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Diffusion Paths for Micro Cogeneration Using Hydrogen in the Netherlands

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Diffusion paths for Micro Cogeneration Using Hydrogen in the Netherlands

Forthcoming in *Journal of Cleaner Production*

Mattijs Taanman [a] [1], Arend de Groot [b], René Kemp [c], Bart Verspagen [d]

[a] Dutch Research Institute For Transitions, Erasmus University Rotterdam

[b] ECN

[c] MERIT and TNO-STB

[d] Eindhoven University of Technology and TIK, University of Oslo

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[1] Corresponding author. Tel: +31 10 4089787, Fax: +31 10 4089039, E-mail address: taanman@fsw.eur.nl

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Abstract

We estimate the diffusion of micro cogeneration systems (MiCoGen) using hydrogen produced from natural gas in the Netherlands for the 2000-2050 period on the basis of economical factors. The diffusion is important for the transition to a hydrogen economy based on renewables, with natural gas paving the way for hydrogen from renewables which. For three scenarios full diffusion takes place in the period 2020-2050. The most important factors behind the diffusion are: growing energy demand, resulting in lower hydrogen costs and higher energy costs in the reference case and lower costs of MiCoGen stemming from learning economies. The model is very advanced by considering all costs components for heterogeneous users which have been calculated for the entire diffusion period. It is the first threshold diffusion model that is being applied to the diffusion of technological clusters involving new or adapted infrastructures.

Keywords; diffusion model; hydrogen; micro cogeneration

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1. Introduction

This paper examines diffusion paths for micro cogeneration (MiCoGen) using hydrogen in Dutch residential areas (with small business). Hydrogen is a clean energy carrier offering environmental advantages especially if the hydrogen is produced through renewables. But the high costs and infrastructure requirements for this are preventing this from happening. A transitional solution is probably needed. In the Dutch context a lot is expected of natural gas based hydrogen for several reasons. Firstly, natural gas (through Steam Methane reforming) is at the moment the most widely used and cheapest way to produce hydrogen and large reserves are still present in the Netherlands. Secondly, the Netherlands has an extensive transportation network for natural gas that can potentially be used to transport hydrogen/ natural gas mixtures as well. Thirdly, even though Dutch natural gas reserves are not expected to last for eternity, expectations are that natural gas will also play a large role in the Netherlands in future, leaving the empty reserves as potential storage space for the sequestration of CO_2. This way the use of fossil fuels will lead to a sustainable future while allowing high emission reductions on route to that future.

To assess the potentials of various technological clusters based on natural gas-produced hydrogen for MiCoGen in fuel cells, a model is developed that simulates the adoption of hydrogen by heterogeneous users in residential areas consisting of homes and small businesses. The individual users in the model have the option to use hydrogen to satisfy a part of their energy needs (hot water, space heating and electricity). Adoption is thought to follow automatically from lower energy costs when using hydrogen, compared with the reference case.

The diffusion is not a simple diffusion process because the hydrogen to be used in MiCoGen requires changes in infrastructure: either pressure swing adsorption technology if hydrogen is transported through the existing pipe lines for natural gas (allowing hydrogen to be separated from natural gas) or new built pipes for hydrogen. Diffusion analysis must take account not only of heterogeneity of the adopter population but also of infrastructure costs for different configurations. In this model we assume that diffusion is governed primarily by economics as the primary adopters are neighbourhoods (see section 4), therefore we use a threshold model for analysing diffusion and not an epidemic model based on information dissemination. Both the model and the application are new. Most diffusion studies consist of curve fitting (see for example [1-2]). Few studies endeavour to model the technology adoption decisions at the micro level using real data about costs and benefits. Studies doing so are Jaffe et al. [3] and Kemp [4] but unlike the present paper they studied past technology patterns of simple innovations whose diffusion was not limited by infrastructure requirements.[†]

[†] Overviews of models of innovation diffusion are given in [2,5-6].

2. Technology: natural gas based hydrogen for micro-co-generation (MiCoGen)

MiCoGen is generally seen as one of the first markets where the use of hydrogen will be competitive with existing energy systems (e.g. [7-8]). Although hydrogen can be used as an energy carrier in other technological systems, we will exclusively focus on MiCoGen in our study of diffusion of hydrogen-based energy systems. The MiCoGen market is one of small users, i.e., small firms and households. In the Netherlands, these users currently represent approximately 40% of total energy demand [9]. The large-scale use of natural gas in the Netherlands provides several reasons why MiCoGen is a particularly advantageous way of using hydrogen. First, Steam Methane Reforming (SMR) is a particularly cheap and well-established way of producing hydrogen [10] (48% energy efficiency over the cycle methane –hydrogen- electricity, vs. 26% for the often-suggested electrolysis over the cycle methane- electricity – hydrogen - electricity) and this method uses natural gas as a primary resource. Second, hydrogen can be transported using the natural gas infrastructure, for example by mixing hydrogen and natural gas in the pipelines used now for natural gas only. This infrastructure consists of various high-pressure transport grids and low-pressure, local distribution grids. Although there is still uncertainty about this, it is currently estimated that up to $15\%_{vol}$ hydrogen can be mixed with natural gas [10]. Such mixing would be useful when hydrogen is produced centrally, and then distributed to end-users through the existing distribution network for natural gas. With mixing, users who stick to natural gas based equipment (such as heaters) can use the natural gas – hydrogen mixture with their existing equipment, while users who switch to a fuel cell will have to install filtering equipment that will extract the pure hydrogen from the mixture that is delivered to the home through a dedicated distribution network[‡]. This avoids the costly investments associated with a completely new transport infrastructure for hydrogen.

Technological scenarios

The choice between centralized and decentralized hydrogen production is the first dimension along which we will distinguish the technological options (scenarios) for which diffusion paths will be analyzed. We distinguish two choices: centralized hydrogen production with transport over the existing natural gas infrastructure (by mixing), and decentralized production of hydrogen. Centralized production provides more opportunities for scale economies, and hence low hydrogen prices. An additional advantage of centralized production is the opportunity for capturing CO_2, which can then be kept out of the atmosphere by storing it, for example, in empty gas fields.

