Sustainable Hydrogen Fuel

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Preface

This report is aimed at an audience that are interested in renewable energies and a more sustainable future. People who are involved with hydrogen and are keen to find out its potential would also benefit from reading this report. The report was written for the intensive engineering visions program. It should provide an insight into how the carbon footprint can be decreased and why hydrogen is a viable energy solution for the future. This report will cover main areas such as hydrogen production, storage and distribution, domestic integration and safety. The team firstly researched the potential of hydrogen as a substitute to natural gas and its feasibility in the future. Tasks were evenly divided within the group and parts of the report were written individually and accumulated at the end. The group worked well together, according to our DISC Personality Tests (Appendix i-v), there is a fairly even split of different personality types which provided a wide range of views and opinions. This greatly benefitted the report writing and other elements of the project.

Abstract

This project details the domestic use of hydrogen for fuel.
The feasibility calculations are mostly made with the Netherlands in mind, but adapting this system to other industrialised nations' infrastructure should not prove much of a challenge. Assumptions were made that once this system gets implemented there will be a sufficient amount of renewable electricity sources that will provide excess energy to convert to hydrogen through methods investigated in this report. Storage and production facilities will be constructed for each residential community or household which use photovoltaic (PV) cells and electrolysis to generate hydrogen.

The resulting hydrogen will be stored and distributed through what is now the natural gas distribution and storage network in the Netherlands. Almost every Dutch home is already connected to the natural gas infrastructure (van 't Hof, 2018). Minor adaptations to older piping and larger pipes would be needed. Trucks carrying hydrogen would be used during the transition periods.
The gas network would be used bidirectional much like the current electricity network, so communities can either contribute or take.
Houses are heated by combusting hydrogen. The by-product of this is water which can again be reused for electrolysis. This creates a sustainable hydrogen cycle.

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Introduction

In the light of global warming, renewable energy sources are becoming increasingly important. Replacing natural gas with hydrogen is one step towards a sustainable future. This could significantly decrease the amount of harmful carbon dioxide in the environment. In 2014 European Commission set sustainable development goals to increase the amount of renewable energy produced to 27% by 2030 (European Commission, 2014). Currently natural gas and petroleum in The Netherlands accounts for most of the fuels used. Renewable energy only provides a small amount of the total fuel consumption (see Figure 1).

To meet these goals the energy sources must change within the near future. Car manufacturers such as Hyundai and Toyota have been developing hydrogen fuelled cars and they have recently become available commercially. These cars use hydrogen batteries which then convert to electricity and the engine works as a regular electrical engine. This highlights how viable hydrogen is in the future of sustainable energy, in the automotive industry and possibly in homes.

The report contains information of the feasibility of hydrogen as a fuel for domestic use. It outlines the acquisition of hydrogen, from existing technologies, such as photovoltaic solar cells, to new and developing innovations, for example photoelectric solar cells. The transport and storage of hydrogen will also be a main topic in this report, it will look at the existing gas infrastructure the Netherlands already has in place and its suitability to transport hydrogen. This report also looks at some short-term solutions while the existing gas pipes are replaced such as the possibility of hydrogen being transferred by truck to local stations. There will be safety issues regarding hydrogen in the home and its transportation which the report will also cover. Finally, the report will look at how hydrogen can be integrated into homes with minimal wastage and expense. The research was conducted by looking at similar schemes already in place in other developed countries. The feasibility of the scheme which the report outlines was based around a street or individual house in The Netherlands and using the existing infrastructure already in place.

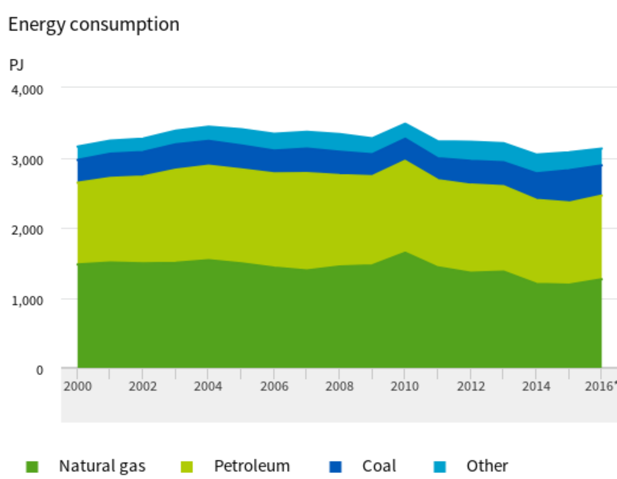

Figure 1: Energy consumption in the Netherlands (Centraal Bureau voor de Statistiek, 2017)

Hydrogen Acquisition

Currently hydrogen production is mainly achieved via steam reforming of natural gas. This is not sustainable as it produces carbon dioxide as a by-product, although the carbon dioxide can be captured and stored in the long term. It is to be replaced with electrolysis of water using renewable energy sources, this produces only pure water as waste.

