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Article

Opportunities and Barriers for Biomass Gasification for Green Gas in the Dutch Residential Sector

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Abstract: The Dutch residential sector is locked-in into natural gas for the supply of heat. The expected depletion of national reserves and induced earthquakes in the production area are reasons to aim to escape this lock-in. The Dutch government and key players in the natural gas sector have expressed large green gas ambitions. This paper explores the opportunities and barriers of biomass gasification for green gas production and application in the residential sector. The Technological Innovation Systems and Multi-Level Perspective were applied as sustainability transition frameworks to explore the current technological state of biomass gasification and the developments in the residential sector. Four limitations were observed from a supply perspective; little financial space for demonstration plants, absence of technology specific policy, lagging market developments and insecurities related to biomass availability. On the demand side, clear barriers hampering change are observed, providing large opportunities for green gas. Key players in the natural gas regime take no substantial responsibility, despite their potential ability to contribute to overcoming systemic barriers. Therefore, this research concludes that the current green gas ambitions set by the Dutch government are not feasible and that the government may address this with technology specific policy, substantial research and development subsidies and funding.

Keywords: biomass gasification; green gas; residential sector; multi-level perspective on sustainability transitions; technological innovation systems

1. Introduction

The necessity for a transition of the energy system is determined by a number of factors relevant on different geographical scales. On a European scale there are three main policy objectives; mitigation of climate change, security of energy supply and economic competitiveness i.e., affordable energy prices [1,2]. These objectives have trickled down to the individual member states, who all have their individual challenges to fulfil such objectives, related to the design of their specific energy systems. The different targets for the share of renewable sources for the individual member states in Annex I of the Renewable Energy Directive [3] not only emphasise the different starting points for the mitigation of climate change of the member states, but also implicitly take into account the individual challenges from the member states. On a national scale, the design of the energy system of The Netherlands is exceptional, due to the historic high share of natural gas in the energy mix. This was 47% in 2000 and 38% in 2015 [4]. The discovery of the Groningen field in the northeast of The Netherlands in the 1960s [5] has led to a large national dependency on low caloric natural gas. In addition, the historic quantities of natural gas in the Dutch sub-soil resulted in The Netherlands becoming an important supplier of natural gas in North-West Europe. However, the field is expected to become depleted in about two decades and the Dutch export position will change into a net dependency on natural gas imports. This awareness has led to the so-called Gas Roundabout strategy by the Dutch government in 2005, which aims to secure the supply of natural gas and to contribute to the continuity of the European natural gas supply [6]. The dependency has in particular led to a lock-in of the Dutch residential sector, where 93% is connected to the low caloric natural gas grid for heating purposes [7]. The average consumption in a Dutch household is about 1500 m^3 $annum^{-1}$ [8] for space heating, hot water supply and cooking, making the residential sector responsible for the consumption of about 11 billion cubic meters bcm, which is almost half of the current annual production from the Groningen field. However, production from this field has led to over 1000 induced earthquakes causing damage to existing buildings and contributing to social turmoil [9].

Recently, the Dutch Petroleum Company (NAM) was forced by the Minister of Economic Affairs to reduce production from the Groningen field to 24 (bcm) or 760 PJ $annum^{-1}$ [10], as a response to induced earthquakes.

During a transitional period towards a sustainable energy system, green gas supply can contribute to a further reduction of the Groningen field production levels; this may result in a decrease in the number and severity of the induced earthquakes [11,12].

A large role for green gas is expected by the Dutch government and key players in the natural gas sector during the transitional period towards a sustainable heat supply system. The most recent agreement related to the supply of heat is the Heat Vision document. It suggests a tripling of renewable heat production is possible from 6.1 PJ to 18 PJ between 2013 and 2023 [13]. This renewable heat should originate from biogas combustion with combined heat and power and green gas through biogas upgrading. The Dutch gas trade company GasTerra states that up to 3 bcm of green gas (or about 95 PJ) can be produced in 2030 [14]. Such quantities require large-scale production of green gas. In order to supply the expected quantities of green gas, gasification technology is thought to have large potential. Gasification can be used to convert basically all carbon containing compounds into gaseous products [15]. Biomass gasification combined with a methanisation unit is an innovative developing technology, which can be used to produce a green gas suitable for injection into the existing gas grid.

The aforementioned factors; climate change, depletion of the low caloric natural gas field, induced earthquakes, a large national dependency on natural gas, and the residential sector being a captive customer, emphasise the need for a transition of the residential heat supply system in The Netherlands in a short timeframe. In this article, the Dutch residential sector is regarded as a captive customer, since the rate of return of renewable heat supply technology is often too long or the capital investments are too high for a large part of the population. Biomass gasification can potentially contribute to all these factors. Green gas produced through biomass gasification can positively contribute to climate change from a greenhouse gas perspective [16]. Furthermore, large quantities of green gas can potentially reduce the dependency on the Groningen field, contribute to reduced production levels from the Groningen field and with that possibly a reduced number of earthquakes.

Biomass gasification can serve as an incremental innovation, since it can stabilise the transition towards sustainable heat supply in the residential sector. Therefore, the aim of this research is to explore the opportunities and barriers of biomass gasification for green gas production and application in the Dutch residential sector.

2. Methodology and Frameworks

The Multi-Level Perspective on sustainability transition (MLP) and the Technological Innovation System (TIS) are the frameworks that have dominated the literature concerning sustainability transition theory [17]. The TIS framework is applied here to explore the current technological state of biomass gasification and with that its technical possibilities to supply green gas.

The MLP is used to explore the position of key players in the natural gas sector and the position of the residential sector as captive customers. The captivity of the residential sector is addressed by exploring the absence or presence of six potential barriers, hampering diffusion of renewable energy technology, provided by Reference [18]. By including so-called socio-technical regimes and landscape pressures in this analysis, the TIS approach can be applied to explore transitions [19] and with that the potential role of biomass gasification and green gas during the transition towards sustainable heat supply in the Dutch residential sector.

2.1. Sustainability Transition Frameworks

The TIS framework provides a check-list, based on a set of seven so-called system functions. According to [20], the functions approach should be regarded as a process or history event analysis. This functions approach has been applied before by References [21,22], on the topic of biomass gasification. These historic case studies aim to explain the failure of the diffusion of biomass gasification. They regard the absence of system functions as indicators for failure of the diffusion of biomass gasification. The functions approach is argued to be generic enough to explore varying TISs and find barriers [19,23]. Therefore, the TIS framework was applied for the analysis of the current technological state of development of biomass gasification. The system functions are listed in the first column of Table 1 and were taken from Reference [20]; the second column lists a number of relevant indicators taken from References [20,24]. These indicators were adjusted for the specific case of biomass gasification in order to find systemic barriers for biomass gasification and form a basis for some policy recommendations to overcome these barriers. The framework in Reference [24] is argued to be suitable for both policy makers and innovation scholars.