The alternative for centralized production of hydrogen is production at the level of the residential area. Small scale, load-following SMR-units are being developed, which can deliver hydrogen to the local distribution net. Capturing CO_2 is now much more costly, because hydrogen production not always taking place at a location where cheap storage of CO_2 is possible (and hence CO_2 would have to be transported).

[‡] Transport networks for natural gas can presumably transport more hydrogen rich mixtures. The distribution networks are however made of material that is too porous to facilitate higher hydrogen concentrations.

The hybridization of user equipment is a second dimension on which we distinguish our technological scenarios. Because of peak demand, a fuel cell that satisfies all user demand must have a rather high capacity. Tilleman and Groot [11] show that for households, investment in a fuel cell that would be able to meet peak demand is too costly. They conclude that a secondary system must be installed to meet peak demand. For electricity, this may take the form of a connection to the standard electricity grid, which also provides the option to deliver electricity from the fuel cell back to the net, when local use is low. For heat production, a separate and local heat-producing unit must be installed, which can either use natural gas or hydrogen as its power source.

This implies that either two (electricity and hydrogen) or three (electricity, hydrogen, natural gas) types of equipment must be available in the local dwelling. The choice becomes one between linking the local building to the natural gas distribution network or not. Without the use of this natural gas network, infrastructure costs will be lower, and the hydrogen infrastructure (including the SMR) will be used more intensively, which provides additional opportunities for producing hydrogen at lower costs (scale economies). On the other hand, natural gas is a cheaper resource than hydrogen (which must be produced from natural gas), and the energy efficiency of using natural gas is higher than for using hydrogen.

Using these two dimensions, we have four technological scenarios, as in Diagram 1.

Insert Diagram 1. Technological scenarios

In all four scenarios, we use only one type of fuel cell: a PEM fuel cell. Fuel cells generate electricity and heat, and both can be applied usefully in the type of applications that we have in mind. However, one may distinguish two different types of fuel cells depending on whether it engages as a result of either a specific demand for heat, or as a result of specific demand for electricity [12]. In the first case, heat is the primary objective of the fuel cell, and the electricity that is produced as a by-product is delivered back to the electricity net. In the second case, electricity is the main product, and heat is either stored (e.g., in a boiler) or exhausted. These two systems have different implications for energy costs.

However, relatively preliminary simulations with the model suggest that there is one crucial factor that determines the choice between these two types of fuel cells. This is the price of electricity delivered by the electricity grid that the user has to pay, relative to the price that is obtained by delivering electricity (from the fuel cell) back to the grid. Because the latter cannot easily be regulated in terms of when it is being delivered, it is commonly assumed that the latter price will be relatively low [11, 13]. In such a case, our model suggests that fuel cells aimed primarily at producing electricity, are the most efficient type of fuel cell for end-users of the type that we analyze. Therefore, we will only take this type of fuel cell into account.

In the reference case, dwellings are equipped with a combination boiler and connection to natural gas and electricity.

3. Modelling users

Economic decisions by users are at the core of the diffusion model that will be set out in the next section. The primary dimension along which users are modelled is a building. Our model distinguishes several types of residential buildings, as well as typical buildings that are used in industrial sectors. The model distinguishes three primary factors that affect economic decisions with regard to energy usage. The first is the general level of demand for energy sources. For this, we use data on the use of natural gas and electricity for households and firms in the Netherlands in 2000, taken from Statistics Netherlands [14]. We extrapolate some of these data (electricity use) using the reference scenario in [7]. For each of the types of building, we distinguish a typical electricity and natural gas use. Figure 1 documents the typical usage per building. For the use of natural gas, we distinguish between existing and newly built buildings (the latter use generally less energy for space heating).

Insert figure 1

The second factor that affects economic decision-making is the variation (over days and weeks) of electricity demand. This affects the capacity of the installed equipment. Typically, electricity demand peaks during certain hours of the day. Electricity demand by households in the Netherlands is typically at its lowest during the time bracket 22.00 – 06.30, and peaks during 17.00 – 20.00. During the first time bracket, the power used was 100 – 200 W, at peaks it was as high as 1700 W. Further variations are caused by variation over weekdays (working days vs. weekend) and seasonal variation. Electricity demand can be presented as a so-called load duration curve describing how long each power level is demanded during the day. For a fuel cell of a particular capacity, we may calculate the part of total electricity delivered by the fuel cell by the surface below this curve at the capacity level of the fuel cell. The rest of the electricity has to be bought from the grid.

Insert Table 1

The third and final factor that affects decision-making is capital costs (including maintenance). These costs are relevant for the six types of equipment in Table 1. We define equipment of standard size, and use a scale rule to determine the relation between capacity and investment price (in USD 2000):

$$\frac{I_0}{I} = \left(\frac{P_0}{P}\right)^n, \tag{1}$$

where I_0 is the reference size (see Table 1 for details per size of equipment), P_0 the price of one unit of the reference size, I an alternative size and P the price for the alternative size, and n is the scale factor. When n=1, price of the equipment type is not influenced by size, $n < 1$ indicates the general rule that smaller equipment is more expensive (per unit of capacity). 0.7 is often considered as a standard case. Using the scale rule, we obtain equipment prices from current market prices in the Netherlands.

Capital costs are calculated as depreciation over the equipment lifetime documented in Table 1, using an annuity rule and a 10% interest rate. For all types of equipment except fuel cells and SMR, we assume that prices will not change in the future. This reflects the assumption that this technology is already mature, due to its relatively long technological history. For fuel cells and the small-scale, load-following SMR for decentralized hydrogen production, this is obviously an unrealistic assumption, and hence we assume that further learning will take place that will lead to a lowering of the price for this type of equipment. For fuel cells and SMR, we follow typical learning rates suggested by [15] (see also the appendix).

4. The Diffusion Model

Like most energy systems, a hydrogen-based system is crucially dependent on infrastructure. By its nature, infrastructural investments cannot be made by an individual user. Adoption of a hydrogen-based energy system is typically made as a collective decision by a group of users in an area. In this way, costs associated to use and adoption can be shared. In such a case, the adoption decision is made by a group of users for whom it is collectively beneficial to adopt the new system.