In the engineering vision for the future, every community of a few households would have their own hydrogen production site which is independent of the larger hydrogen grid and self-sustainable. Electricity from rooftop solar PV cells is used to generate hydrogen using electrolysis and then stored in tanks and then distributed to households using the existing natural gas network. PV cells are a good candidate for electrolysis because they generate DC and not AC current like alternators do. In more rural areas, it makes more economic sense to have the infrastructure for electrolysis in each individual household since the buildings are further apart.

According to our calculations (Appendix vi), if the natural gas that is currently used in the Netherlands was to be replaced with this system each household would need 38 m^2 of rooftop PV. The efficiencies used for the calculation are not currently commercially available but are predicted to be in the near future. Electrolysis and PV are very active fields of research so their efficiency and economic viability is predicted to improve.

Additionally, the excess electricity produced by renewable sources such as wind turbines and PV power plants will be stored in the form of hydrogen by also using it for electrolysis. This is a sustainable and efficient alternative to storing it in batteries or as potential energy by pumping water up to higher elevations. This means that homes could deal with the peaks and troughs of gas usage effectively through hydrogen reserves.

Photoelectrolysis is another promising upcoming option. According to recent studies it’s considered to be a feasible way of hydrogen production due to its potential efficiency, renewability and inexpensiveness. However, the efficiency of these cells is currently about 18% (Hsu, 2018) under laboratory conditions. This is significantly lower than photovoltaic electrolysis. The technology is in its infancy, further research and studies are required to make these photo electrolysis panels viable domestically.

Storage and Distribution

Current Distribution Network

Natural gas is mostly extracted from underground regions that are offshore. The gas is usually found in a liquid state and after extraction it is separated into useable oil and water. Afterwards the natural gas is transported to gas processing plants where it is filtered and converted to gas. The remaining product is sent off to compression stations which either go to main line sales, such as industry, underground storage facilities or to natural gas companies. These natural gas companies then distribute the gas to different consumers.