Table 1. Technological Innovation System (TIS) system functions and operationalised indicators applied in this research.

System Functions	Indicators
1 Entrepreneurial activities	Entrepreneurs experimenting with biomass gasification Varying feedstock Varying output Varying scales Specific research about technological performance
2 Knowledge development	Scientific theory and experiments Actors responsible for financial space Applied research projects National research and technology programs Pilot and demonstration plants
3 Knowledge diffusion	Partnerships Publicly available feasibility assessments Actors contributing to knowledge development
4 Guidance of the search	Policy documents, strategies and agreements Induced government activities Technology specific policy Green gas policy Technological expectations Policy documents from the natural gas regime
5 Market formation	Market size Current and potential users Leading parties Institutional incentives/barriers
6 Resource mobilisation	Adequate public funding Adequate risk capital Actors with resources and capabilities Supportive networks for innovation Biomass supply and supply expectations Biomass prices
7 Counteracting resistance	Supportive bottom-up initiatives Legitimate investment decision

System functions were taken from Reference [20]. Indicators were taken from Reference [25] and from an extensive list provided by Reference [24]. Indicators were operationalised for this specific research when necessary.

The MLP on sustainability transitions is a qualitative framework, suitable for the analysis of long-term transitions related to challenges such as resource depletion [26]. It applies three levels of change (i.e., the landscape, regime and niche level), where respectively the dynamics between macro developments, existing configurations and developing technology can be explored. Geels [27] defined the niche level as "[. . .] 'protected spaces', such as Research and Development (R&D) laboratories, subsidised demonstration projects, or small market niches where users [. . .] are willing to support emerging innovations [. . .]". The regime level was defined as "[. . .] the deep structural rules that coordinate and guide actor's perceptions and actions [. . .]" within "[. . .] the alignment of existing technologies, regulations, user patterns, infrastructures and cultural discourses [. . .]". The landscape was defined as "[. . .] the wider context, which influences niche and regime dynamics", which "[. . .] includes spatial structures [. . .] political ideologies, societal values, beliefs, concerns, the media landscape and macro-economic trends" [27]. General patterns in transitions are described by the interactions between these levels. The approach is graphically presented in Figure 1. In this figure, biomass gasification is presented as a niche technology and explored with a TIS analysis.

2.2. Data Collection

Empirical evidence was gathered by a number of semi-structured interviews and literature review by looking through scientific databases. Semi-structured interviews were conducted with key players, including representatives from a leading housing corporation (J. Leistra, Wold en Waard), municipality (B. de Boer, Municipality of Leeuwarden), province (H.J. Bouwers, Province of Friesland), energy supplier (M. van Son, NLDenergie), and of main companies in the natural gas sector involved in the trade (G. Martinus, GasTerra), infrastructure (W. de Groot, Gasunie), transmission (W. de Groot, GTS) and distribution (M. van Dam, Enexis) of natural gas. Additionally, policy from the European Union (EU), i.e., the Renewable Energy Directive (RED) [3] and the Energy Performance of Buildings Directive (EPBD) [28], were analysed as landscape pressures. The national policy documents taken into account are the Energy Agreement on Sustainable Growth [29] and the Heat Vision [13]. The future role of natural gas and with that the potential for green gas was estimated by extrapolating the ambitions formulated in current policy when it comes to increased energy efficiency and alternative technology in the residential sector until 2030. The expectations towards green gas in the natural gas sector were explored by combining the semi-structured interviews with annual reports from actors dominating the natural gas sector (between 2011 and 2016). The developments in the residential sector were explored by reports from housing corporations and scientific literature.

This article is structured as follows. The results and discussion section starts with possible green gas production routes after which the TIS analysis for biomass gasification is presented. Subsequently, the change in energy performance and diffusion of renewable heat technology in the residential sector is explored. In addition, the natural gas regime is delineated on a sectoral basis. The discussion section is applied to address the methodological choice for such regime delineation and to present the observed opportunities and barriers. The concluding section combines the observed insights from the supply (biomass gasification technology) and demand side (residential sector) in combination with the expectations of the government and the natural gas regime.

