Displacing process-related natural gas use in the service and industrial sector

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Summary

In order to reduce emissions from the building sector process-related natural gas use in the service and industrial sector must be displaced by renewable energy sources. While there has been much recent focus on the residential sector, less is known about natural gas use in commercial and industrial applications. More insight is needed into which end-uses of natural gas contribute substantially to process-related natural gas use in the service and industrial sectors and how this gas use can be displaced by renewables. The following research question was therefore formulated: "How can process-related natural gas consumption in commercial and industrial applications be reduced and displaced by renewables?". To determine which subsectors of the service and industrial sectors were likely to harbour significant process-related natural gas use a stock-level approach to benchmarking was performed using information on the relative energy intensity of different categories of buildings and the Vesta Mais model's procedure to forecast building energy demand for space heating. It was found that swimming pools and commercial laundries had significant natural gas use in the services sector and the food industry, manufacture of basic metals, paper and building materials sector among industrial subsectors. Interviews were conducted with companies from three sectors, restaurants, swimming pools and commercial laundries, to determine the end-uses associated with process-related natural usage. Industrial process heat was found to be the predominant source of natural gas use for swimming pools, commercial laundries, while restaurant's made use of a variety of gas fired cooking appliances in addition to process heat in the case of one restaurant that operated a brewing facility. A literature review was performed to identify possible renewable energy options to these natural gas end-uses. These include solar applications (flat-plate collectors, evacuated tube collectors, photovoltaic direct heating, hybrid PV/T), heat pumps, geothermal, biomass heaters, PCM thermal energy storage, waste heat recovery and Power-to-Gas options.

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1. Introduction

1.1 Context

In order to achieve the goals set forth in the 2015 Paris Climate Agreement and limit global average temperature increase to below 1.5 C, it is required that the Netherlands transition away fossil fuels as its primary source of energy and towards sustainable, low-carbon alternatives. In the national Climate Agreement the Dutch government has committed to a 49% reduction in greenhouse gas emission by 2030 and a 90% reduction by 2050 (Klimaat Accoord, 2019).

The building sector, composed of the services and residential sector, is responsible for 36% of final energy usage and 25% of greenhouse gas emission resulting from energy consumption (RVO, 2018), with economic activities in the industrial sector contributing another 30% to final energy usage (RVO, 2018) as shown in fig. 1. Reducing emissions from the built environment is therefore critical to achieving the goals under the Paris agreement.

