as a whole (including packaging and food transport) is responsible for broadly one third of all global greenhouse gas emissions. Food manufacturers and retailers are therefore under pressure to demonstrate greener food production routes – from the initial crop in the ground to the final packaged product.

Food retailers may therefore be prepared to pay a potential premium for crops or product grown in a more sustainable manner: similar to the way in which organic foods had a price premium attached in the past. Consumers may also be more inclined to buy a product which has been produced with the aid of sustainable fertilisers.

The **'wind-to-food'** cycle therefore has some interesting green credentials which could interest the large blue-chip food manufacturers and retailers.

Figure 10: The 'Wind-to-Food' cycle for greener food production.



5.2.2 Increased investment through more wind/ PV and ammonia systems

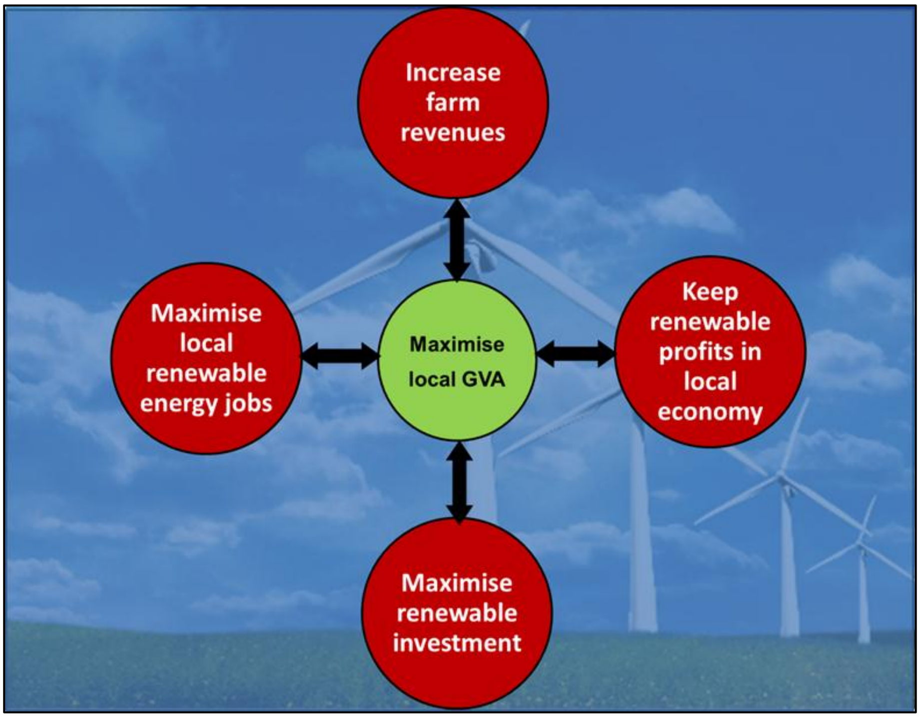
If wind-ammonia can indeed be shown to open up new wind sites, (potentially in more remote areas where grid connection costs stand in the way of current wind development) – then this could lead to an increase in wind investment in Scotland – another potential major benefit.

Such systems are far more likely to be owned and operated by local farmer-owners for their own benefit – and therefore the profit-streams would be retained locally rather than diverted offshore as is the case in some large renewables projects.

The economic drivers are therefore:

- Increased farm revenues for farmers
- Increased investment in wind and ammonia systems with profits staying local
- Increased jobs for those working in these industries

Figure 11: Optimised economic model for Scotland GVA.