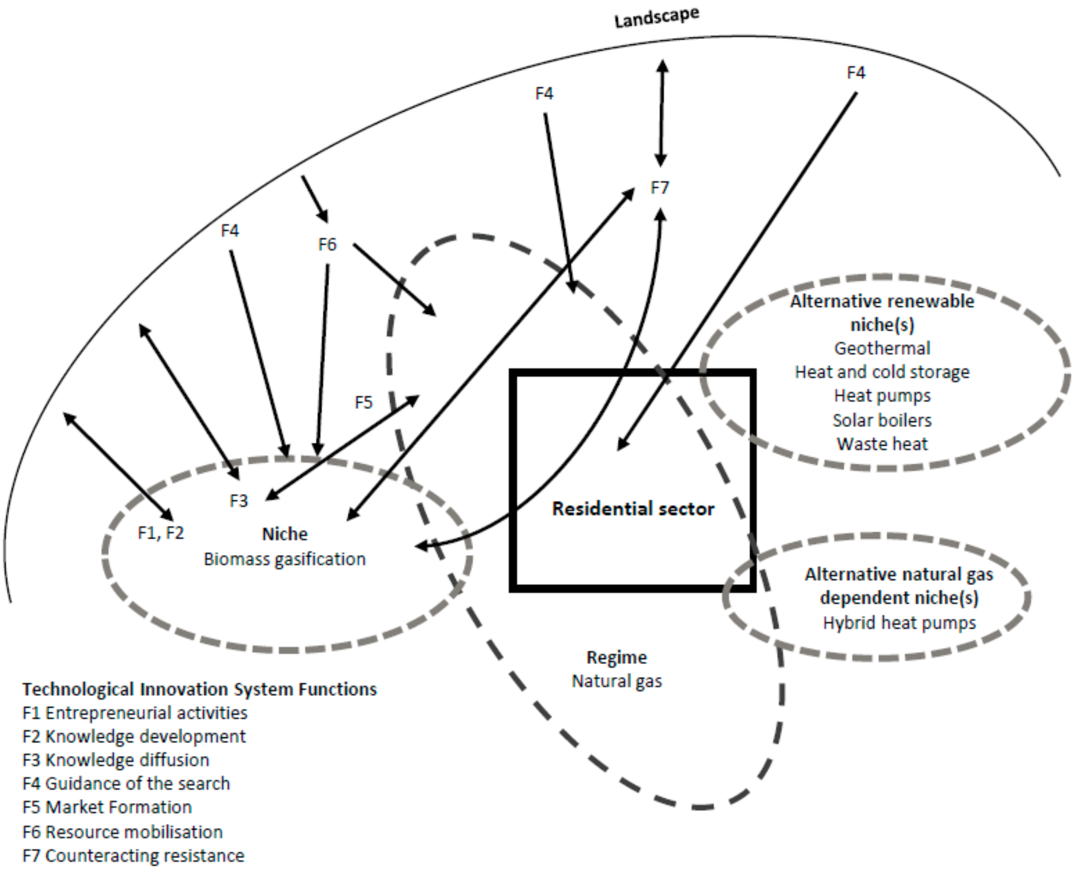

Figure 1. Overview of the TIS functions for biomass gasification, including alternative niches for residential heat supply, the natural gas regime, the residential sector and the landscape level. The arrows indicate the dynamics between different levels and the TIS functions, single arrows indicate unilateral pressures, whereas double arrows indicate bilateral dynamics combined with the system functions from TIS. The residential sector is presented as a black box to emphasise its position as a captive customer within the natural gas regime. Figure 1 is based on Reference [30].

3. Results

3.1. Green Gas Production Routes

In order to supply the envisioned quantities of green gas two technologies can be applied, i.e., biological or thermochemical. Currently, the largest part of biogas is produced through the biological route, with anaerobic digestion (AD) processes in The Netherlands. With AD about 13 PJ of biogas was produced, of which 2.6 PJ was converted into green gas and injected into the grid in 2016 [31]. Figure 2 gives an overview of the green gas production routes for AD and gasification, including the production of alternative energy carriers. This research focuses on the gasification route emphasised by the dashed square in Figure 2. AD is included in the figure, since it is the only option for green gas production currently installed in The Netherlands on a substantial scale. Given that production of biogas is 13 PJ [31], roughly a doubling of installed capacity would be required when an overall efficiency of 75% is assumed for biogas upgrading to green gas [32], if the target of 18 PJ is to be met in 2023. In addition, almost half of the biogas is produced trough co-digestion of manure at a farm level [31] in rural areas. All this biogas is combusted with Combined Heat and Power (CHP), with the main purpose of electricity production and supply of the required process heat [31]. Adjustments of these plants, with an upgrading step would be required in order to produce a green gas. However, the produced quantities are limited by demand, since these farms are connected to the low pressure distribution grid. Continuous production may result in supply problems, because the low pressure distribution grid has limited injection capacity [33], since it is a unidirectional grid. This causes local limitations, especially in summer when there is low demand ([33]; personal communications with M. van Dam, Enexis on 10 March 2015 and H.J. Bouwers, Provinsje Fryslân on 20 March 2015). The high pressure transmission grid is therefore more suitable for injection of green gas (personal communication with H.J. Bouwers, Provinsje Fryslân on 20 March 2015). In addition, linepack can be applied as a source of flexibility when there are imbalances between injection and extraction [34]. Producing substantial amounts of green gas in 2030 is therefore not expected from AD. Biomass gasification should result in centralised production of large quantities of green gas and therefore the high pressure transmission grid can be used for injection, overcoming the capacity issues.

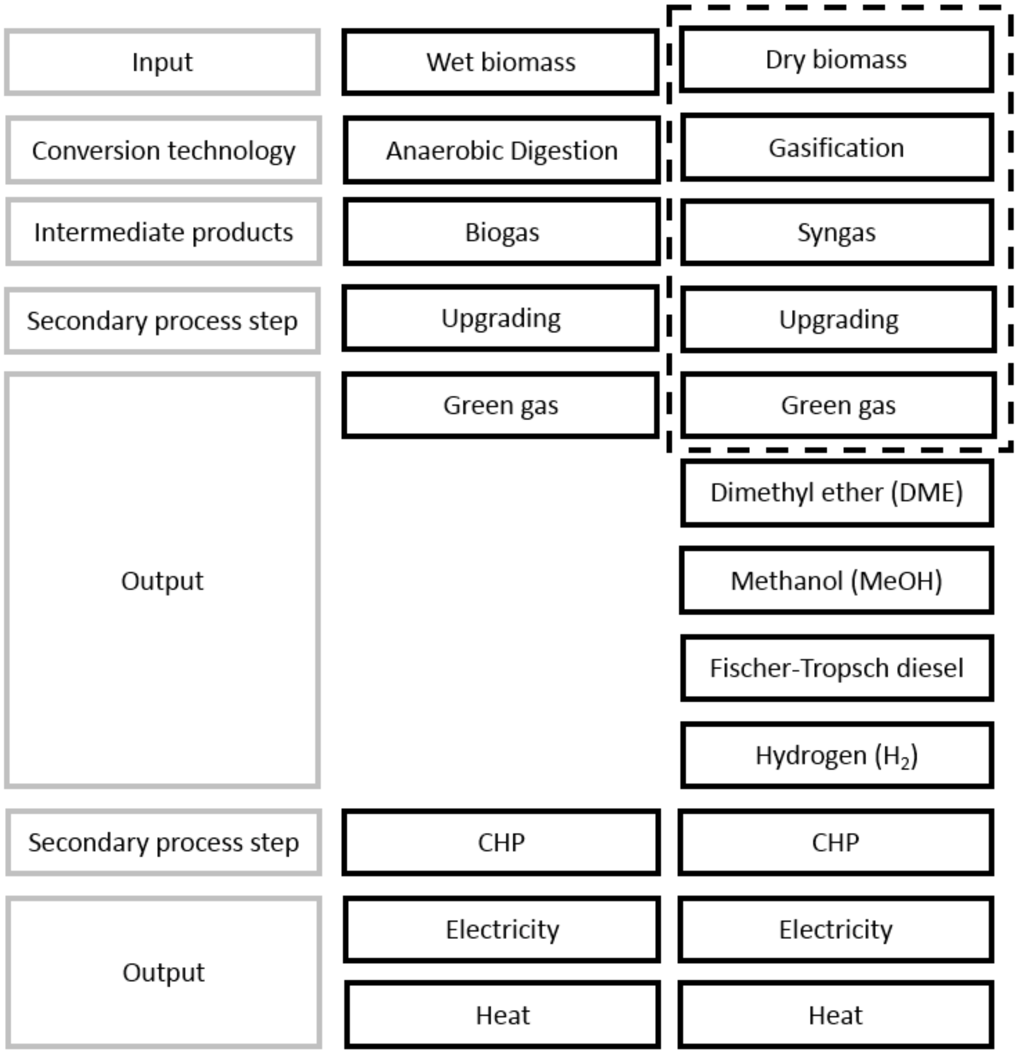

Figure 2. Overview of the possible green gas production routes from anaerobic digestion (AD) and gasification, including alternative output fuels.

