# Tri-generation in the built environment

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**Abstract**

The world faces large sustainability challenges especially when it comes to the energy provision of the – growing – world population. Not only the supply of fossil fuel is limited, but also exhaust like $SO_x$, $NO_x$ and $CO_x$ either directly pollute the local environment and affect air quality or contribute to the greenhouse effect.
A proven concept to increase efficiency of energy production is cogeneration. By co-producing electricity and heat, efficiency can rise up to 100 percent because all heat produced as by-product of electricity generation is used for heating. In several countries, like the Netherlands, the cogeneration concept is downscaled and implemented at district level or at household level. Downscaled cogeneration fits within the category of decentralized energy production. However, current cogeneration systems lack the flexibility to adapt to power demand and price.
In this paper we will explore the innovative concept of tri-generation which is a similar technology to cogeneration, but is also capable of producing hydrogen, besides electricity and heat. Moreover, we will also address how this concept could contribute to a transition to a more sustainable energy system.

## 1 Introduction

The world is facing enormous sustainability challenges. Energy demand and production are key issues when it comes to climate and affluence. Firstly, a large part of the world economy is based on fossil fuels. As the world population and economy are still growing so is the demand for fossil fuels which causes depletion of natural resources and production to stay behind. As demand exceeds production prices are rising and we are slowly running out of fossil fuels. Secondly, burning fossil fuels contributes to the greenhouse effect on a global scale but also to local pollution by exhausting CO, SOx and NOx. To be able to deal with these challenges we need a transition to a more sustainable energy system based on renewable energy sources and non-polluting ways of energy generation.
Recognizing this need, all member states of the European Union have agreed to the 20-20-20 goals reducing $CO_2$ and energy use with 20% by 2020. As in the Netherlands about 20 percent of all energy is used by households a large contribution to this goal is expected from this sector [1]. In that context, on the one hand the Dutch government aims at promoting energy saving through better insulation. On the other hand she aims at increasing the role of cogeneration, also known as 'combined heat and power', in the built environment which has a theoretical efficiency on energy generation of 100%. Next to that the Dutch government also acknowledges the fact that hydrogen can play an important part in the transition towards a

sustainable energy system [2]. Two main potential future roles are assigned to this clean energy carrier. Firstly, it can be used as an energy storage medium and facilitate the integration of inconsistent energy sources (such as wind or solar) into the grid. Secondly, hydrogen can be applied in the transport sector to contribute to the transition towards sustainable mobility [2]. However, before this can happen, a number of challenges have to be overcome. This includes improvements in the technical and economic performance of fuel cells and the development of a hydrogen infrastructure.

This paper will shortly elaborate on the different principles of cogeneration and their advantages and disadvantages. Then, a new concept of energy generation will be introduced which is based on high temperature internal reforming fuel cell being tri-generation. Afther that we will explain how this new concept could be applied in the built environment and how it could be a stepping stone towards a hydrogen based economy.

The main question of this paper is:
*Is tri-generation a good option to increase sustainability of the Dutch energy system in terms of efficiency, feasibility and suitability?*

## 2 Principles of cogeneration and efficiencies

The advantage of cogeneration is that it produces electricity and heat at the same time whereas all heat that is produced in conventional power plants is wasted or cooled away – which even requires more energy. Conventional electricity production reaches an average efficiency in the Netherlands of about 42% [3]. A high efficiency boiler has an efficiency of up to 100%. Therefore, in order to improve sustainability the main challenge is not to increase efficiency but to reduce exergy loss. Cogeneration can theoretically increase efficiency of energy generation with up to 60%. Heat has a very low exergy value whereas fossil fuel has the highest value possible. Thus, in order to reduce exergy loss the heat that is used in households should not be produced from a primary source (like natural gas) but from waste heat, which is the main principle of cogeneration. This means that out of 100 units of fuel 40 units of power and 60 units of heat are produced (presumed that the cogeneration unit has an electricity efficiency of 40%). In the conventional situation 60 units of heat (presumed efficiency 100%) and 100 units of electricity are needed to produce the same amount of energy (presumed efficiency 40%). So, by using cogeneration 100 units of fuel are needed instead of the 160 units in the conventional situation to produce the same amount of energy. An additional advantage of this system is that households only need one system to produce heat and electricity. Thus, theoretically cogeneration can improve the efficiency of the energy system enormously.