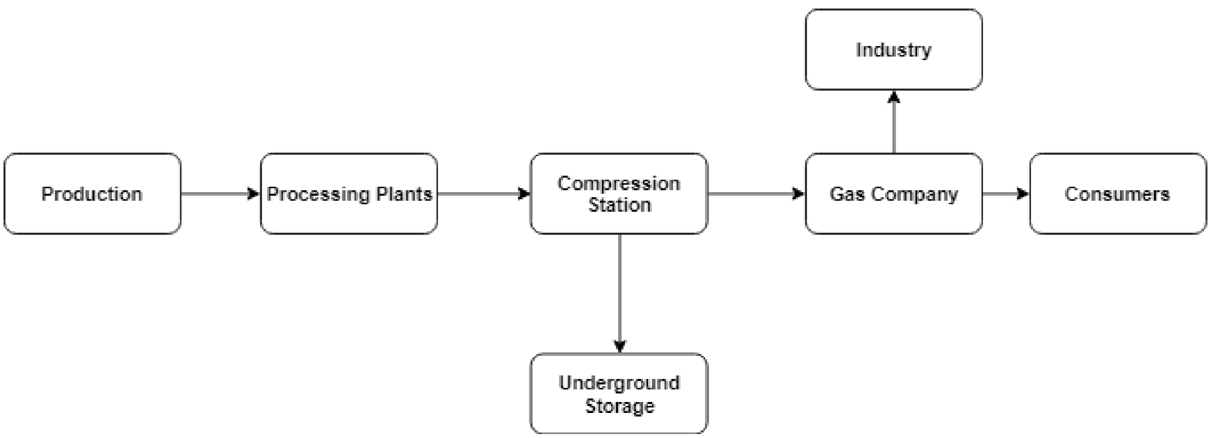

Figure 2: Simple representation of the current gas distribution network

Converting the Distribution Network

Currently the pipes used for transporting natural gas are made from either steel or polyethylene. In recent years steel pipes are starting to get replaced with polyethylene pipes as they need repaired, however a fair number of older pipes are still made from steel.
One of the problems with using these steel pipes is hydrogen embrittlement (E.Dodds, 2013). This is the principle of a metal becoming brittle and subsequently developing fractures because of the prolonged exposure to hydrogen. These fractures can grow over time which will eventually lead to material failure and leakage of hydrogen.
High pressure gas lines, mostly used between processing plants and compression stations, are almost solely made of steel which means polyethylene cannot be used as a substitution. Therefore replacing natural gas with hydrogen would result in replacing almost all of these high pressure gas lines with pipes made of a softer steel which reduces the rate of embrittlement.
The pipes between consumers and gas distributors are, for the most part, made of polyethylene. According to research presented at the International Gas Union Conference 2017 (Iskov, 2017), long term exposure of hydrogen has no influence on the integrity of polyethylene pipes.
As a result the current low pressure piping system can for the most part stay the same.

Smart Hydrogen Monitor System

Converting the current gas infrastructure from natural gas to a renewable hydrogen system would mean that there would be multiple sources of gas production, some of the hydrogen is produced by excess wind energy while other parts are produced by PV-solar panels. This means that the current methods of monitoring in gas infrastructure could need somewhat of an overhaul.

Smart Gas Grid

Electricity companies have the same problem, where electricity is produced from different sources and the grid needs to be monitored to meet the demand. The solution of the electricity companies is the principle of a “smart grid” (Smart Thinking, 2018) where sensors are implemented into the grid for monitoring shortages and overload. A smart grid can redirect excess energy depending on the demand and can monitor electricity usage for each household. Being able to show the consumer what their current electrical usage is gives electrical companies the opportunity to charge different rates during different times. An example of this would be charging less during off-peak hours to prevent gas shortages during peak-hours.

A similar principle needs to be implemented into the gas grid before different renewable energy sources can be used as the main source of heating. Sensors in the gas grid would monitor the amount of excess energy converted to hydrogen by the windmills, the amount of hydrogen produced by the PV-panels and the amount of hydrogen needed by the consumers. Just like in the electrical smart grid higher gas prices during peak hours could lower the amount of gas usage during current peak hours. Furthermore, the monitoring of all produced hydrogen versus the amount of hydrogen necessary would prevent shortages and help gas companies prepare for peaks and troughs of gas usage.

Current Storage Techniques

Keeping up with the demand of natural gas is a challenging task and to ensure that at every peak and trough of usage during the day is met, storage tanks between compression stations are used. These compression stations are needed every 50 to 150 km and use an industrial electric motor.
Hydrogen has a high energy content of about 120 MJ/kg (DoE, sd).
One of the main problems with this is that hydrogen is not a particularly dense gas, resulting in hydrogen under 700 bars having an energy content of about 5 MJ/l (DoE, sd).
Storing hydrogen as a liquid gives it a higher energy content of about 8 MJ/l (DoE, sd), however converting hydrogen from a gas to a liquid and afterwards converting the liquid hydrogen back

to gaseous hydrogen is considered very inefficient which makes using liquid hydrogen as a renewable energy carrier not viable.
Therefore the gaseous hydrogen has to be stored as a gas in specialised tanks.
According to our calculations (Appendix vi) an average Dutch household needs 41 145 MJ of hydrogen for all of the heating in a year.
Assuming the pressure in the tanks is 700 bars, which gives an energy content of 5 MJ/l, the total volume of a tank needed to store the hydrogen needed by one family for a year is about 41 145/5 = 8229 l.
There is no need to store the hydrogen that an average household needs for a year, however this does give an indication of how much storage space will be needed for a single home or a community of homes. Storage techniques similar to the current approach can be used for the switch to hydrogen, the conversion will not be seamless, the current infrastructure will need to be changed.
In the Leeds H21 City Gate project, converting the city of Leeds in Britain to hydrogen fuel through steaming. Their excess hydrogen will be stored in underground salt caverns that already existed a short distance from the city. The hydrogen can be stored here long term and when it is needed in the city it can be extracted quickly and with ease. (Sadler, 2018)