3.2. *TIS Description of Biomass Gasification*

Contrary to AD, biomass gasification technology for green gas production is not implemented on a large scale. Coal gasification for the production of synthetic natural gas is a proven technology (see e.g., Reference [35]); biomass gasification is still subject to technological challenges which need to be resolved. Therefore, this paper continues with a systemic approach to explore the factors that form barriers for diffusion of biomass gasification.

A variety of companies, research institutes, universities and collaborations between these three have led to a number of pilot and demonstration plants [36–38]. There is a variety in bio-based feedstock, from woody lignocellulosic biomass, gaseous and liquid fuels (e.g., syngas and black liquor) and waste (refuse derived fuel). The output products vary between electricity, heat and different liquid and gaseous fuels. The gaseous fuels are biogas, syngas and Synthetic Natural Gas (SNG). SNG is a green gas suitable for injection into the natural gas grid. Liquid fuels are dimethyl ether (DME) and Fischer-Tropsch diesel (FT diesel), which are renewable transport fuels. Given the variety of possible output products for biomass gasification (Figure 2) that are being researched, selection of an optimal design for the biomass gasification technology has not taken place. A number of biomass gasification initiatives can be identified in Europe. An overview of biomass gasification projects in Sweden and Denmark is provided by Reference [37]. Of the 19 identified projects only one demonstration plant was designed with the purpose to produce green gas. In addition, Reference [36] identified 23 thermochemical conversion initiatives on a global scale. Two additional initiatives were found that produce green gas in The Netherlands. Furthermore, Reference [38] gives an overview of 14 biomass gasification projects in Europe, with five additional initiatives of which one semi-commercial plant aimed to produce green gas. This semi-commercial plant was however, put on hold [38]. The emphasis on green gas production lies therefore in The Netherlands. The second plant mentioned by References [36,38] is, however, still in its planning stage. The first Dutch plant is a 800 kW pilot installation by ECN, which had successful trials [39,40], and they aimed to increase the scale to about 10 MW, since 2010 [40]. Currently, the plans for this demonstration plant are renewed by a collaboration between the province, municipality, and various actors being part of the biomass gasification niche and the key players in the natural gas sector [41,42] and construction is being planned for 2018 [43]. The Dutch province of Noord Holland has agreed to invest about €1 million in the development of a biomass expertise centre and €0.5 million in the development of a demonstration plant for biomass gasification technology as developed by ECN [41]. Total costs are in the order of €23 million; this collaboration has agreed to foresee in the remaining €21.5 million. Other initiatives in The Netherlands related to biomass gasification are from BioMCN (biofuel production), Synvalor (engineering consultant), Torrgas (small-scale syngas production), Heveskes (conversion technology), HVC Alkmaar (waste treatment), HoSt (engineering) and ECN (research institute) [44]. These are currently quite small initiatives when looking at scales of production (aside from BioMCN).

The output of theoretical scientific knowledge related to biomass gasification increased on average with 20% per annum since 2000 when looking at results from Web of Science when using biomass gasification as keyword. Furthermore, The Netherlands had the EDGaR program, in which research addressing biomass gasification for green gas also had a substantial role between 2010 and 2015 [45]. A follow-up program was not realised. Experimental knowledge is developed through a number of pilot and demonstration plants. However, increasing the scale from a pilot plant to a demonstration plant or from demonstration to a commercial plant proves difficult. Reference [38] mentions the example in Finland, where a 12 MW pilot plant had successful trials, but still stopped experiments afterwards. In addition, Reference [46] observe a more general trend where the shift from demonstration plants to a commercial scale hampers. In The Netherlands this story is similar, since the aim to increase the scale of the 800 kW pilot plant to a 10 MW demonstration plant exists for eight years already. In addition, further development to early commercialisation and full scale commercial plants is a lengthy process. Furthermore, Reference [46] argue that it takes at least three years after the construction of a demonstration plant is finished, before the performance is good enough to find investors for a pre-commercial plant. Further upscaling, permits for construction and construction itself of a full-scale commercial plant that can contribute to the transition in the Dutch residential sector is a process that will take more than a decade at best.

Technology specific policy could contribute to such developments, but the Dutch government has only put in place an operating grant for promotion of renewable energy, called SDE+, which provides the opportunity for investors to receive financial compensation for the production of renewable energy for a certain period. This should accelerate the implementation of renewable energy technology. The high initial cost of such a large plant are however difficult to overcome and an operating grant is therefore not useful. Despite the absence of technology specific policy, lower governments play a facilitating role by supporting local initiatives and bringing entrepreneurs together ([29]; personal communications with H.J. Bouwers, Provinsje Fryslân on 20 March 2015 and B. de Boer, Municipality of Leeuwarden 5 November 2014). The current planning of the 10 MW demonstration plant by ECN, Gasunie, Dahlman and HVC in Alkmaar is an example of collaboration and the facilitating role of lower governments.

Furthermore, a market for green gas should be present. This could be the residential sector, but this is highly dependent on future natural gas and green gas prices, and the cost for alternative renewable technology to supply heat. Thus, besides the technical development, the development of both the natural and green gas prices are of importance. Depending on the feedstock cost the green gas cost will be €14–24 GJ^{-1}, which is currently twice the price of natural gas [47]. However, natural gas prices are expected to rise (€11–14 GJ^{-1} in 2030) and therefore green gas has possibilities to become competitive in the coming decades. A low feedstock price can be attained by the application of waste instead of biomass as feedstock. Future biomass prices are insecure, given the expected global availability of 33 to 1135 EJ a^{-1} in 2050 [48]. Besides that, biomass for energy purposes is subsidy-driven, since there is a direct relation between biomass co-combustion in coal fired power plants and national subsidy structures in The Netherlands [49]. The most recent estimates for demand and supply of biomass within the Dutch bioeconomy show that demand exceeds domestic supply with at least a factor two and possibly a factor nine in 2030 [50]. This is emphasised by the example of a relatively small-scale initiative like the biomass incineration plant from Eneco (49.9 MW_e), that requires waste wood, which is already imported from neighbouring countries ([51]; personal communication with J. de Haas, CEO at Eneco on 9 December 2015). When green gas production is combined with higher value renewable products, the additional profits can be applied to reduce the cost for green gas production. Co-production of value-added chemicals may result in a cost reduction of €4.5 GJ^{-1} [47]. This would require flexible production of which the importance, when it comes to input and output products, is emphasised in literature [52–55].