This raises the question which groups of users can usefully be understood as the decision-making units in such an adoption process. Our model takes neighbourhoods as the unit of decision-making. A neighbourhood is defined as a collection of buildings from the set defined in Figure 1. At this level, the construction of a hydrogen infrastructure becomes manageable, and the costs associated to this can be envisaged to be earned back over a reasonable period of time.

The use of neighbourhoods has intuitive appeal in the context of our model, for a number of reasons. First, our model is a rational decision model, in which economic motives completely drive the adoption decision. At the level of a neighbourhood, it is likely that such rational calculations are the dominant mode of decision-making, for example, when a new neighbourhood is being built, feasibility studies on energy systems and other issues are likely to be undertaken. Second, new neighbourhoods are natural environments to experiment with hydrogen. Investment in new infrastructure can be done efficiently during the construction phase, and new neighbourhoods are actually being built rather often (as opposed to, for example, new cities). Third, at the level of a neighbourhood, it seems to be manageable to redistribute costs and benefits, e.g., compensation of those who do not benefit much from a hydrogen system by those who do.

The model distinguishes three standard neighbourhoods types (a total of 6475 neighbourhoods in 2000), each of which is made up of a typical number of building that were documented in Figure 1 above. We picked these standard areas in such a way that they roughly correspond to the classes ‘urban’, ‘semi-urban’ and ‘non-urban’, used by Statistics Netherlands. The buildings that are found in these standard neighbourhoods are documented in Table 2.

Insert Table 2

In order to model explicitly the emergence of newly built neighbourhoods, which are an interesting market for hydrogen energy systems, we explicitly model the demand for housing. This is done by taking projections on population and average size of households from Statistics Netherlands. The growth of the number of households that results from this is then taken as the growth of the number of residential dwellings. Whenever 1000 new residential dwellings (this is the approximate size of a standard neighbourhood, see Table 2) become necessary, a new neighbourhood is built. It is assumed that only urban and semi-urban neighbourhoods are built (in equal amounts), newly built non-urban areas do not exist in the model. Our calculations imply that approximately 40 new neighbourhoods are built per year over the period 2000 – 2030, after which the number of new neighbourhoods quickly converges to zero (and actually becomes slightly negative).

For each year in the period 2000 – 2050, we have a ‘population’ of neighbourhoods (starting with 6475 neighbourhoods in 2000). This population consists of 5 different types (the three standard types in Table 2 in existing form, plus the urban and semi-urban newly built neighbourhoods). For each of these types, we make the calculation of the energy costs of the hydrogen technology (we consider each one of the four in turn), and compare these to the costs associated with the existing system (without hydrogen). If the costs for hydrogen are lower, the neighbourhood will adopt the hydrogen system.

The elements of the cost calculation have been described above. To the extent that we cannot document all exact assumptions behind the calculations, we refer the interested reader to the appendix and [16]. In summary, there are four driving forces behind the adoption decisions in the model:

1) Technological learning: as described above, it is assumed that fuel cells and the small scale SMR equipment is subject to (investment) cost decrease as a result of learning.
2) The growth in electricity demand. This is assumed to follow the pattern described in the reference scenario in [7].
3) The building of new neighbourhoods as a result of population increase in the Netherlands.
4) The price of hydrogen. This is fixed at 0,11 €/ Nm^3 in the case of centralized hydrogen production. In the case of decentralized production, the hydrogen price results from the price of natural gas (fixed) and the cost of equipment used to produce hydrogen from natural gas (endogenous).

6. Results

The results for the diffusion paths of the four scenarios are depicted in Figure 2. Because of the limited number (five) of neighbourhoods in the model, the diffusion curves resemble step functions (all neighbourhoods of a specific type adopt at once; hence there are five steps at most). First, newly built urban neighbourhoods adopt, followed by existing urban neighbourhoods and newly built semi-urban neighbourhoods.

Insert Figure 2

The model predicts complete adoption of hydrogen systems by 2050, i.e., all users in the Netherlands are ‘predicted’ to be using hydrogen within a period of 45 years from now, in three of the four scenarios. Interestingly, the differences between the technological scenarios in terms of the time at which adoption takes off, are small, while significant differences remain in terms of whether or not full adoption is reached, and if so, at what time.

Scenarios with centralized hydrogen production (1 & 3) are marginally quicker in terms of take off. Scenarios with larger technological hybridization at the user side (3 & 4) will less easily reach full adoption. Especially scenario 2 (limited hybridization and decentralized hydrogen production) shows remarkably fast diffusion: it takes only 8 years from take-off to reach full adoption in this scenario. The slowest scenario (3, i.e., centralized production and high hybridization) only reaches 70% adoption by 2050, but is the first one to take off.

Insert figure 3

The most important mechanisms behind the differences in diffusion paths are the price of hydrogen, the price of fuel cells and the growing demand for electricity. Figure 3 shows that the price of hydrogen falls in all four scenarios. An important driving force behind the falling price for hydrogen in all four scenarios is that the hydrogen infrastructure is modelled as fixed costs. With increasing demand for hydrogen, the average fixed costs (per Nm^3) will fall. Scenarios with centralized production of hydrogen (and mixing) show a less steep decline of the price of hydrogen, because the technologies that are used to separate hydrogen from natural gas are modular, i.e., do not show any scale economies and the production costs are fixed. Neighbourhoods that don't use natural gas for heating (1&2), use the hydrogen infrastructure more intensively, resulting in lower hydrogen prices.

Insert figure 4

A typical result for the energy costs that is produced by the model is depicted in Figure 4. We take a terraced house as the example, and focus on Scenario 4. The top panel displays the costs associated to a non-hydrogen system. Energy costs rise mainly as a result of electricity. In the bottom panel, costs for a hydrogen system are falling, mainly as a result of a cheaper fuel cell.

7. Sensitivity analysis

In order to investigate how sensitive the model's results are for certain assumptions of the model, we performed a sensitivity analysis. For the assumptions listed in Table 3, we increased or decreased the values that were fed into the model in the runs discussed above by 10%. Thus, for example, we decreased the discount rate (which has an impact on capital costs) from 10% (reference value) to 9% (first line of the table). Similarly, we varied the price of natural gas, electricity, the fuel cell, the SMR and the hydrogen infrastructure, as well as the efficiency of the fuel cell.