Hydrides

Despite liquid hydrogen having a much higher energy content than hydrogen in the gaseous form, converting the gaseous hydrogen to a liquid and then converting it back to a gas requires huge amount of energy. It would make the process significantly more inefficient.
Hydrogen can be stored as a gas; however, this will take a great deal of storage space.
This is the reason hydrides can be considered as a future storage method for hydrogen.
A hydride is a particular element that can create a bond with hydrogen (Grossman, 2012).
The strength of this bond is dependent on the element, in general an element which the bond is not too strong with but also not too weak is considered as a viable hydride.
In hydrides the bond between the hydrogen and the hydride element needs to be strong enough to keep the hydrogen in place and for it not to dissipate into the environment but also weak enough so that it does not require huge amounts of energy to split the hydrogen again.
Storing hydrogen in hydrides would mean that high pressure tanks or the conversion of gas hydrogen to liquid hydrogen would not be necessary. An optimum hydride would be one that could be split and reused multiple times, this results in minimal wastage and reduces the costs involved in hydrogen storage. Currently the perfect goldilocks material has not been found as the material both needs to be relatively inexpensive and also needs the perfect balance of strength. Further research is needed in this field, but hydrides ultimately should be a valid option for hydrogen storage in the future.

Domestic Integration

Hydrogen Conversion for Domestic Appliances

For the hydrogen system to be cost effective regular methane gas appliances, such as boilers and cookers, must be converted to support hydrogen gas. This ensures that old appliances are not being wasted, resulting in the scheme having minimum impact on the environment. Research shows that existing natural gas appliances can be used with hydrogen so long as the seals are made tighter and the burner heads are either replaced or tightened. (Dodds, 2013). For the Leeds H21 project for the full city with a population of 780.000 as of 2018 (Leeds City Council, 2018) the total cost of converting the cities domestic gas appliances was estimated at £1053m (Sadler, 2016) converting to €1166m. This money cost is being spread out among the gas networks users over multiple years and will therefore not majorly affect the consumers gas bills. This was the business plan used in 1970s in the UK when converting from local gas plants to a national network.

The Hydrogen Cycle Within Homes

The vision is for homes in the Netherlands to be almost self-sufficient when it comes to hydrogen with the aid of photo electrolysis cells placed on rooftops or in gardens much like photovoltaic solar cells are today. These photo electrolysis cells are currently in their infancy however with further research and investment these could be a viable option for the future. Current photovoltaic solar cells already installed in houses could also be used for hydrogen production in the immediate future. A cycle of hydrogen can be put in place in future hydrogen fuelled homes as shown in Figure 3.

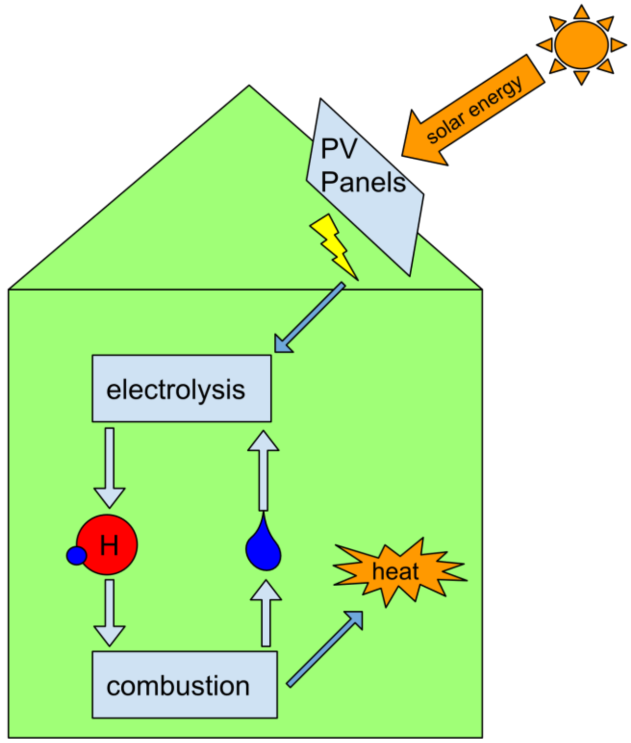

Figure 3: A Happy Hydrogen House

The hydrogen cycle in homes works as demonstrated in appendix ix, it is assumed the conditions are perfect and there are no losses.