The results of this TIS analysis are summarised in Table 2, where the systemic barriers are also included. The TIS analysis shows that the development of biomass gasification technology for green gas in The Netherlands is still in the formative phase. The larger part of the systemic barriers are institutional and lacking financial or knowledge infrastructure. The required network interactions between the players in the biomass gasification TIS and key players in the natural gas sector have led to a collaboration that is aiming to continue with the currently planned demonstration plant in The Netherlands. Further technological development and diffusion of biomass gasification is limited by four factors. The first is the inability of the involved actors to increase the scale to demonstration and subsequent pre-commercial or full scale commercial plants. In The Netherlands, this inability results from the absence of financial infrastructure for investments, and not because of unsuccessful testing. High capital investments are required; with insecure profits, this results in large investment risks. Expectations for green gas are, however, large; this holds for key players in the natural gas sector, but also for Dutch politics and parties involved in the development of Dutch energy strategies. The second factor is institutional and involves the absence of technology specific policy. Lower levels of the Dutch government aim to facilitate initiatives in line with the existing strategies and key players in the natural gas sector collaborate with the technology developers. Key players contribute to the direction of the technological development of biomass gasification, but the current quantity of the investments does not guarantee successful diffusion of biomass gasification to foresee in the desired quantities of green gas in 2030. Third is the absence of a substantial market. A market share of 5% for green gas, as envisioned by the Dutch government in 2023, which is a requirement for successful diffusion of a technology [56] is not guaranteed. Fourth are limitations related to knowledge and financial infrastructure, which involve the insecurity related to future biomass prices and availability as feedstock for energy purposes.

Table 2. Overview of the present (+) and absent (−) system functions and the systemic barriers.

System Functions	Indicator	Present	Remark	Systemic Barrier
1 Entrepreneurial activities	Entrepreneurs experimenting with biomass gasification	+	A variety of institutes in the European Union (EU) and multiple small initiatives/companies in the NLs not all related to green gas	
	Varying feedstock	+	Biomass and waste in the EU, biomass in the NLs	
	Varying output	+	Electricity; renewable gases; liquid fuels; building blocks for chemical industry in the EU, green gas in the NL	
	Varying scales	+	500 kW to 160 MW in the EU, 800 kW for green gas is present in the NLs	
	Specific research about technological performance	+	A variety of institutes in Europe, ECN in the NLs	
2 Knowledge development	Scientific theory and experiments	+	Clear increase in theoretical scientific output since 2000; gasification was part of the Energy Delta Gas Research	
	Actors responsible for financial space	+/-	Financing is difficult, there are delays; Dutch national subsidies are focused on production (SDE+) not on construction and development;	Institutional and financial infrastructure
	Applied research projects	+/-	Lower level governments facilitate niche and regime initiatives	Institutional and financial infrastructure
	National research and technology programs	-	EDGaR was finished in 2016, no follow-up programme	Financial and physical infrastructure
	Pilot and demonstration plants	+/-	Financing is difficult; there are delays; construction of 10 MW demonstration plant is planned in the NLs since 2010	Institutional and financial infrastructure
3 Knowledge diffusion	Partnerships	+	Collaboration between niche players and the natural gas regime	
	Publicly available feasibility assessments	+	Green gas production costs, technological assessments of biomass gasification	
	Actors contributing to knowledge development	+	Both on niche level and natural gas regime	
4 Guidance of the search	Policy documents, strategies and agreements	+/-	Energy Agreement and Heat vision; implementation is behind schedule	Institutional
	Induced government activities	+/-	Facilitating role for lower governments; financial means are too small	Institutional and financial infrastructure
	Technology specific policy	-	No specific support schemes for biomass gasification	Institutional
	Green gas policy	+/-	Subsidy schemes are present; high green gas expectations; aim is 18 PJ in 2023, no clear role for biomass gasification	Institutional, interactions and actors
	Technological expectations	+/-	No clear view on the future role of biomass gasification	Knowledge infrastructure, network interactions
	Policy documents from the natural gas regime	+	Annual reports of players in the natural gas regime show openness towards green gas;	

Table 2. *Cont.*

System Functions	Indicator	Present	Remark	Systemic Barrier
5 Market Formation	Market size	+/-	Currently a niche market, potentially large in the residential sector	Institutional
	Current and potential users	-	Potential in the residential sector	Institutional
	Leading parties	+	Players within the natural gas regime	
	Institutional incentives/barriers	-	Upscaling of technology is difficult due to financial means	Financial infrastructure
6 Resource mobilisation	Adequate public funding	-	ISDE subsidy is only available for proven technologies	Institutional
	Adequate risk capital	+/-	Over €20 million from public and private parties, not enough for upscaling	Institutional, network interactions
	Contributions from actors with resources and capabilities	+	10 MW demonstration plant in Alkmaar	
	Supportive networks for innovation	+	United in a consortium of niche an regime players	
	Biomass supply and supply expectations	-	Small projects already require imports	Knowledge infrastructure
	Biomass prices	-	Unpredictable	Financial and knowledge infrastructure
7 Counteracting resistance	Supportive bottom-up initiatives	-	Small energy corporations have little access to green gas	Institutional
	Legitimate investment decision	-	Investment risk is high, due to uncertain outcomes	Knowledge infrastructure

3.3. Implementation in the Residential Sector

Now that the barriers for green gas on the supply side are identified, this section explores the developments in the residential sector in order to find the potential for green gas on the demand side. The residential sector is regarded as a captive customer within the natural gas sector. In order to get insights in the potential for green gas, this section is used to indicate the existing barriers towards implementation of improved energy performance measures and alternative heat technology in the residential sector. Six potential barriers limiting the diffusion of renewable energy technology, namely; awareness and information, economic and financial constraints, technical risks, institutional and regulatory barriers, market barriers and behaviour, were provided by Reference [18]. The actors influencing change in the residential sector are divided in three groups. These are the owners in the private sector, the housing corporations and its tenants. The EPBD [28] is the overarching European policy that focuses on the energy performance of the built environment and with that the residential sector. It aims to have new houses built that, on average, produce similar quantities of energy as they consume. The EPBD introduced the energy performance certificates for buildings, ranging from A+++, being the best to G, being the worst performer. A minimum of a certificate C is required in the private sector and a minimum of certificate B for property of housing corporations, in 2020 [57].