### Cogeneration: categories and technologies

Three categories of cogeneration can be distinguished: micro (up to 5 kW), mini (up to 100 kW) and macro (more than 100 kW). On average a Dutch household uses 1 kW so macro systems can produce enough power for about 100 households. For domestic application four technologies are available to generate energy: the Stirling engine, the piston engine, the gas turbine and fuel cells. Currently most market developments in the Netherlands are aimed at production and demonstration of the Stirling engine [4], which is not the most efficient technology considering electricity generation – as can be found in table 1.

**Table 1**: Overview of technological sustainability potential of different micro and mini-cogeneration technologies [1]

| | | Efficiency (%) | | | Emission | Readiness for Market |
|---|---|---|---|---|---|---|
| | **Scale** | **Heat** | **Electr.** | **Total** | **$NO_x$ (g/GJ)** | |
| **Stirling** | Mini | 80-90 | 10-25 | 90-100 | n/a | - |
| | Micro | 75-90 | 8-25 | 90-100 | 8 | 0 |
| **Piston** | Mini | 50-60 | 25-35 | 85-95 | < 140 | ++ |
| | Micro | 70-75 | 20-25 | 90-95 | 80-110 | + |
| **Gas turbine** | Mini | 40-60 | 20-43 | 60-80 | 40-60 | ++ |
| | Micro | 50-60 | 23-33 | 60-80 | 10-20 | ++ |
| **Fuel cells** | Mini | 25-50 | 30-70 | 85-90 | < 1 | 0 |
| | Micro | 45-70 | 35-45 | 85-100 | < 1 | - |

Legend for readiness for market introduction (readiness market):

**-** Not ready but technology is under development or market is not really interested
**0** Technology not ready, but research is done or demonstration projects are running
**+** Technology on the market but not commercially or in the Netherlands
**++** Technology commercially available in the Netherlands

Co-production of heat and electricity is the main advantage but also the main disadvantage of cogeneration. For energetic gains to be maximized no energy should be wasted at all. This implies that cogeneration systems should always be heat-demand driven. It also implies that if no heat is needed, the system cannot be used and households will be dependent on the central electricity grid with its low efficiencies.

The situation is not necessarily more positive if cogeneration systems are used to meet the entire energy demand of households. Because when electricity demand exceeds heat demand, surplus heat is wasted (except if proper heat storage is installed) and the total energy efficiency of the system will decrease enormously, due to the low electric efficiency of micro-cogeneration.

Interestingly, both heat and electricity demand fluctuates on a daily and seasonal basis. However, on the one hand peaks of heat and electricity demand in households do not necessarily take place simultaneously. Moreover, on the other hand, in summer electricity demand remains the same or even increases due to demand for air conditioning while heat demand is low because there is only demand for domestic hot water.

Higher efficiency mini-cogeneration systems can only solve part of the problem as the seasonal demand gap remains. So, cogeneration is a valuable concept but mainly in cases of high (domestic) heat demand throughout the year. This is why in the next chapter a new concept is introduced which has lower heat production, higher (exergetic) efficiencies and more flexibility than cogeneration: tri-generation.

## 3 The concept and potential of tri-generation

The concept of tri-generation goes one step further than cogeneration. Using a high temperature internal reforming fuel cell it produces combined generation of three different products electricity, hydrogen and heat. When producing hydrogen together with electricity, less heat is generated. As such two products with a high exergetic content, namely electricity and hydrogen, are generated and the exergetic efficiency of the system increases.

As explained previously, a number of technologies can be used in combined heat and power application. Among them are high temperature internal reforming fuel cells (HT-IR fuel cells) such as solid oxide fuel cells or molten carbonate fuel cells. In the following sections, we will first describe how HT-IR fuel cells can be used in tri-generation systems. Next we will describe how the concept could be applied in the built environment.

### HT-IR fuel cell as tri-generation: a technological perspective

Tri-generation systems are an extension of combined heat and power units in the sense that besides electric power and heat, a third product can be produced. New developments in the area of HT-IR fuel cells allow production of hydrogen as a third product, whereas in the conventional situation hydrogen is only used as a input for the system and not produced as an output.

The main characteristics of these fuel cells are that they run directly on natural gas which they can convert internally into hydrogen. This takes place by so-called steam methane reforming, an endothermic reaction. The hydrogen produced is then used by the fuel cell for its internal consumption in electrochemical reactions under the production of electric power and heat. Part of that heat is effectively used for the endothermic reforming reaction thereby minimizing waste heat and increasing overall efficiency.