One water atom H_2O is composed of two hydrogen atoms and one oxygen atom. Therefore, per hydrogen atom there is half an oxygen atom. When hydrogen is ignited it comes into contact with oxygen in the air and water is formed. If we take the ratio of the weight of oxygen to hydrogen 8:1 it shows that 9 times the weight of water will be produced for every hydrogen atom. As a result, a significant amount of water by-product is formed.
$9 \times 345 = 3111\,kg\ or\ 3111\,l\ \ of\ pure\ water$

When photo electrolysis is available in homes this wastewater could be recycled and put through the hydrolysis process again, thus completing the cycle. This results in almost self-sustaining houses with only the need for extra hydrogen during peak winter months.

Safety

Hydrogen is odourless, invisible and extremely flammable which makes dealing with hydrogen incredibly dangerous. It must be handled with extreme caution. The current natural gas distribution network has multiple systems in place to prevent accidents, but to change the natural gas network in its entirety to a hydrogen network would mean that these preventative systems might not be enough.

Detecting Hydrogen

Hydrogen is an incredibly flammable and combustible element, it has a relatively high energy density which is why it is a suitable substitute for natural gas however it also makes it extremely dangerous. The same could be said about the safety issues for natural gas. In contrast with hydrogen, natural gas burns with a blue flame and has odorant added so people can detect it. The same protocols that are in place for the prevention of natural gas accidents can be modified to be able to handle hydrogen. An odorant needs to be added to hydrogen to give consumers a way of detecting a leakage. The odorants used in natural gas can be used for hydrogen, however combining those odorants with hydrogen in a fuel cell can cause sulphur poisoning. Alternative odorants need to be researched before hydrogen can be widely used as a natural gas replacement.

Hydrogen is also invisible to the eye (US DoE, sd) which means that a colourant could to be added to the hydrogen to make it visible and easier to detect with the human eye. Unfortunately there is no solution for this yet , which means that this is one of the main problems that need to be resolved before hydrogen can be implemented as a natural gas alternative.

Hydrogen Sensor Systems

Being able to detect a hydrogen leak as fast as possible is necessary for a world where hydrogen is one of the main source of fuel. Currently there is no hydrogen detector commercially available in the same way as carbon monoxide detectors, however, this does not mean that a hydrogen detector does not exist, there is just no current domestic needs.

There are many different sensors that can be used for the detection of hydrogen, such as a Gas Field Effect (GFE) sensor or a Thermal Conductivity Detector (TCD) (HySafe, 2009).

Further research in this field is required before hydrogen can be considered as a viable natural gas replacement. A positive aspect of hydrogen is that no carbon monoxide can be produced when it is combusted.

Ventilation

Ventilation is a safety measure already used in most places where natural gas is the main source of heating. Being able to circulate the air will prevent dangerous gasses from building up to an amount which would be harmful to life.

It is recommended to ensure that all consumers have a ventilation system which meets a certain standard before implementing hydrogen as the main fuel source in homes.

Conclusion

In our work, we firstly strived for a holistic picture of the hydrogen economy. We started researching common ways of acquiring hydrogen and converting it from and to other forms of energy. From this we found that hydrogen can be acquired from steaming methane gas which is the most common hydrogen source, and from splitting water to form hydrogen and oxygen using electrolysis. We found that hydrogen could be made using 100% renewable energy by using the electrolysis method, this made the energy source completely carbon emission free, so we decided electrolysis would be the optimum for hydrogen production. Hydrogen could also be produced by using excess energy from wind turbines and photovoltaic plants when demand of electricity dips. Photo electrolysis was a promising new technology we found out about during research and although currently it is not viable we believe that within the next few decades it could result in homes being completely self-sufficient with hydrogen fuels. All of the technologies need further development to be made more efficient and cost effective for them to be a viable solution to natural gas.

The report then focused on the logistics of hydrogen and how it could be transported to homes in The Netherlands. It became clear that the gas pipes have to be gradually replaced to polyethylene pipes which are suitable for the transportation of hydrogen. The only pipes that need upgrading are the larger pipes coming directly from gas storage plants but there are suitable materials already available for this. We also explored the possibility of storing hydrogen as a hydride, this could be a viable solution however the perfect hydride which is both inexpensive and has the correct strength still eludes researchers.