5.3 Calculation of potential economic and jobs benefit for Scotland

5.3.1 High and low uptake scenarios

2 Scenarios are presented: (illustration only – based on Scotland only)

- **High Adoption :**

  Assumes 200 MW of wind power converted to ammonia production and 20 MW PV

  (Corresponds to 850 50-tonne systems)

- **Low adoption:**

  Assumes 20 MW wind and 2 MW PV

  (Corresponds to 85 50-tonne systems)

Table 3: Summary of potential benefits

Beneficiary	Potential benefit type
Farmer	Saving on cost of wind installations (lower grid connection cost)
	Saving on fertiliser cost (£330 per tonne for AN)
	Potential revenue stream from selling ammonia fertiliser to other farmer (£600-650 per tonne)
	Potential revenue stream from selling ammonia for higher value industry (unlikely in initial small-scale ventures)
	Increase FIT (Feed-in-tariff) revenue from additional wind or PV
Scotland	More wind investment generally (200MW in high case, 20 MW in low case)
	More wind-related employment
	More ‘home-owned’ wind farms – therefore profit remains in Scotland
	More Solar-PV installed on farms – PV installation employment benefit
	Saving on imported fertiliser cost
	New jobs in wind-ammonia systems installation / operation
	More investment in hydrogen-ammonia systems (potential for Scotland manufacturing base)
	New jobs in related hydrogen industries (Aberdeen already becoming a focus for this with H2-bus project)
	Increased R&D / scientific activity in Scotland in this area (research funding / employment)
	Potential for increase in farm/food output via ‘green food’ potential
	Potential new jobs around the supply of new equipment needed for farm ammonia ground-injection

Based on some of these considerations – the following table gives an assessment of the potential for capital investment, cost savings, turnover improvement and new jobs that could result if the high / low uptake option was be realised. Note that these numbers are estimates and are based on a number of assumptions. The timescale to achieve such numbers is estimated at 10 years.

Table 4: Estimates of relevant jobs / costs / investment potential after 10 years

Item	Est. of benefit based on High / low	
	High uptake scenario (200 MW wind and 20 MW PV)	**Low uptake scenario (20 MW wind and 2 MW PV)**
New wind investment initiated (total Capex)	**£220m** (£1.1 m per MW)[9]	**£22m** (at £1.1 m per MW)
New PV investment (Capex)	**£20m** (£1m per MW)	**£2m**
Hydrogen-Ammonia systems investment – (Based on £2m per MW in low case – £1.5m in high case)	**£330m**	**£44m**
Ammonia Fertiliser produced pa (added farm T/O and saving on fertiliser cost)	68,000 tonnes ammonia (value £600 per tonne = **£41m**)	6,800 tonnes (value £600 per tonne = **£4m**)
Jobs in ammonia systems (Based on 1 per 1MW systems in operation)- *(assumes systems built locally)*	200 in manufacture, 50 in installation and maintenance, 44 in operations **Total 294**	25 in manufacture, 10 in install & maintain) **Total 35**
Potential jobs lost in traditional ammonium nitrate supply	**Est. 4***	**Negligible***
Est. new jobs in hydrogen related equipment *(assumes local build)*	**Total 50** as 1 significant supplier relocates to Scotland and expands.	**Total 4**
Potential jobs from supply of ammonia injection equipment	**Total 10** in supply & maintenance	**Total 2**
New research funding and jobs	**Est. £5m pa / 10 research posts**	**Est. £1m pa / 2 research posts**
Total £ Investment (after 10 years)	**£570 million**	**£68 million**
Total income benefit (per annum after 10 years)	**£46 million**	**£5 million**
Total Net Jobs added**	**360**	**43**

***Note:** *Most traditional fertiliser (ammonium nitrate) is now produced outside of Scotland and UK: therefore no real jobs loss from introduction of a new process. Only potential for job loss in in the distribution and sale of AN.*

**** Note:** *temporary jobs resulting from wind/PV installation not considered.*

[9] http://www.wind-energy-the-facts.org/en/part-3-economics-of-wind-power/chapter-1-cost-of-on-land-wind-power/cost-and-investment-structures/

The assumptions are based on a significant movement of manufacturing potential to Scotland for hydrogen and ammonia systems. We would recommend that all the major hydrogen / ammonia components are manufactured within Scotland to maximise this potential and to lock in science and engineering expertise for the future.