The impact of the changed assumptions is evaluated in two ways. The first (Δt) measures the time that elapses between the years at which 10% and 90% adoption is reached. The second (Max) gives the year in which 100% adoption is reached. The bottom line of Table 3 gives the values of Δt and Max for the references run (Figure 2). The values in the table show the increase (positive numbers) or decrease (negative numbers) in either Δt or Max for the alternative assumptions, relative to the reference run. In cases where the diffusion paths for the alternative assumptions are not complete (or do not reach 90%) at 2050, we cannot calculate these differences. In such cases, we can only calculate an upper limit for the time difference, and this is indicated by < (in case of negative differences) or > (in case of positive differences) sign. A question mark "?" denotes the cases where the direction of change could not be determined.

Insert Table 3

The single largest impact in terms of sensitivity is associated to the price of electricity. We have not attempted to predict this price, and have assumed that it will remain constant over the period for which we simulated. Lower electricity prices than what we assumed generally lead to lower diffusion. This is most dramatic in scenarios 1 and 3, i.e., with decentralized hydrogen production.

8. Summary and Conclusions

The model that we have used is based purely on economic factors (total user energy costs). Although costs are an important factor in user decisions, they are not the only factor. In the case of hydrogen, safety concerns and perceived advantages for end users may also have an important impact. Experts argue that the risks associated with hydrogen are from a different nature but not necessarily bigger [17]. Users however may still show a negative attitude towards hydrogen, because of the perceived risk. Secondly, apart from cost advantages, there are no large advantages in terms of comfort etc. as was the case in the historical diffusion of the use of electricity and natural gas. Especially because the economic benefits of a hydrogen-based system are low around the time of adoption, it may be the case that the economic factors that we have modelled are, in the end, not decisive.

Given the focus on economic decision making, our model for the diffusion of hydrogen technologies for micro cogeneration in the Netherlands leads to the conclusion that all four possible technological scenarios that we have envisaged are feasible in the time period up to 2050. The four technological scenarios are distinguished on two dimensions: centralized vs. decentralized hydrogen production, and the hybridization of the user equipment (presence or absence of an installation for heating using natural gas).

We find that early adopters will adopt hydrogen some time during the 2020s. Which of the four technological scenarios is used does not have a large impact on the time of first adoption, although the model shows small lead times for the scenarios with centralized hydrogen production. In terms of user system hybridization, the model shows that the use of a separate heating installation using natural gas does not slow down the time of first adoption of hydrogen systems very much. However, the time at which full adoption (100% use of hydrogen) is reached is significantly slowed by a larger degree of hybridization.

What do these conclusions imply for the transitions paths towards a cleaner and safer energy system in the Netherlands that we may envisage? The hydrogen systems that we have analyzed still depend on natural gas as an input for the production of hydrogen. Environmental gains are therefore low. As a secondary effect, the hydrogen systems that we have analyzed may lead to a more peaked demand for electricity (when the capacity of the installed fuel cell is not enough for total local electricity demand). Central power stations using natural gas may be more suitable for this type of demand than coal-based stations and hence the dependency on natural gas may even increase as a result of the transition to hydrogen.

Appendix. Diffusion model

Insert figure 5

The modeling method is presented in figure 5. The scenario influences the characteristics of hydrogen production (centralized or decentralized) and whether an individual connection to the natural gas infrastructure is present. For each year the hydrogen demand of heterogeneous users within a certain type of neighborhood is calculated. With the resulting aggregate hydrogen demand per neighborhood and other neighborhood characteristics (urban, semi-urban or rural and new or existing), the hydrogen price is calculated. Now all information is available to determine the energy costs for individuals. If the aggregate costs per neighborhood are lower than in the reference scenario, adoption occurs for this type of neighborhood, leading to the number of adopters for that year.

The calculation of infrastructure costs, depreciation costs and energy costs are shown. For some formulas, we use the hydrogen reference case of [11]:

Insert table 4

Infrastructure costs are scale independent of the length and diameters (if small) [18] and can be calculated for all neighborhoods using;

- They are estimated at 300 USD per connection in a new semi-urban neighborhood [19].

- Experts-interviews have confirmed the costs of building new infrastructures in existing neighborhoods as 3 times that of new neighborhoods.
- The relation between infrastructure costs in urban, semi-urban and non-urban environments is assumed to have the relation 1:2:4.
- All distribution grids require a distribution station at 42000 USD [19].

Prices of the fuel cell and small Steam Methane Reformer drop exogenously due to the use of these technologies in the world. Installed capacity is deduced from the reference scenario in [7]. Estimates for 2000, 2010, 2020, 2030, 2040 and 2050 were used to fit an S-curve with the help of loglet software [20], which used additional parameters of a max of 3x the amount in 2050, a diffusion time of 55 years and 2050 as a center point. This resulted in a diffusion curve for SMR of;

$$InstCap_{SMR}(t) = 750\left(1 + e^{-0.08(t-2059)}\right)^{-1} \tag{2}$$

And for PEM Fuel cells of;

$$InstCap_{fc}(t) = 3500\left(1 + e^{-015(t-2055)}\right)^{-1} \tag{3}$$

Installed capacity and the technological lifetime produced the *cumulative* capacity. With the help of the learning rate β and the number of times cumulatively installed capacity doubled ND_t, the cost price index CI_t can be calculated with;

$$CI_t = \left(2^{-\beta}\right)^{ND} \tag{4}$$

The learning rates are estimated at 50% until 2010 (R&D phase), 28% until 2030 (niche market application) and 15% after 2030.

Electricity demand. Dutch electricity demand per type of dwelling in 2000 is based on Statistics Netherlands and is thought to grow with the reference scenario of [7].

The load duration curve (in hours) is assumed to resemble

$$P(t) = P_0 + 0.93 P_{\max} e^{-ct} \tag{5}$$

With the minimal power requirement (P_0) being 7% of $P_{\max}$. $P_{\max}$ is calculated with the Model of Strand-Axelsson;

$$P_{\max} = \alpha \cdot El + \beta \cdot \sqrt{(El/n)} \tag{6}$$

With El being the annual electricity demand equaling the area under (1) and n = 20 for apartments and 1 for all other dwellings. Coefficients α and β correspond to different dwelling types and are listed among others in [21].