Moreover, recently it was discovered that by decreasing electric power output or increasing natural gas input, the exhaust gas of the fuel cell still contains significant amounts of hydrogen which essentially is reformed natural gas. The hydrogen can be separated from this off-gas as done in conventional hydrogen production by steam methane reforming of natural gas for instance in oil refineries. An interesting beneficial side effect for the fuel cell is that apart from the already mentioned efficient use of waste heat inside the fuel cell, the fuel cell also becomes more efficient because significant amounts of hydrogen exit the fuel cell. In conventional application of fuel cells, the hydrogen content is decreased to a minimum by internal consumption in the fuel cell. This means that at the output side of a fuel cell only a low fuel concentration is available. This leads to the so-called Nernst loss constituting about 50% of all the losses in the fuel cell. By producing hydrogen this Nernst loss is minimized [5].

Therefore, overall system efficiency for the production of hydrogen and electric power can reach 90%. Note that this is excluding heat as often done in combined heat and power efficiency definitions. So, it should be compared to the Electrical Efficiency column in table 1. Of course, to reach this high efficiency the concept can only be applied if there is a (nearby) market for hydrogen. In this paper we assume the development of local hydrogen filling stations for the transport sector.
Besides its high efficiency the system also allows for very flexible supply of energy provision. First, the system can be switched from conventional operation as a combined heat and power unit, to the above described tri-generation system. Besides, the ratios between electricity, heat and hydrogen production can be varied within certain technical limits. Simulations have also shown that by combining hydrogen production and efficient internal use of waste heat, the fuel cell can be operated at double power density. This results in the production of twice the amount of electric power compared to conventional operation and with on top of that an equivalent amount of energy per time unit in the form of hydrogen. Thereby the valuable output of the fuel cell system can be increased by a factor of four [5].
To summarize, HT-IR fuel cells can be operated in tri-generation mode, increasing the system's efficiency. Moreover, they can do so in a flexible way. In the following section, we will describe how this flexibility could be applied in the built environment.

## 4 Tri-generation in the built environment

The flexibility of the fuel cell in tri-generation mode can be used to adapt heat production to the dynamic local heat demand as described in chapter 2. This fuel cell system could supply a domestic area of a few hundred houses with electricity and heat. At the same time it can provide a sufficient and steadily growing amount of hydrogen for the assumed growing number of fuel cell vehicles owned by the inhabitants in this living area. Hydrogen could be produced in times of low heat demand, increasing potential profit and thus overall economic feasibility.
At this moment it is not clear whether hydrogen vehicles will be standard in the future. In the case electric vehicles will rule the market the tri-generation can supply electric power to a fast charging station for battery electric vehicles. So, tri-generation systems can power all potential transport scenarios.

In previous projects we have studied the flexible co production of hydrogen and power by internal reforming fuel cells [5, 6]. Also the use of this concept to compensate for fluctuations in the production of electricity by wind turbines in the so-called Superwind project was studied [7]. The concept of hydrogen production from this type of fuel cell is relatively new, while also the market for conventional CHP use of fuel cells is still under development.
In short, new technology based on fuel cells is being developed capable of producing hydrogen power and heat in varying and flexible amounts at very high efficiency adapted to a specific demand that usually fluctuates in time.

## 5 Potential contribution to a transition to more sustainable energy systems

In the sections above we have argued that tri-generation as a niche technology that is still in the very early phases of development can compete with cogeneration in technical terms. The system's electric efficiency is higher, heat losses are lower and flexibility is higher, which makes it better suitable for implementation in the built environment with its varying heat demand. Furthermore, the ratio of electricity versus heat production is higher, which also makes the system more suitable for the built environment with its declining heat demand because of for example better insulation.

Besides these advantages, the system could be very useful in the energy transition of both the domestic and the transport sector as tri-generation is a very efficient means to produce hydrogen and electricity on a local level. In order to speed up this transition off, several aspects are important. Recent research has stressed the importance of aspects like raising expectations [8], decreasing uncertainties for actors involved [9] market formation (see e.g. [10]) and stimulating learning processes [11],[12].

When it comes to market formation in the energy transition the chicken-and-egg problem in the development of hydrogen infrastructure or fuel cell vehicles is an important obstacle. Fuel cell vehicles are not developed in large numbers because there is no hydrogen infrastructure. Accordingly no hydrogen infrastructure is implemented because only very small numbers of fuel cell vehicles are on the market. As tri-generation can produce hydrogen as a by-product of electricity and heat production it can be used in the transition towards the hydrogen economy. It can produce the relatively low quantities of hydrogen that are needed then in order to stimulate the market for fuel cell vehicles.