We discussed in the report integrating hydrogen into homes, it became clear that this would be no real problem as existing gas appliances and heaters can be converted inexpensively and work the same as with natural gas.

Finally, the report looked at the safety hazards of hydrogen in the home. The safety issues are similar to natural gas, but natural gas has been made safer by using detectors and odorants. This could be the same for hydrogen, there are already detectors available however no suitable colourants or odorants are available. this is a necessity for hydrogen integration into the home as humans will need to be able to detect it by either smell or sight.

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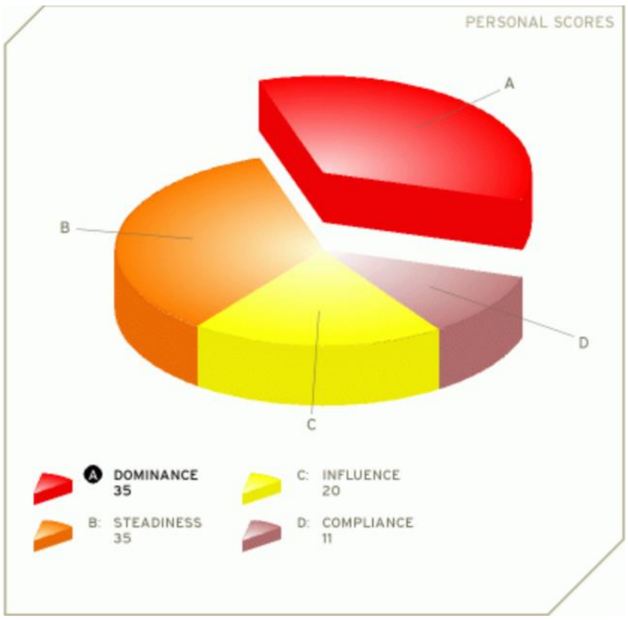
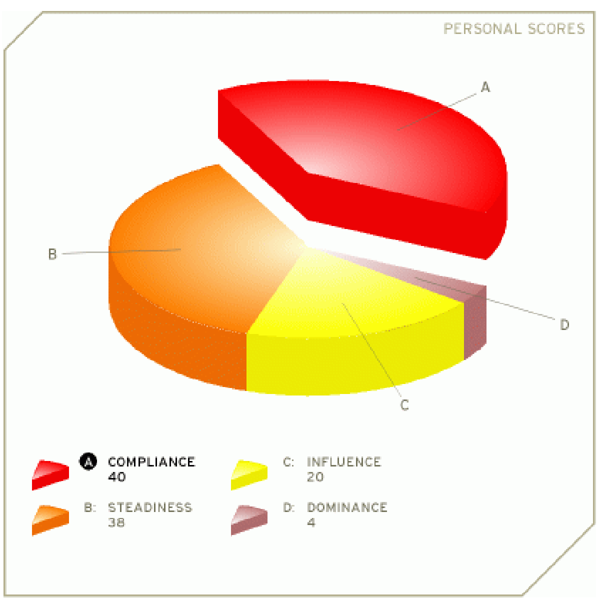
Appendices