Fuel cell size (P_{fc}) is proportional to $P_{\max}$ in the reference case.

Electricity production of fuel cell (El_{fc}) is the area under the line $P=P_{fc}$ in the load duration curve:

$$El_{fc} = El - \int_0^{t_{bc}} \left(P_{el}(t) - P_{fc}\right) dt, \text{ with } P_{el}\left(t_{bc}\right) = P_{bc} \tag{7}$$

Heat production of fuel cell follows from

$$Q_{fc} = \frac{El_{fc}\eta_q}{\eta_{el}\eta_{BOP}} \tag{8}$$

Where BOP is the balance of power that is connected to the fuel cell stack and has a 95% efficiency.

Heat demand is constant per dwelling. New Dutch dwellings comply with Dutch norms (Energy Performance Norm). Energy costs have been calculated for each dwelling based on these norms. Existing residential buildings in the period 2000-2050 are assumed to have the norms for 2000. New buildings use half the amount of existing buildings. Residential buildings require heat for space heating and for hot water (Q_{tap}).

Effective heat production is for residential buildings;

$$Q_{fc,eff} = Q_{fc} \text{ when } Q_{fc} \leq Q_{tap} \tag{9a}$$

Or

$$Q_{fc,eff} = Q_{tap} + 0.5\left(Q - Q_{tap}\right) \text{ when } Q_{fc} \triangleright Q_{tap} \tag{9b}$$

Existing utility buildings use 2/3 of the heat requirements in 2000 and new utility buildings 1/3. For utility buildings the effective heat production is

$$Q_{fc,eff} = 0.5Q_{fc} \qquad \text{when } Q_{fc} \leq 2Q \tag{9c}$$

Peak heat demand equals the heat demand and the heat loss of the boiler minus the effective heat production.

Boiler and furnace. The furnace size is constant for residential buildings, proportional to the root of the relation between the peak demand for heat and the peak demand in the reference case. Boiler size is proportional to the fuel cell size.

Electricity and Natural gas prices are fixed (Dutch prices in 2000). Both electricity and natural gas connections require a yearly fee, independent of the usage.

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Vitae/ Adresses

Mattijs Taanman; Erasmus University Rotterdam, Faculty of Social Sciences, Burgemeester OUdlaan 50, M-building, room M5-26, P.O. Box 1738, 3000DR, Rotterdam, The Netherlands

Arend de Groot, ECN, Unit EEI, postbus 1, 1755 ZG, Petten

René Kemp, MERIT, Maastricht Economic and social Research and training centre on Innovation and Technology, Keizer Karelplein 19, 6211 TC Maastricht, The Netherlands

Bart Verspagen, Eindhoven University of Technology, Faculty of Technology Management, room Pav Q1.24, PO Box 513, 5600 MB Eindhoven, The Netherlands

Figure Captions

Figure 1. Use of electricity and natural gas, 2000 (Source: Statistics Netherlands)

Figure 2. Diffusion paths for the four technological scenarios

Figure 3. The price of hydrogen in the four scenarios

Figure 4. Energy costs for a terraced house for a non-hydrogen system (top panel) and a hydrogen system under scenario 4 (bottom panel)

Figure 5. General data flow within the diffusion model

Tables and Diagrams

Diagram 1. Technological scenarios

	Hydrogen production & distribution:	
⇩ **Hybridization of user systems:**	*Centralized, mixing with natural gas*	*Decentralized, neighbourhood production system*
Hydrogen and electricity	Scenario 1: Hydrogen produced centrally and distributed by mixing with natural gas; Hydrogen users do not use any natural gas for heating	Scenario 2: Hydrogen produced decentrally; Hydrogen users do not use any natural gas for heating
Hydrogen, electricity and natural gas	Scenario 3: Hydrogen produced centrally and distributed by mixing with natural gas; Hydrogen users use natural gas for additional heating	Scenario 4: Hydrogen produced decentrally; Hydrogen users use natural gas for additional heating

Table 1. Capital costs for equipment in the model

	Price (US$/unit)	Size	scale-factor	Lifetime (years)	efficiency	Maintenance
Combination boiler	63,09	22 kW	0.7	15	95 %	2%
Central heating boiler	66,00	10 kW	0.7	15	95 %	2%
Boiler	4,80	100 liter	0.7	15	99,99%/uur	2%
Fuel cell	Dependent on time	1 kWe	0.85	10	60% el 40% heat 95% BOP	2.5%
SMR	Dependent on time	1000 Nm^3/uur	0.7	20	80%	7%
PSA	85,00	1 Nm^3/uur	1	-	100%	-
Hydrogen distribution net	Depending on type of area	-	1	25	100%	2%

Table 2. Composition of the standard neighbourhoods

	Urban	Semi-urban	Non-urban
Surface (Ha)	40	200	1000
Number of residential dwellings	924	1040	1029
Of which:			
% Detached	6,00%	12,50%	25,00%
% Semi-detached	6,00%	9,75%	20,00%
% Corner houses	10,00%	14,25%	14,00%
% Terraced	28,00%	30,50%	27,50%
% Apartments	50,00%	33,00%	13,50%
Number of non-residential dwellings	114,5	101	130,5
Of which:			
Small industrial	3	6,5	14
Agriculture	1	13	35
Construction	7	10,5	13
Shops	53	34	26
Transport and communication	5	5	5,5
Banks	2	3	4,25
Commercial services	25	17	22
Public services	1,75	0	0
Education	4,75	3	1
Health Services	9	7	4
Other	3	2	5,75