5.4 Conclusions

- Renewable ammonia can be shown to demonstrate a reasonable revenue stream for farmers – in the supply of fertiliser to neighbouring farms and in savings on their own fertiliser cost.
- Ammonia from wind can improve the prospects for wind-investment and reduce grid connection costs which are currently holding back expansion.
- Renewable ammonia from wind / PV could generate significant new investment in Scotland.
- Assuming full realisation of the concept, and allowing for forward projections which could see an expansion of the concept based upon the high and low uptake scenarios, the following is an indication of potential financial and jobs benefit to Scotland (based on a significant proportion of Hydrogen, Nitrogen, and Ammonia systems built in Scotland):

- **High Scenario (220 MW renewable to ammonia):** (after a 10 year period)
  (Represents 850 mini systems producing 50 tonne ammonia each)
  - £570 million investment
  - £46 million per annum income benefit
  - 360 added jobs.
- **Low Scenario (22 MW renewables to ammonia):** (after 10 years)
  (Represents 85 mini systems producing 50 tonne ammonia each)
  - £68 million investment
  - £5 million per annum income benefit
  - 43 added jobs

6 Capital costs and estimated payback

Capital costs are difficult to predict for the following reasons:

- No commercial developers of 'mini' ammonia systems have launched product yet.
- Some developers have developed prototype product / or 'drawing-board' concepts – but are yet to produce units commercially.
- Commercial costs for such units will be initially high but will fall with increased take-up.
- Some 'mini' concepts have been considered at the 1000 tpa (tonne per annum) scale – the cost to do this at the 50-100 tpa scale needs further clarification.

6.1 Conclusions on capital cost and payback

The hydrogen component (electrolyser, compressor, storage) is expected to constitute in the region of **70% of total capital cost.**

On that basis and via discussions with system developers the following cost-ranges have been estimated:-

- For a complete bespoke mini system (in the range 230-kW H_2 production) - designed to be capable of producing 50 tonnes ammonia per annum: capital cost would be in the range: **£1.2m - £2.0m**
- Choosing a larger 200 tonnes per annum system (850-kW H_2 production) will increase the capital cost - however will allow increased revenues from sale of ammonia to 3rd party farms.
- For the existing (already designed) 1000 tonne per annum 'mini-system' available from Proton BV – cost is in the region of **£3m.** By reducing H_2/N_2 capacity and running this larger unit at 100/200 tonnes per annum it is estimated that cost could reduce by 25%: **£2.25m**
- Increased revenue for farmers could be in the range **£35k pa** (small 230 kW system) to **£100k pa** (larger 850 kW system)
- Additional revenue could be realised from increased FIT (feed-in tariff) from new turbines and a 'one-off' cost saving on grid connection cost (typically 20-30 % of turbine cost – however could be greater than 50% in some cases.)
- At present the overall payback for such a system will be long: in the region of **15-30 years** depending on scale of the system and circumstances.
- Costs may come down significantly over time as more units are developed should this technology take off.