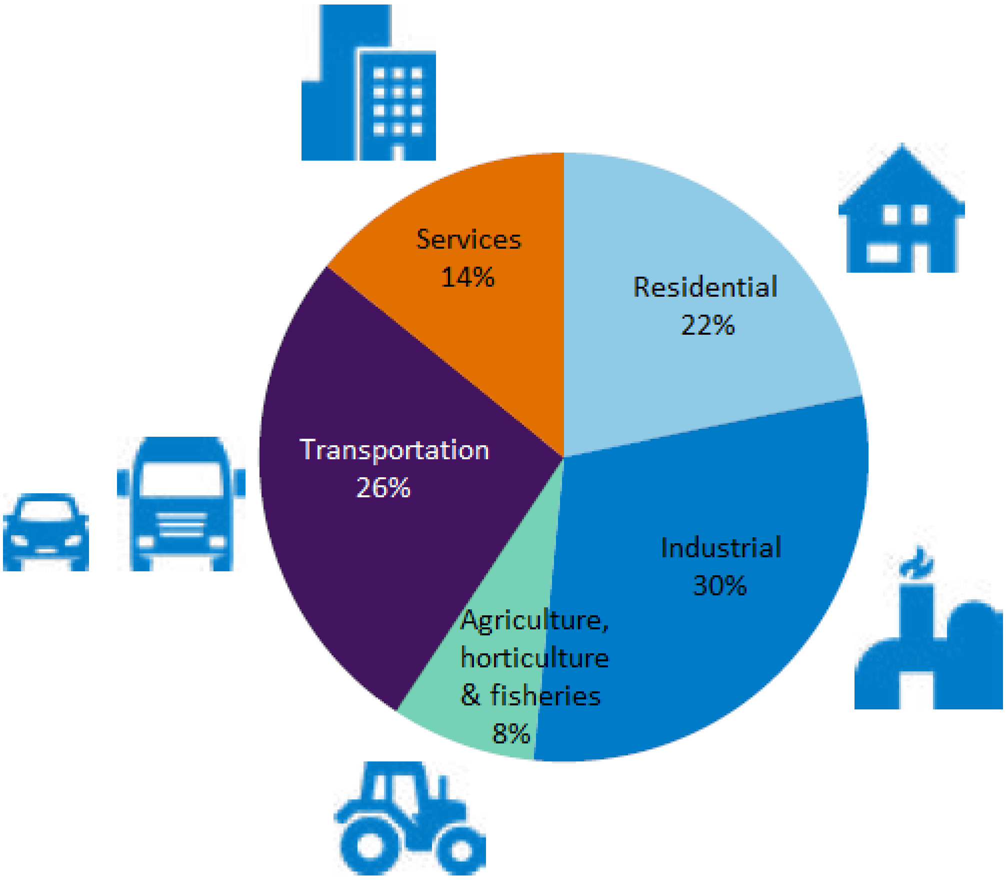

Figure 1: Distribution of final energy use in 2017 by sector, adapted from (RVO, 2018)

Natural gas constitutes a significant contribution to energy usage in the built environment, supplying 47% of final energy demand (CBS, 2020a). In order to reduce greenhouse gas emissions from the building sector, as well as to address concerns over energy security and gas-drilling induced earthquake damage in the province of Groningen, the Dutch government intends to disconnect all buildings from the natural gas grid by 2050 with the goal of reducing emissions from the built environment by 80% in 2050 (Energie Agenda, 2016).

As part of the ‘heat transition’, a total of 7 million homes and 1 million buildings will be disconnected from the gas grid by 2050 (van den Ende, 2017) and new sustainable alternatives to space heating processes will be progressively implemented. Local authorities will play a key role in implementing this transition. They will have to decide for each neighbourhood, block or even individual house what the best alternative heating source is. Consequently, Dutch municipalities have been tasked to develop a heat transition plan.

While much progress in identifying alternatives to natural gas has been made with regard to the residential sector, due to its larger energy consumption and the fact that the sector comprises the vast majority of buildings, many challenges remain with regard to the service and industrial sectors. While decoupling from natural gas in the residential sector is primarily concerned with identifying alternatives to space heating, a considerably greater variety of applications for the use of natural gas exists in the service and industrial sectors that also require an alternative. These applications include, among others: hot water production for use in swimming pools and industrial applications, hot air production for purposes of food-processing in the food production industry, cooking in the hotel and catering industry and use as a carbon feedstock in the petro-chemical industry for the production of plastics and other high-energy intensive products.

In order to enable implementation of the transition away from natural gas, greater insight is required into what applications exist in the service and industrial sectors that make use of natural gas apart from space heating, the amount they contribute to total gas consumption in the service and industrial sectors, and what alternatives exist for these processes.

In addition, realistic implementation of the policy of disconnection from the gas grid precludes disconnection on a building by building basis. Disconnection will occur on at least the sub-neighbourhood level over the period 2020-2050. In order to determine in which order neighbourhoods will be disconnected in a heat plan, insight is required into the potential costs and challenges to disconnect each neighbourhood. As the types of natural gas applications in a building are likely to be strongly affected by the economic activities performed in that building, spatial information on natural gas consumption by economic subsector can provide valuable insight into the types of natural gas applications present in each neighbourhood that can be used in the development of such an assessment. In addition, it has been indicated that spatially explicit energy consumption can be a valuable tool for the development and determining the cost-effectiveness of renewable energy policies (Howard et al., 2012). An understanding of the spatial distribution of natural gas consumption is therefore required to support implementation planning.

1.2 Problem definition

As mentioned earlier, prior research has thus far been focussed predominantly on the identification of suitable alternatives to space heating in the residential sector. This includes research on the influence of building efficiency improvements and forecasting of heat demand based on building and household characteristics.

A broad dichotomy is discernible in studies focussed on forecasting building energy demand, with studies tending to either focus on the level of one or several individual buildings, or on the population of buildings as a whole, the building stock (Geraldi & Ghisi, 2020). Distinct methodologies and research purposes are associated with each approach. Studies focussed on the building-level tend to be performed for the purpose of conducting energy audit studies, retrofit savings assessments, Zero Energy Building evaluations or exploring the performance gap between forecast and actual building energy performance. Studies focussed on the stock-level tend to be for the purpose of benchmarking, developing and enforcing regulations for the building stock, and the development of strategies to overcome climate change effects. The lack of high resolution energy consumption information (Jaber et al., 2003), the lack of consensus on a universal classification of building archetypes (Pérez-Lombard et al., 2008) and the heterogeneity within building archetypes (Booth et al., 2012) have been consistently mentioned as obstacles to improving accuracy in stock modelling. An attempt was made at identifying the proportion of energy used for different end-use applications by means of surveys in Howard et al. (2012) (New York City) and Segers et al. (2017) (Dutch industrial subsectors) and by means of physical modelling in Meijer & Verweij (2009). Energy disaggregation where available data is analysed using statistical or machine learning algorithms is also sometimes used to obtain end-use energy consumption (Mulder & Groot, 2011). Research on the Dutch non-residential building stock has thus far been primarily concerned with establishing and improving reference values for benchmarking purposes for building archetypes in the Dutch services sector. An overview of the literature consulted can be found in table 1.