About one-third of the residential sector is managed by housing corporations [58,59]. Although [60] argue that the financial space for housing corporations is large enough, the main goal of a B certificate for this sector [57] is not expected to be met in 2020 [58,61]. In addition, AEDES (the national organisation that promotes the interest of almost all housing corporations [62]) argues in their annual reports that the financial space for investments of the housing corporations is not as strong as thought [63,64]. Proposed adjustments to the Heat Law are expected to indirectly force housing corporations to switch from collective heat supply to individual natural gas boilers [65]. Collective heat contributed for 5,5% to heat supply in the residential sector in 2016 [66]. Collective heat supply is mainly driven by natural gas and is assumed to increase up to one-third of the total supply in 2030 [13]. Visscher et al. [58] argue that convincing tenants to participate in energy saving measures, that result in an increase in rent, is challenging. In addition, the energy certificates A and B underestimate the actual natural gas use, whereas the certificates E, F and G overestimate the actual natural gas use [58,67]. An increased cost for rent due to energy saving measures, combined with lower energy cost is therefore no guarantee that tenants will end up with lower monthly costs. In addition, Reference [68] argues that this risk of increased cost is especially relevant for tenants who already use little energy for heat for economic reasons. Furthermore, a large part of tenants was found to have little interest in the energy performance of their homes [69]. Besides that, Reference [70] emphasise that investments in the private sector in energy performance of buildings offers economic benefits. Despite this, private owners are not easily convinced to improve the energy performance of their households [70]. In addition, residents' behaviour and heating technology are two important factors in the total energy consumption in the Dutch residential sector [70–72]. Van Middelkoop et al. [70] recognise the importance of heating behaviour, but also argue that this importance is not visible in Dutch policy. Brounen et al. [72] mention that efficiency increases may be annihilated, due to the behavioural aspects related to an ageing Dutch population. In addition, smart-metering technology may contribute to awareness within households, but does not guarantee behavioural change. Currently, the effect of smart-meters has offered no more than 1% reduction in heat demand [73]. When it comes to heating technology, Reference [74] mention that with current policy 9% of the high efficiency boilers in the residential sector will be replaced in 2030. The expected substitute technologies are hybrid boilers, which still have a natural gas dependency, and electric heat pumps. When considering the government's heat specific policy [13] it aims to avoid increasing dependency on politically instable regions by diversifying the heat supply in The Netherlands. They see potential for a variety of technologies, like heat and cold storage, geothermal heat, solar boilers, biomass and (hybrid) heat pumps. Collective heat supply could be up to a third of the total heat demand in 2030. In regions where heat supply remains dependent on gas (i.e., in areas with a low population density), the goal is to replace this to a large extent with renewable gases. The contribution of green gas to heat supply is expected to be between 6.1 and 18 PJ in 2023 [13], of which the latter is 5% of the current natural gas consumption in the Dutch residential sector. Schoots and Hammingh [7] argue that the largest challenges, when it comes to the implementation of this policy, are the absence of a market model and infrastructure. The absence of physical infrastructure does not hold for green gas, since green gas can be distributed via existing grids. Table 3 summarises the existing barriers hampering change in the residential sector.

Figure 3 is used to determine the minimum market share for natural gas in the residential sector in 2030, by extrapolating the government's policy targets for 2023 [13] until 2030. The ambition to increase the energy performance of 300,000 existing buildings with two certificate steps until 2020 [29] is taken into account, by assuming a reduction in heat demand due to improved insulation, of 1.4% and 1% respectively, between 2010 and 2020 and 2020 to 2030 (based on Reference [61]). Starting points for geothermal, heat and cold storage, heat pumps, solar boilers, waste heat and green gas in 2013 were taken from Reference [13]. For collective heat supply 8 PJ was used as a starting point in 2013, which is roughly a third of the available collective heat [75], but results in an overestimation when compared to [76].

In Figure 3 the total heat supplied with natural gas is half of the demand, with the assumption that collective heat is based on natural gas, resulting in a demand around 5 bcm from the Groningen field in 2030. In addition, the government's heat policy is not very specific on the sector where renewable heat should be applied. All renewable heat that is not specifically allocated to a sector in the existing policy is assigned to the residential sector, which means that the demand for natural gas in the residential sector in 2030 is an underestimation. The captivity of the residential sector in the natural gas regime becomes smaller, but remains substantial. The market share for natural gas in the residential sector remains large and with that the potential for green gas as a means to foresee in renewable heat.

Table 3. Barriers affecting change in the residential sector.

Barriers	Housing Corporations	Tenants	Private Owners
Lack of awareness and information	Difficult to convince tenants to accept increased rent prices	Large part shows little interest in energy performance	Despite economic benefits owners are not easily convinced to implement technology
Economic and financial constraints	Limited financial space for investments	Insecure net effect of increased rent and decreased energy cost	Captive customers
Technical risks	Absent infrastructure for centralised renewable heat supply besides green gas		Absent infrastructure for centralised renewable heat supply besides green gas
Institutional and regulatory barriers	Heat Law may provide adverse incentives Policy agreements are not mandatory	Policy agreements are not mandatory	Policy is not mandatory
Market barriers	Absent market model		Absent market model
Behaviour	Positive attitude towards change	Smart meters have little effect on behaviour	Smart meters have little effect on behaviour

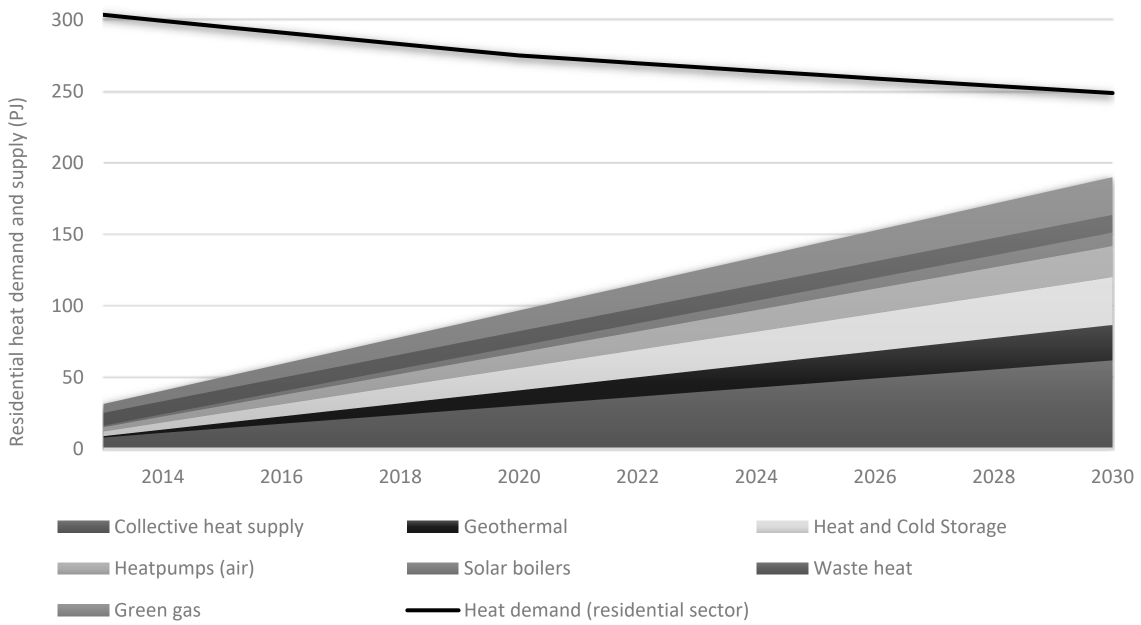

Figure 3. Residential heat demand for space heating, hot water and cooking. The demand for cooking is marginal (i.e., roughly 7.5 PJ, based on 32 $m^3 \cdot household^{-1}$ [77]); the demand for hot water is about 63 PJ based on an average showering time of 8.12 min [77], a flow rate of 10 $litre \cdot min^{-1}$ and a temperature difference of 30 Kelvin. The remainder is required for space heating. Data are in petajoule (10^{15} joule).