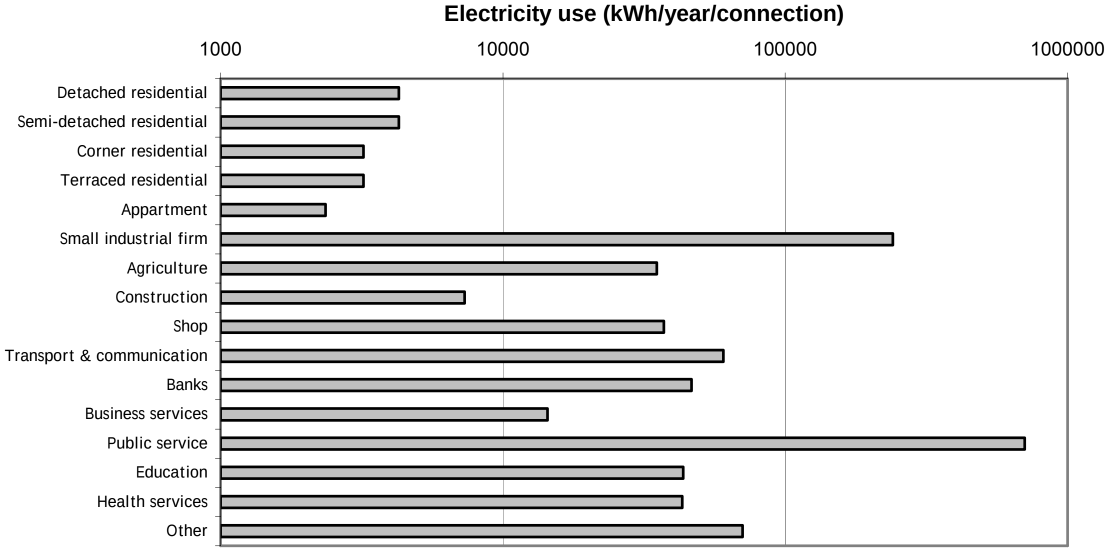
Table 3. Sensitivity analysis

Variable	Suppose:		Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	+/-	%	Δt	Max	Δt	Max	Δt	Max	Δt	Max
Discount rate		9	-2	-3	-2	-3	<-1	<-2	-2	-3
		11	2	3	1	2	?	?	?	3
Price of natural gas	+	10	-1	-2	1	2	<-1	<-1	1	2
	-	10	1	2	-1	-2	?	?	-1	-2
Price of electricity	+	10	-5	-10	-2	-6	<-7	<-11	-5	-9
	-	10	>3	>11	3	9	?	?	?	>3
Price of fuel cell	+	10	2	4	1	2	?	?	0	2
	-	10	-2	-4	-1	-3	<0	<-2	0	-2
Price of SMR	+	10	n.a.	n.a.	1	2	n.a.	n.a.	0	1
	-	10	n.a.	n.a.	-1	-2	n.a.	n.a.	0	-1
Efficiency fuel cell	+	10	-2	-3	-1	-2	<0	<0	0	0
	-	10	3	4	1	2	?	?	0	0
Infrastructure	+	10	2	2	1	1	?	?	2	3
	-	10	-2	-2	-1	-1	-3	<-3	-3	-3
Model result			**13**	**2039**	**7**	**2034**	**>25**	**>2050**	**19**	**2047**

Table 4. Hydrogen reference system

P_{fc}	Q_{fc}	El_{fc}	Furnace	Q_{buffer}
1 kWe	594,6 Nm^3	3371 kWh	10 kW	7,8 MJ

Figure 1


Electricity use (kWh/year/connection)
1000
10000
100000
1000000
Detached residential
Semi-detached residential
Corner residential
Terraced residential
Appartment
Small industrial firm
Agriculture
Construction
Shop
Transport & communication
Banks
Business services
Public service
Education
Health services
Other

.

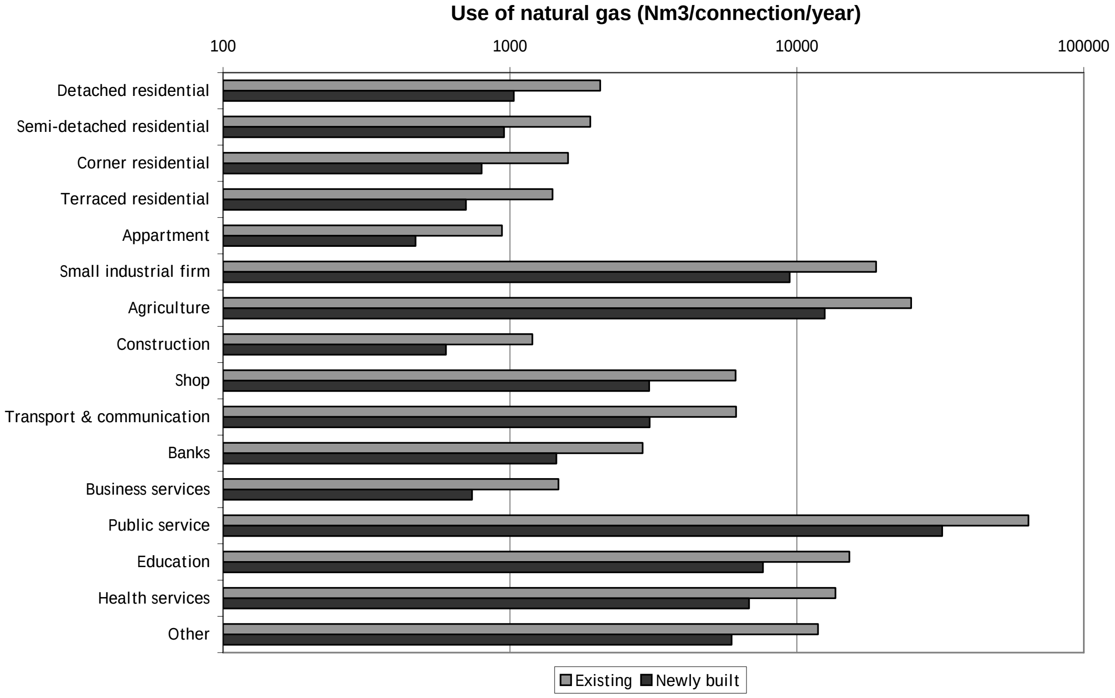

Use of natural gas (Nm3/connection/year)
100
1000
10000
100000
Detached residential
Semi-detached residential
Corner residential
Terraced residential
Appartment
Small industrial firm
Agriculture
Construction
Shop
Transport & communication
Banks
Business services
Public service
Education
Health services
Other
Existing
Newly built