7 Anhydrous ammonia: greenhouse gas emission benefits

7.1 Emissions impacts

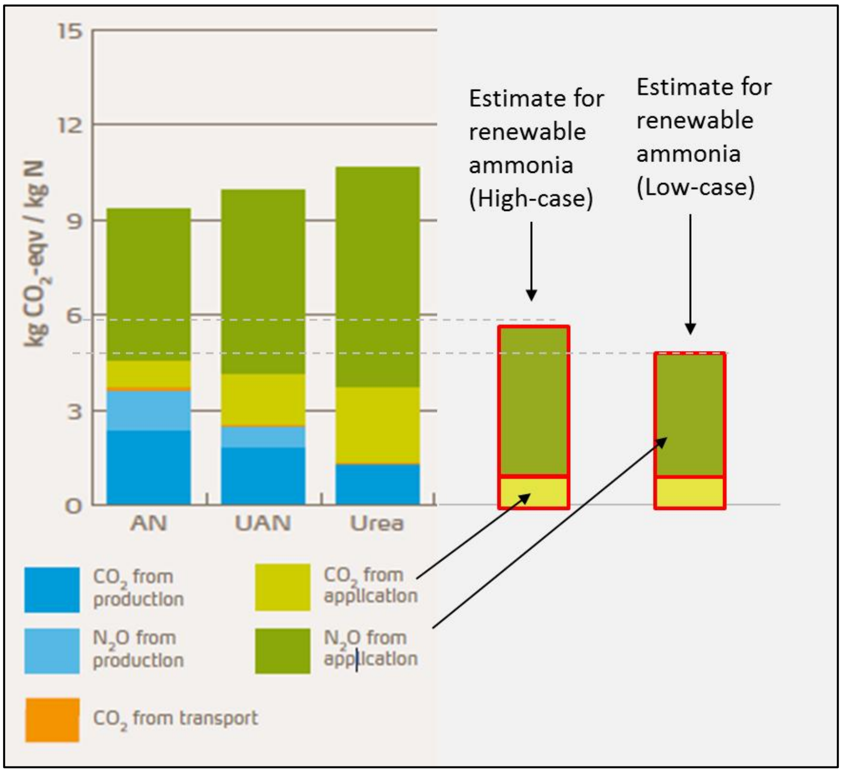
Renewable anhydrous ammonia has zero production emissions since its production will be entirely based upon electrical power from wind. It will also produce no direct CO_2 emissions in application and produce arguably lower N_2O emissions in application if it is injected below the soil surface.

Some CO_2 emissions will result from vehicle movements during application which may be slightly greater than with solid forms – however overall vehicle emissions will be lower since the product is manufactured close to the point of use.

No comprehensive LCA studies for injected anhydrous ammonia appear to have been completed previously – and this was outside of the scope of this report –however an estimated GHG analysis for renewable ammonia is shown below for comparison. This estimate has been made conservatively and a high and low estimated value attributed to potential overall GHG emissions.

As the graphic in below shows, the overall equivalent GHG emissions of renewable ammonia from wind would be considerably reduced when compared to existing fertiliser production and application and would be roughly half those of traditional materials.

Figure 12: Estimated GHG emissions for renewable ammonia when compared to existing fertiliser product (based on best assumptions from available literature)



From the above:
Estimated saving = ***4 to 5 kg CO2 (equiv.) per kg Nitrogen***

7.2 Total potential carbon saving by adopting renewable fertiliser.

Table 5: Potential for GHG saving in Scotland from adopting renewable fertiliser production

Fertiliser type	Total use in Scotland k-tonnes pa	Total equiv N content in Scotland k-tonnes pa	Est. CO2 eq. saving per kg N by switching from trad. fert to NH3 (CO2 kg eq.)	Est. GHG saving (k-tonnes CO2 eq.)
AN (34% N)	116	39.4	4	157.6
Urea (46 % N)	13	6	5	30
UAN (28% N)	27	7.6	4.5	34.2
Total	**156**	**53**	**-**	**222 k-tonnes**

Based upon the figures shown in the total potential carbon saving from moving all of Scotland's straight Nitrogen fertiliser usage to ammonia from wind would represents a global carbon saving of **222 k-tonnes CO2 eq.**

Based on the latest Scottish data for GHG emission (51.3 million tonnes CO2 eq. in 2011)[10] – this carbon saving would be equivalent to **0.4%** of all Scotland's GHG emissions

The total carbon saving within Scotland would require a closer analysis – since not all fertiliser used in Scotland is produced here at present. Therefore all of the agricultural savings would be realised in Scotland, however some of the production savings would be experienced elsewhere – at the point of fossil fertiliser production.

7.3 Conclusions on GHG impacts of renewable ammonia

- Considerable GHG results from the application of traditional ammonium nitrate and urea as fertiliser – these are primarily due to the release of CO_2 and N_2O during manufacture and application.
- Asian fertiliser trends using ammonia from coal will significantly worsen the carbon emissions.
- Using renewable ammonia from wind would reduce present overall emissions by an estimated 50%.
- Across the whole of Scotland a saving of some 222 k-tonnes of GHG (CO2 eq.) could result from a complete switch from fossil fertiliser to renewable nitrogen fertilisers. This represents approximately 0.4% of Scotland's current GHG production from all sources.