In summary, the efficiency targets are not likely to be met in 2020 [69], and the expected share of installed renewable heat technology in the residential sector is low in 2030 [74]. Given that the required infrastructure for distribution and consumption of natural gas is present in The Netherlands, and landscape factors, such as the coming depletion of the Groningen field, the resulting import dependency and the continued captivity of the Dutch residential sector, a renewable alternative for natural gas, such as green gas, has large potential for renewable heat supply in the residential sector.

3.4. The Natural Gas Regime

The previous sections showed that biomass gasification technology cannot supply large quantities of green gas in the short term, whilst meanwhile a transition in the residential sector is lagging behind. In this section the natural gas regime is delineated to explore their perceptions towards green gas and their potential ability to contribute to overcoming systemic barriers. Here, the natural gas regime is defined as: The parties involved in the supply chain from natural gas production from the Groningen field, including end-use in the residential regime. The residential sector is a part of the natural gas regime, as shown in Figure 1. Key parties are the joint venture between Royal Dutch Shell and ExxonMobil known as the NAM. The NAM is responsible for the natural gas production in the Groningen field. The produced natural gas by the NAM is purchased by GasTerra, the Dutch gas trading company. Their mission is to maximise the Dutch value of natural gas reserves in The Netherlands [14]. GasTerra is owned for 25% Shell, 25% ExxonMobil, 40% Energiebeheer Nederland (EBN) and 10% Ministry of Economics. GasTerra has the responsibility to maximise the value of the Dutch natural gas reserves and thus serves as a natural gas trade company. GasTerra expected 0.3 bcm of green gas to be produced in 2014 and an increase to 3 bcm (95 PJ) in 2030 already in 2011 [78]. In this same year, GasTerra started with green gas contracts [78]. In practice, GasTerra purchased about 60 million cubic meters of green gas in 2016 [14], which is about 0.5% of the natural gas consumed in the Dutch residential sector [8]. In 2016, GasTerra stated that energy should be saved and renewable energy, with an emphasis on green gas, should be promoted [14]. Partnership Groningen (Maatschap Groningen) consists of NAM for 60% and EBN for 40%. This partnership was constructed in order to give the Dutch government the possibility to participate in the development of the Groningen field; the consequence was that the NAM became the operator for the concession and responsible for the risk. Furthermore, the NAM is obliged to sell all the produced natural gas from the Groningen field to GasTerra [79]. EBN, which is fully owned by the Dutch state is responsible for participating in, and facilitating the, exploration and production, trade, transport and storage of oil and gas. Gasunie is fully owned by the Dutch government (Ministry of Finance) and is responsible for the natural gas infrastructure. Gasunie is the owner of the high-pressure natural gas transmission grid, and facilitates the use of pipelines, LNG facilities located near Rotterdam and gas storage. Gasunie mentions an expected increase in green gas in the order of 2.2 bcm (70 PJ) in 2030 [80]. Gasunie Transport Services (GTS) is a subsidiary company of Gasunie and is the transmission system operator. They are responsible for management, functionality and development of the Dutch transmission grid [81]. The transmission system operator GTS expects a shifting role of gas to a more supporting role to facilitate decentralised energy sources [82]. Distribution system operators (DSOs) manage the low-pressure distribution grid, such as Alliander and Enexis. The DSOs are directly or indirectly owned by the national government, provinces, municipalities or other public bodies [83,84]. Enexis is in favour of green gas, since their revenue depends on the use of their grid based on capacity and not on volumes (personal communication with M. van Dam, Enexis on 10 March 2015). The risk for the DSO when it comes to loss of revenue is in disconnection of the residential sector from the existing distribution grid. This could lead to shorter depreciation periods for infrastructure then estimated, but they expect to distribute green gas instead of natural gas in the future [85]. Furthermore, there are energy supply companies that use the grid in order to supply energy to the end-users, in this case the residential sector.

The delineation on a sectoral basis emphasises the large involvement of the Dutch state in the natural gas regime. The contribution to the national income has, however, rapidly decreased from 15.4% in 2013 to 0.8% in 2016, due to decreased production and lower energy prices [86]. The latest projection for natural gas production from the Groningen field stems from 2013 [87]. The additional annual reviews (2014–2016) do not provide a long-term projection, due to ongoing research on induced earthquakes [88–90]. The insecure future production rates comprise a risk for the existing natural gas regime responsible for the supply of heat in the residential sector. High expectations for green gas are present for a longer time in the natural gas regime. The trade, infrastructure and transmission companies in the natural gas regime show awareness of a changing role for natural gas, since an increase in green gas is expected.

Given the expected quantities of green gas, large scale production is required. The expressed expectations in 2011 for green gas production in 2016 by GasTerra are a factor five lower than the actual produced quantities. In addition, in order to end up with 95 PJ green gas in 2030, current quantities purchased by GasTerra should increase fiftyfold. When produced with biomass gasification the required installed capacity is in the order of 5 GW, assuming an efficiency of 70% [91] and 7500 h of production per annum. A strategy concerning who is responsible, or how the future production of green gas should be addressed, is not presented by these central companies.

4. Discussion

This section is used for two purposes. First, to discuss the methodological choice for the delineation of the regime on a sectoral basis. Second, to deepen the presentation of the opportunities and barriers for the use of green gas from biomass gasification in the Dutch residential sector.