Other obstacles for a larger production of fuel cell vehicles are the low efficiency of (small scale decentralized) hydrogen production for fuel cell vehicles and the high price of fuel cells, mainly caused by the small market. Also here, tri-generation can play an important role by enlarging the market for fuel cells and therefore decreasing the price.

Local production of hydrogen at high efficiency enables the development of fuel cell vehicles without the need for a large-scale hydrogen infrastructure in the form of pipelines. The high efficiency is in fact obtained because the hydrogen is more or less produced out of waste heat of the fuel cell in electric power production. The fuel cell can be fuelled by almost any mixture of natural gas and locally produced biogas depending on price and availability. However, when mixing biogas the operation of the system becomes more complex and requires detailed information about the demand for hydrogen, electricity and heat throughout the complete day.

The two key words describing the concepts are flexibility and high efficiency. The outputs of the fuel cell in terms of absolute and relative quantities can be adjusted within certain technical limits to meet the fluctuating demand for heat, power and hydrogen. The produced hydrogen can be fed to a local gas station possibly

equipped with a small hydrogen storage facility to supply hydrogen for a growing number of fuel cell vehicles. In case fuel cell vehicle development does not take place the installation can still produce economic valuable goods (power and heat) thus decreasing investment risk. Next to that it could supply the already existing (industrial)_market with hydrogen.
These aspects combined show that tri-generation can play an important role in the take-off phase of the transition to an energy system based on hydrogen with relatively low economic risks. This can increase expectations [8]and reduce uncertainty for investors and other actors [9] setting in motion so-called 'motors of change', virtuous cycles in the innovation system [13].

## 6 Tri-generation today: markets and developers

The most advanced internal reforming fuel cell that is commercially produced is the so-called hot module by CFC solutions (Germany) in co-operation with Fuel Cell Energy (USA). The most recent type can deliver 300 kilowatt of power using natural gas or biogas as inputs or a mixture of the two. The concept of hydrogen production from the fuel cell however is only explored in the USA by Fuel Cell Energy in cooperation with the large gas company Air Products that takes care of the gas separation and cleaning of the hydrogen and the supply of hydrogen to a fueling station.

In Europe CFC solutions follow a different strategy for their company: they presently focus on conventional combined heat and power applications for their fuel cell, preferably fed with biogas.
As long as the market for (decentralized) hydrogen has not developed, the tri-generation concept can only be used as a familiar combined heat and power installation. Therefore it has to compete with conventional combined heat and power technology. This is difficult because fuel cell technology is still more expensive. Next to that for some types endurance is a problem while for other types the technology is less mature and the capacity per unit is limited.

If a market for hydrogen is developing the market opportunities for internal reforming fuel cells (in tri-generation applications) will grow and subsequently prices will be lowered. This enables a growing demand also in conventional combined heat and power applications for these fuel cells. Therefore the tri-generation concept could also help to solve the chicken and egg problem between the price of fuel cells and number of fuel cells sold.

## 7 Conclusion

The current energy system is rather inefficient. In electricity generation a lot of waste heat is created while at the same time in other places primary fossil fuels are used to generate heat which involves enormous exergy losses.

One way to increase efficiency of the system is by using waste heat by the implementation of cogeneration systems. Unfortunately cogeneration is heat-demand driven. This causes cogeneration to only solve part of the problem as on the one hand total heat demand of households is decreasing and on the other hand in summer domestic heat demand is limited to the use of hot tap water.

In this paper, a new concept being tri-generation based on high- temperature internal reforming fuel cells is presented that can theoretically solve these problems. Part of the waste heat generated by the fuel cell during the production of electricity can be converted into hydrogen. This introduces flexiblility and makes the system more efficient in terms of exergy as well as energy efficiency.
First of all it can produce hydrogen and electricity with an efficiency of up to 90% which implies a large exergy gain even compared to cogeneration. Secondly, the system can be adjusted to the dynamic local demand since the amount of electricity, heat and hydrogen produced can be varied. Even the electric power production from the same installation can be doubled and the total output capacity of the system in terms of hydrogen and electricity can increase up to four times compared to its standard electric power production. Thirdly, it provides local production of hydrogen on demand, which makes a complete hydrogen infrastructure unnecessary. This solves the chicken and egg problem in the development of fuel cell vehicles and hydrogen filling stations.
Finally, installation of the tri-generation system creates a market for fuel cells thus accelerating its development and application in other areas. So, we can conclude that tri-generation is an interesting option to implement in the built environment and that it can contribute to the transition towards a more sustainable energy and transport system.

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