Figure 2

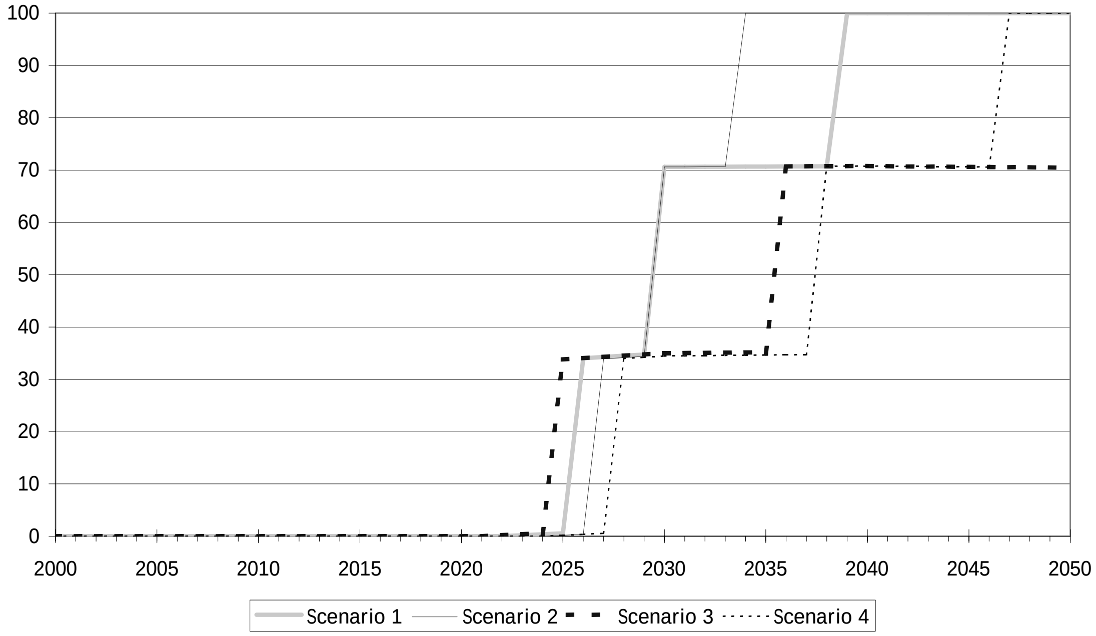
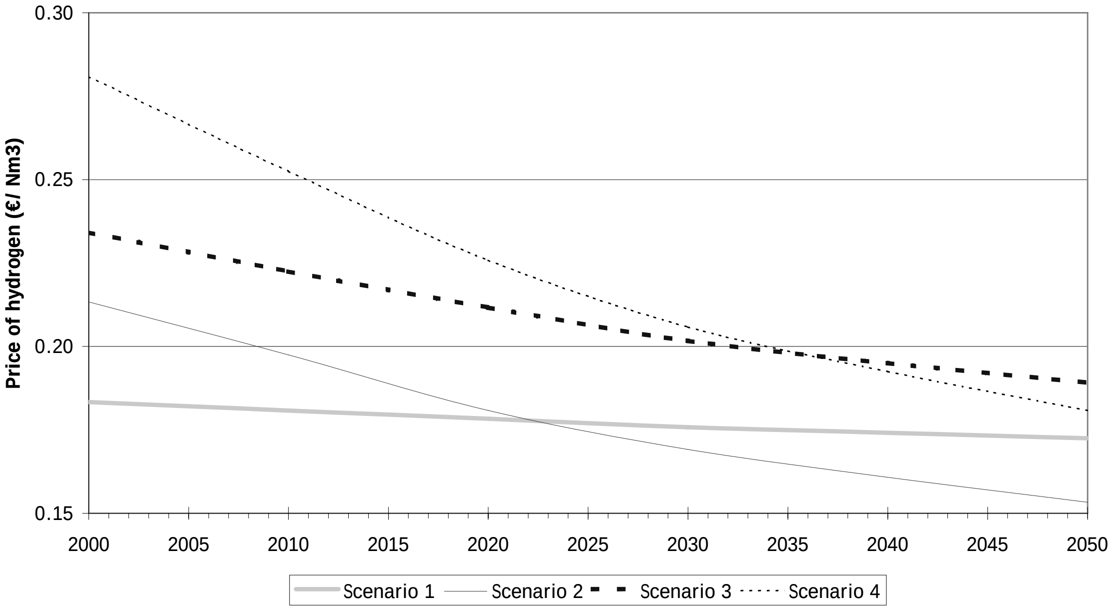

100
90
80
70
60
50
40
30
20
10
0
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
Scenario 1
Scenario 2
Scenario 3
Scenario 4

Figure 3



0.30
0.25
0.20
0.15
Price of hydrogen (€/ Nm3)
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
Scenario 1
Scenario 2
Scenario 3
Scenario 4