A delineation of the regime on a sectoral basis is sufficient to explain the inertia in the natural gas regime [30]. A regime shift, which is challenging to address when defining a regime on a sectoral basis [30] is not explored here. Hence, biomass gasification technology for green gas can be considered an incremental innovation and its future contribution is therefore not expected to result in a regime shift. This is in line with [92], who argues that regimes generate incremental innovation and therefore this paper looked at the possible contribution of the natural gas regime to the diffusion of biomass gasification technology. In addition, Kern [93] states that scientific literature addressing the diffusion of renewable energy technologies shows little evidence of "creative destruction"; renewable energy technologies are often complementary to the existing regime and do not overthrow incumbent regimes. In this research, energy policy was analysed as a landscape pressure on the natural gas regime. The landscape level comprises a variety of insecure and unpredictable pressures on the natural gas regime that may or may not provide incentives to adjust the heat supply system. However, political ideologies, societal values, beliefs, and concerns, which are part of the landscape level are implicitly taken into account by this approach, since the Dutch energy policy is an outcome of agreements with a large number of involved parties [29].

In the following, the observed opportunities and barriers are presented from a political, economic, societal and technological perspective, from both the demand and supply side.

The demand side is subject to technological lock-in, due to an absent infrastructure for alternative heat supply. This holds for both private owners and housing corporations with its tenants. The dependency on low-caloric natural gas from the Groningen field is, however, going to change. Given the technological lock-in; green gas, and thus change on the supply side, is an obvious solution when the dependency on natural gas is to be reduced. From a societal point of view, large scale green gas production with biomass gasification has a preference over other renewable alternatives in the Dutch residential sector, since the use of green gas requires no technological adjustments. Technological adjustments on the demand side are limited by social and economic barriers. In the case of tenants, the insecure effect of increased insulation on their monthly cost, combined with little interest in the energy performance of their residence, hampers change. In addition, housing corporations argue to have limited financial means for investments and find it difficult to convince tenants to accept increased rent prices in order to generate the financial means for investments. Private owners can be considered captive customers. Hence, a switch to another technology requires large investments in insulation and for example, a heat pump. Increasing the amount of insulation reduces the natural gas consumption, which can result in a subconscious lock-in effect where the residential sector does not feel the economic incentive to switch from natural gas to another heating technology. The current aim to have energy performance certificates B and C, for respectively the property of housing corporations and the private sector, in 2020 [57] could actually facilitate such a subconscious lock-in, by stimulating insulation measures.

These technological, social and economic factors emphasise the challenge to generate change on the demand side and guide the transition to a sustainable heat supply system. There is a large potential market for green gas from biomass gasification, given the aim to have a decarbonised building stock in 2050 [94] and the currently lagging technological change and lock-in of the Dutch residential sector. The development of the potential green gas market is, however, affected by the natural gas prices, which are expected to rise, the availability of biomass feedstock and the implementation of the biomass gasification technology to produce green gas on a large scale.

On the supply side the technological barrier is the upscaling of the biomass gasification technology. This upscaling is hampered, because of the high investment risk and unpredictable biomass prices. In addition, there is no clear policy on the expected role of biomass gasification for green gas. The key players in the natural gas regime have expressed clear expectations for green gas, but hesitate to take a risk by investing in gasification technology on a large scale. Therefore, this technological barrier can be regarded as the result of an economic and political barrier. The natural gas regime does not take responsibility, guidance on a political level is absent and subsequently, the gasification technology developers cannot get past the demonstration phase. A possible solution to overcome this status quo may be by public private partnerships or joint ventures. Fantozzi et al. [95] argue that such partnerships could reduce risks for private parties and can link technology to the market or the needs on the demand side. They illustrate this by analysing the economic feasibility of two cases in Greece and Italy, where the different risks related to bioenergy projects are allocated to public and private parties.

Such a joint venture strategy could be an option in The Netherlands to link large scale biomass gasification to the potential market for green gas in the Dutch residential sector. This requires, on a political level, not only a facilitating but also a guiding role on the implementation of bioenergy technologies. A guiding role with a clear vision from the national government is difficult to establish, since the Dutch energy policy is the result of agreements with many parties. However, Section 3.4 shows the large in involvement of the Dutch government in the natural gas regime, suggesting that such structures should also be possible in bioenergy projects.

Aside from the implementation of biomass gasification technology, the availability of biomass for energy remains an insecure factor. Shortages in domestic biomass supply of a factor two to nine are expected in 2030 [50], therefore import of biomass will be required. International supply chains to realise biomass imports can be feasible from an economic perspective [96]. The potential market for green gas from biomass gasification in the residential sector can correspond with multiple gigawatts installed capacity, emphasising the need for the development of such international biomass supply chains. Given the expected domestic shortages and the potentially large demand, such international supply chains need dedicated energy crop production systems.

5. Conclusions

This research emphasised the large challenges with which The Netherlands is confronted; the expected depletion of the Groningen field, induced earthquakes in the production area and the large residential dependence on this field. Therefore, the barriers and opportunities for biomass gasification to supply green gas to the Dutch residential sector were explored.

From a supply perspective, the TIS analysis showed that there are four limitations that hamper the diffusion of biomass gasification for green gas, which are systemic barriers mainly related to institutional challenges and financial and knowledge infrastructure. A substantial contribution of biomass gasification on the short term in The Netherlands is therefore not obvious. On the demand side, i.e., the residential sector, the rate of change related to energy performance is behind schedule. In the rental sector this is due to limited financial means, absence of a market model and policy agreements, which are not binding. Resistance of tenants to change, due to lack of interest in energy performance and/or insecurity about the effect on their monthly costs are therefore difficult to overcome. In the private sector, the absence of mandatory policy and lack of awareness hamper change in energy performance. In addition, for both the housing corporations and the private owners, the absence of infrastructure offers technical risks, and have a negative effect on implementation of renewable heat technology and energy performance. The absence of a market model results in lack of implementation on both the demand and supply side.

In conclusion there are optimistic expectations for green gas both on a governmental level and by key players in the natural gas regime. The lagging developments in the residential sector and the issues related to depletion and induced earthquakes emphasise the urgency to change. Theoretically, green gas is an ideal solution to address the challenges the Dutch residential sector currently faces, but in practice there is no strategy concerning the implementation of the required technology. In addition, the required technology to produce green gas is not ready for large scale implementation. Key players in the natural gas regime take no substantial responsibility, despite their potential ability to contribute to the systemic barriers related to knowledge and financial infrastructure. This emphasises that the shift towards a sustainable heat supply system in the residential sector requires policy aimed to overcome institutional barriers and a clear implementation plan that is mandatory for all parties on the demand and supply side. Substantial risk capital is absent, but required if the goal is to produce substantial quantities of green gas. The natural gas regime can foresee in this requirement, but incentives to do so are absent. In addition, the government can stimulate this with technology specific policy, substantial R&D subsidies and funding. When the green gas ambitions are to be reached in The Netherlands in 2030, substantial policy pressures should occur on the short term. Assuming that such pressures occur then the key players in the natural gas regime can contribute to the diffusion of biomass gasification technology.

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