[10] http://www.scotland.gov.uk/Topics/Statistics/Browse/Environment/TrendGasEmissions

8 Roll-out Strategy

8.1 Target applications

The proposed wind-ammonia system was investigated in detail in Phase 2: The target application and system specifics are as follows:

- The ideal test-ground for such a device is on farms with good wind resource, existing wind-turbine systems above 100-kW (or similar PV), and a requirement for Nitrogen-based fertiliser
- Farms which currently have costly export-connection costs will be ideal test-cases as the device has the ability to reduce dramatically (or eliminate) grid-export connection costs.
- Sites where ammonia could be applied to the land without undue risk to NVZ (Nitrogen vulnerable zones) (although this risk should be no greater than with AN application).

8.2 Considerations for roll-out / system scale

The roll out of such novel technologies should be approached in a step-by-step manner – such that lessons can be learned during the development process and expensive mistakes avoided.

For the initial roll-out of a wind-ammonia system in Scotland, we recommend the following:-

- The initial development should be designed on a modest basis to prove the principle and the commercial readiness of the concept.
- Capital Cost is the key challenge here – keeping the cost low may be enhanced by the use of standard (off-the shelf) systems.
- If the system can be designed to be scalable – such that a relatively small scale system may be readily expanded in future - this may pose some significant benefits for future expansion and keeping initial cost lower. Once the system was proven – up-scaling could impact positively on revenues.
- The ultimate location of the unit will be on a farm where there is significant wind energy resource, existing wind-turbine / PV output – and where the requirement for ammonia for crop application is significant.
- There is logic in housing the facility within an academic research environment initially – to interrogate system operation, efficiency and application. The system could be subsequently moved to a farm environment.
- For practical purposes, the prototype site should reasonably close to a large commercial centre such as Aberdeen. This will be beneficial from the perspective of initial installation, site visits by engineers, and future dissemination / collaboration activates.

8.3 Roll out plan

A plan for how the concept could be rolled out gradually in Scotland could look like:

Stage 1: Tender for consortia to build modular 100-300 kW device / seek funding to start: 2014.

Stage 2: Design and build of prototype device on small (100-300 kW scale): 2014/2015.

Stage 3: Trial running period to assess effectiveness: 2015 (possibly on an academic site).

Stage 4: Move prototype to ‘real-world’ farm environment – expand production if appropriate: 2016

Stage 5: Roll out further medium scale (300 kW+) devices in suitable parts of Scotland (based on lessons from prototype 1): 2017.

Stage 6: Potential Roll out larger scale units (1000 kW+): 2017:2020.

8.4 Roll-out sites

The choice of Aberdeenshire for the initial prototype roll-out is made for several reasons:

- **i.** A suitable site has been found for this (Mackie's farm in Aberdeenshire)
- **ii.** The location close to Aberdeen opens up a number of benefits (good communications, travel proximity for system-build engineers) and hence may reduce installation cost.
- **iii.** The site is close to the proposed Aberdeen Hydrogen bus project which may present some collaborative or synergistic benefits.
- **iv.** The site is close to the All-Energy exhibition site and can provide for maximum publicity for the initial device by site tours of UK/international parties.
- **v.** Close to a major urban centre / Universities etc. for collaborative purposes.
- **vi.** Potential for replication by other farmers in Area A, as grid constraints are a common issue for farm scale wind in this area.