Figure 4

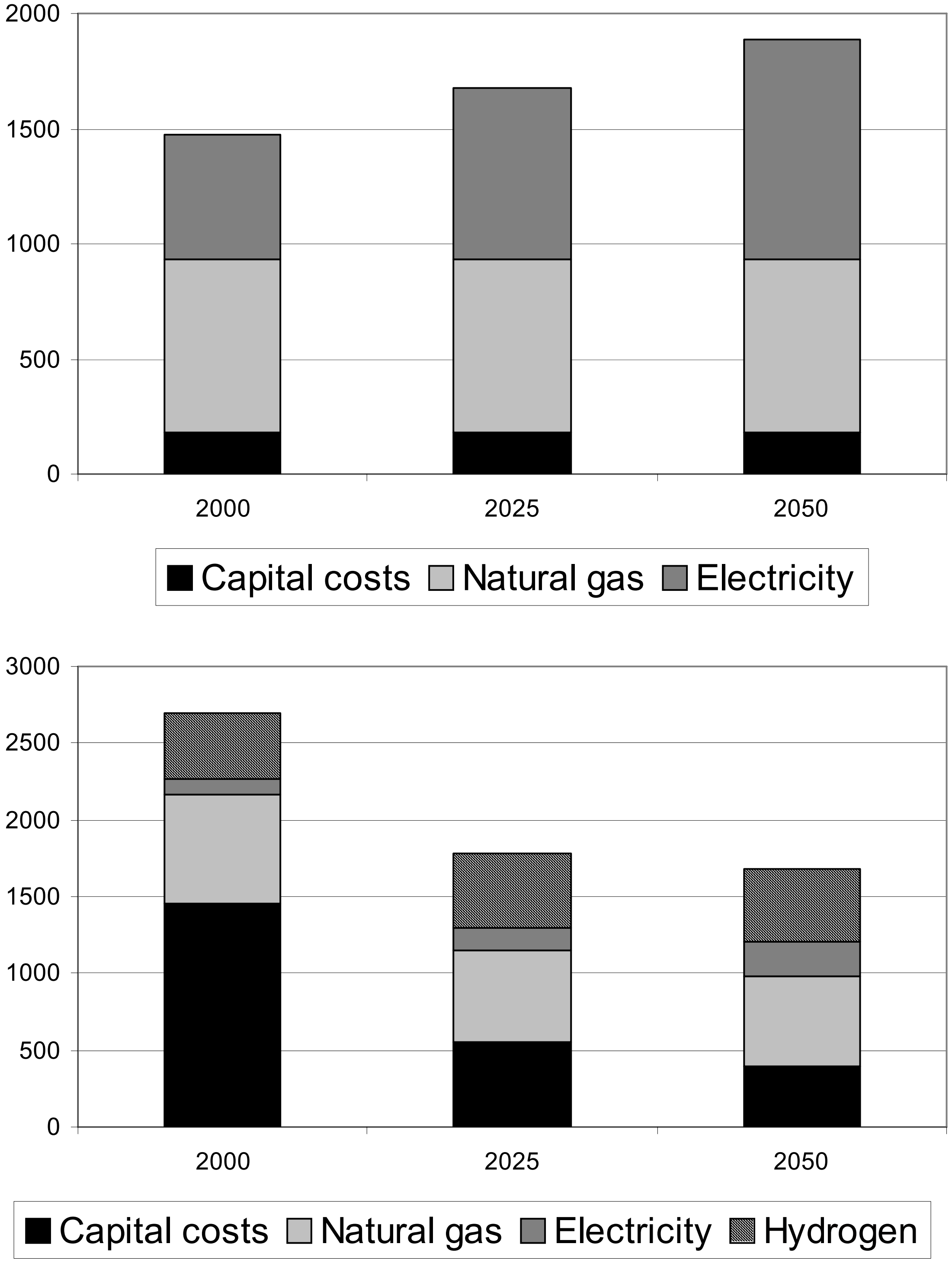
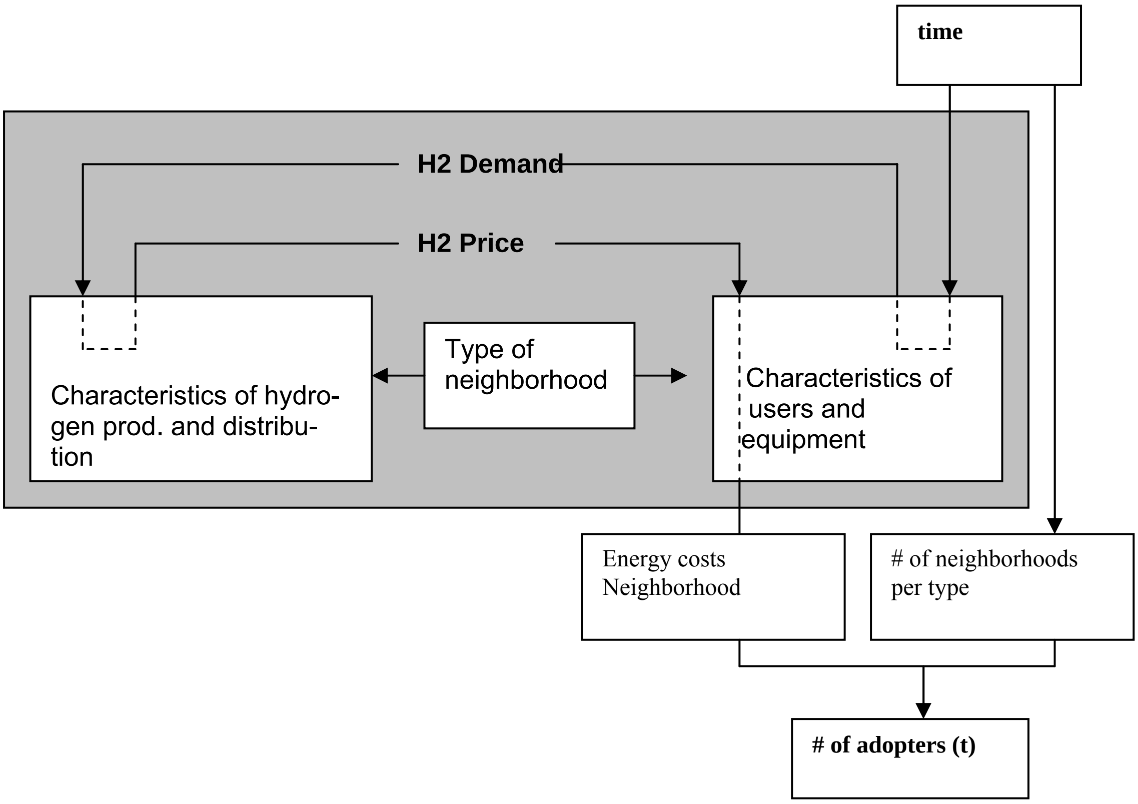

2000
1500
1000
500
0
2000
2025
2050
■ Capital costs
■ Natural gas
■ Electricity
3000
2500
2000
1500
1000
500
0
2000
2025
2050
■ Capital costs
■ Natural gas
■ Electricity
▨ Hydrogen

Figure 5


time
H2 Demand
H2 Price
Characteristics of hydrogen prod. and distribution
Type of neighborhood
Characteristics of users and equipment
Energy costs Neighborhood
# of neighborhoods per type
# of adopters (t)

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