Disc Personality Test results

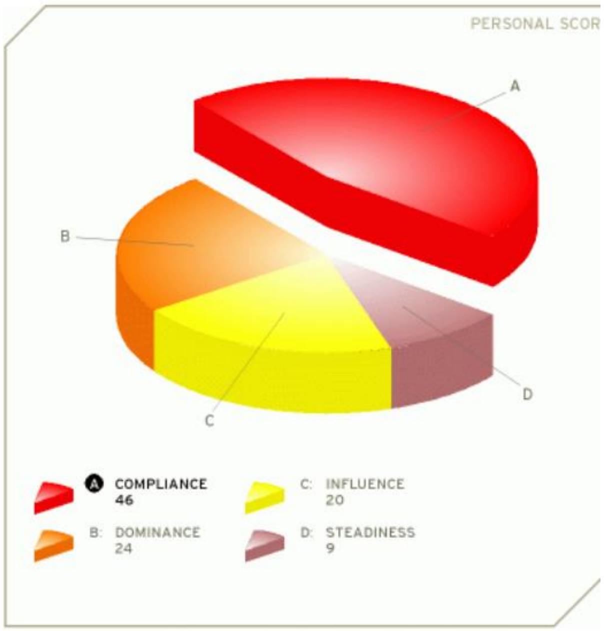
i) Alexander Nenno



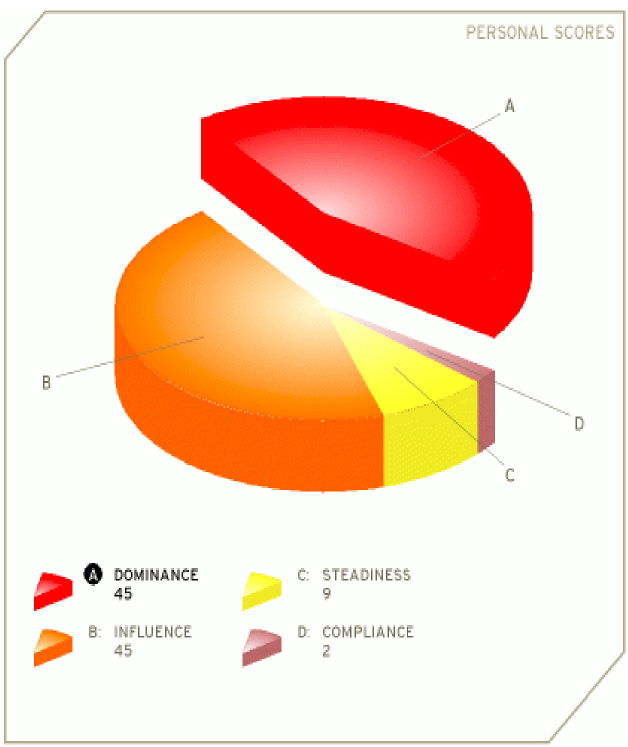
ii) Johannes Neyer Disc Personality Test results



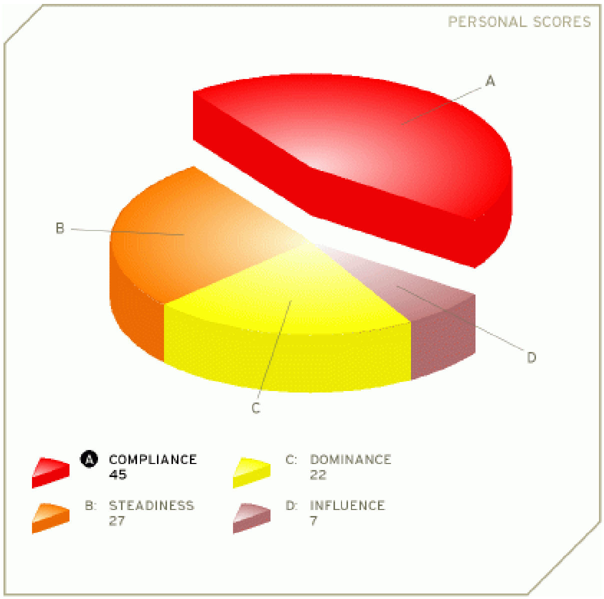
iii) Kasia Szymańska



iv) Junaid Qazi



v) Mollie Reid



Calculations

vi) $Energy\ per\ m^3\ produced\ when\ natural\ gas\ is\ combusted:\ 31.65\ MJ/m^3$(Tombleur, 2018)

$Natural\ gas\ used\ per\ year\ in\ an\ avg.house\ in\ The\ Netherlands:\ 1300\ m^3$(Statline, 2018)

$Energy\ produced\ when\ 1\ kg\ of\ hydrogen\ is\ combusted: 119\ MJ/kg$(Fung, 2005)

$$Energy\ needed\ in\ natural\ gas\ per\ household\ per\ year:\ 31.65 * 1300 = 41145\ MJ$$

$$hydrogen\ needed\ per\ household\ per\ year: \frac{41145\ MJ}{119\ MJ/kg} = 345\ kg$$

$\boldsymbol{Photovoltaic - electrolysis}\ efficiency: 30\%$(Jia et al., 2016)

$Average\ amount\ of\ solar\ energy: 1000\ kWh/m^2 * 3.6 = 3600\ MJ/m^2$(figure 1.x)

$$PV\ rooftop\ area\ needed\ per\ household\ = \frac{41145MJ}{30\% * 3600MJ/m^2} \approx 38m^2$$

Figure 4:Sunshine in the Netherlands (Solargis, 2018)