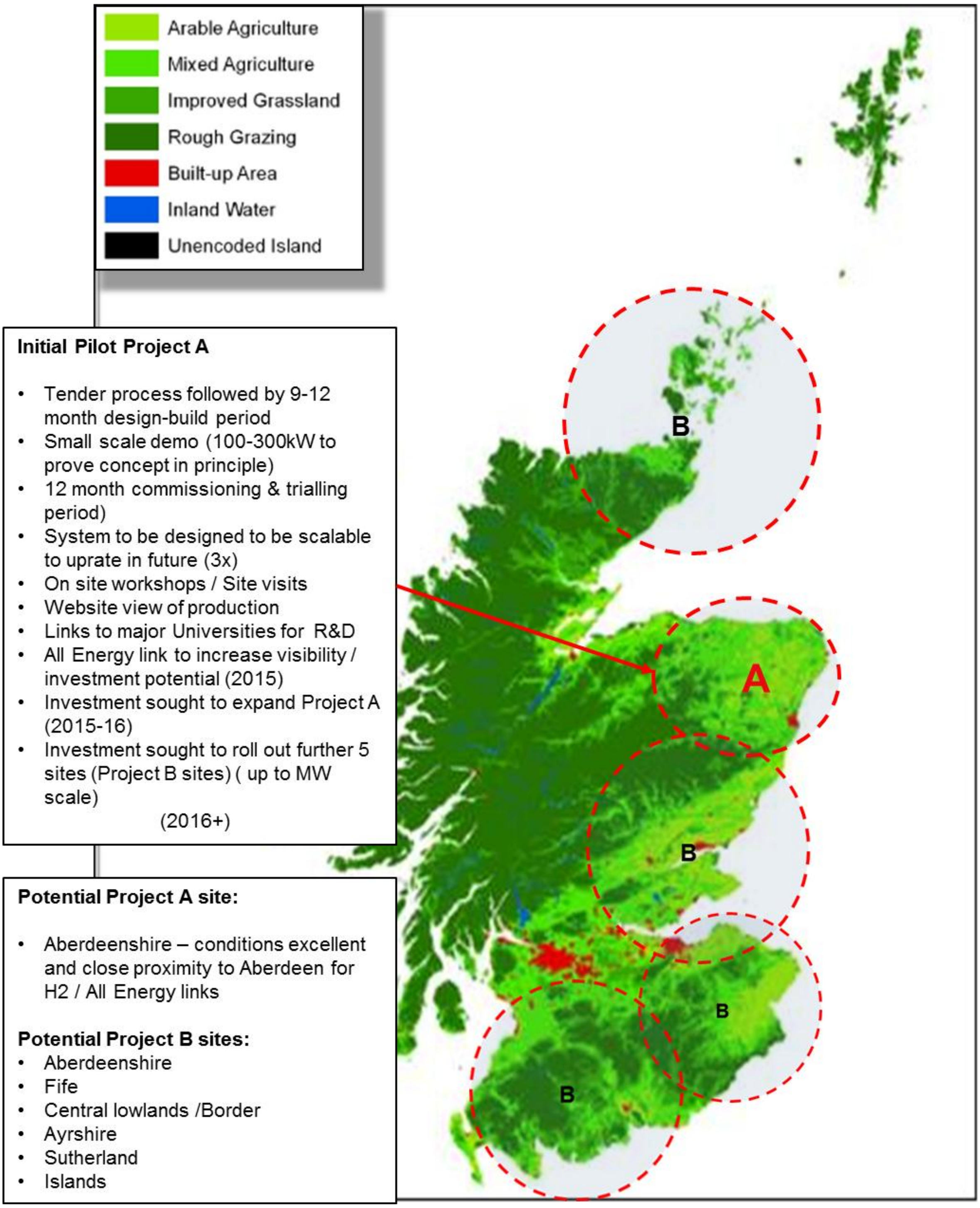
The location of subsequent sites is less prescriptive – these could be anywhere where there is a good facility for wind and a requirement for ammonia-based fertiliser for mixed-mode farming.

Such sites may include:

- **i.** Fife,
- **ii.** Aberdeenshire,
- **iii.** Sutherland
- **iv.** Scottish Islands (where there is mixed farming – not merely sheep grazing)
- **v.** Central lowlands
- **vi.** Borders
- **vii.** Ayr

The map of potential A and B locations is shown in Fig 13.

Figure 13: Potential A and B sites



Note: The brighter green areas above indicate arable or mixed agriculture and are therefore most highly suited to the application.

8.5 Additional issues to consider for future roll-out sites

One of the main benefits of wind-ammonia is the reduction in potential grid-export costs for wind turbines (since the vast majority of wind energy will be used on site rather than exported to grid).

This being the case it may be worth selecting future roll-out sites on this basis: i.e.: where grid export connection is currently very high or non-feasible (e.g.: Aberdeenshire and other remote but windy locations) – there may be a stronger case for implementation here.

Island groups can have extremely high wind resource – however limited wind energy requirement. Here there may be a stronger case for siting a large wind-ammonia plant which could supply a large proportion of the Island's fertiliser needs.

8.6 Other issues to consider with roll-out

The initial prototype will be the most costly device to build – as it will involve much initial design work and first-consideration of many of the issues. Subsequent device cost should then fall: the following may be important to ensure this is the case and to ensure maximum benefit for Scotland:-

- **i.** The first prototype unit could initially be housed within an academic unit for initial technical assessment - before being moved to a rural site (see conclusions).
- **ii.** The design of the initial prototype could be replicated for the first handful of second-stage sites – thus reducing the unit cost.
- **iii.** For the ammonia synthesis plant - a further option may be to buy / license a design from an existing (non-UK) ammonia system supplier – and build in Scotland using local engineers / contractors – or to use the existing supplier and insist on a local build.
- **iv.** Where possible the build of the key sub-systems (hydrogen unit, ammonia plant, nitrogen plant, storage tanks, control systems) should be built locally. There are a number of companies either within Scotland or with strong links to Scotland who could be involved is such design and build work.

8.7 Conclusions on Roll-out

- The initial prototype should be produced on a modest scale to test the concept in principle. This design could be modular - such that the device could be up-scaled in future (cost permitting).

- The location of the initial device should be in a location where wind/ammonia constraints are fewest – but also in a location which lends itself to easy access, communication, links to industry etc. A site close to Aberdeen is logical.

- The concept of a high-temperature / high-pressure ammonia synthesis plant on a farm environment does raise some realistic H&S concerns relating to training of farm personnel in the case of the first development: An option has been raised by St. Andrews University to house the unit initially within a University environment (Guardbridge campus in Scotland where St Andrews is establishing a Green Energy Centre and a Knowledge Exchange Centre for spin-out companies, new business and prototype testing on the site of the former Curtis Fine Papers Mill).[11]

[11] http://www.st-andrews.ac.uk/news/archive/2012/title,85147,en.php

- Such an approach would facilitate opportunity for detailed studies to be carried out on the unit (efficiency, productivity, impact of fluctuating power supply etc.) in combination with training and assessment of any H&S issues in a 'safe' environment. The farm staff from Mackie's could easily travel to this site for training in the system operations & maintenance.
- Additionally the St Andrews staff could investigate the feasibility of solid fertiliser production Vs. injected liquid ammonia.
- The build of the unit should be carried out with as much Scottish engineering input as possible – thus ensuring that the expertise exists locally from the outset.
- The second-phase of devices: location and scale should be carefully considered – these considerations should be based on the experience of running the prototype for at least 1 year.

- **Pre-build fact finding:** Before any design process goes ahead it is recommended that a team with engineering and agricultural knowledge carry out the following fact-finding visits:-

  - USA, to observe the first prototype unit built at University of Minnesota, and also visit a number of local farms using anhydrous injection to better understand the issues. Michael Reese, Professor at University of Minnesota may be able to engage in such a 2-way visit arrangement with a return visit to Scotland (All-Energy) planned for the future.
  - Canada, to view the progress on testing prototypes at NH3Canada.
  - Proton-ventures / Casale in Switzerland where a 20 tpa ammonia plant is running.

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