Comparatively little research has been done in the Netherlands on both the amount of gas consumption in the service and industrial sectors for applications other than space heating, on identifying the economic subsectors that contribute most to this usage, and on the types of applications using natural gas. An overview of alternative options for processes in the service and industrial sectors that consume natural gas other than for space heating, their cost and emission reduction potential, has not yet been developed. Due to the greater diversity of building types, comparatively less research has been done with regard to heat demand forecasting and energy reduction potentials of building improvement measures in the service and industrial sectors. Further knowledge on the amount, spatial distribution and purposes of natural gas usage in the service and industrial sectors is critical to the development of a natural gas transition policy.

Table 1: Literature sources consulted

Data source	**Title / description**	**Scope** (sector; region)	**Purpose of research**
Bandeiras et al. (2020)	Towards net zero energy in industrial and commercial buildings in Portugal	5 Industrial & commercial buildings; Portugal	Zero Energy Building (ZEB) Evaluation
Geraldi & Ghisi (2020)	Building-level and stock-level in contrast: A literature review of the energy performance of buildings during the operational stage	Literature review on building energy performance studies	Synthesize approaches to and identify purposes of building energy performance studies
Beath (2012)	Industrial energy usage in Australia and the potential for implementation of solar thermal heat and power	Industrial sector; Australia	Strategies to overcome climate change effects
Booth et al. (2012)	Handling uncertainty in housing stock models	Residential sector; UK	Benchmarking
Howard et al. (2012)	Spatial distribution of urban building energy consumption by end-use	Residential & services sector; New York City	Benchmarking
Mulder & Groot (2011)	Energy Intensity across Sectors and Countries - Empirical Evidence 1980–200	Agriculture, industrial & Services sector; EU, USA, Japan	Regulations and directives for the building stock
Pérez-Lombard et al. (2008)	A review on buildings energy consumption information	Residential & services sector; UK, Spain, USA, EU	Strategies to overcome climate change effects
Jaber et al. (2003)	Energy analysis of Jordan's commercial sector	Services sector, Jordan	Retrofit Savings Assessment
Data sources on service, industrial and agricultural sector buildings in the Netherlands			
Sipma (2019b)	New benchmark methodology energy usage office buildings	Office buildings; Netherlands	Benchmarking
Sipma (2019a)	The actual energy consumption of labelled and non-labelled restaurants	Restaurant buildings; Netherlands	Benchmarking
Sipma & Niessink (2018)	Energy labels and the actual energy usage of schools and nursing homes	Schools & Nursing homes; Netherlands	Benchmarking
Niessink et al. (2017)	Exploration of the non-residential building sector	Agriculture, industrial & services sector; Netherlands	Regulations and directives for the building stock
Sipma et al. (2017)	Energy labels and the actual energy usage of office buildings	Office buildings; Netherlands	Benchmarking
Sipma & Rietkerk (2016)	Evolution of key figures for the non-residential building sector – An analysis of 24 building types and 12 industrial subsectors	12 Industrial subsectors & services sector; Netherlands	Retrofit Savings Assessment; Benchmarking
Sipma (2014)	Improvement of the reference benchmark for the non-residential building sector	Agriculture, industrial & services sector	Regulations and directives for the building stock
Meijer & Verweij (2009)	Energy usage per building function for SenterNovem	Services sector; Netherlands	Strategies to overcome climate change effects

1.3 Research aims

The aim of this research is threefold:

- To gain insight into which economic subsectors and which building types contribute to non-space heating related gas consumption, how much, and the way this consumption is spatially distributed.
- To identify which processes exist in the service and industrial sectors that are responsible for non-space heating related natural gas usage.
- To gain insight into what low-carbon alternatives exist for these processes.

Therefore, the following research question is formulated:

How can process-related natural gas consumption in commercial and industrial applications be reduced and displaced by renewables?

The research question will be investigated by performing a case study of the municipality of Utrecht. To support answering the research question the following sub-questions are formulated:

Q1: Which economic subsectors and which building types have the highest non-space heating related gas consumption per unit of floor area (i.e. gas intensity)? And total non-space heating related gas consumption?
Q2: Which geographic regions have the highest non-space heating related gas consumption per unit of floor area? And total non-space heating related gas consumption?
Q3: Which applications are responsible for this gas consumption within each economic subsector?
Q4: How can these applications be substituted by a low carbon alternative?

1.4 Scientific relevance

With their significant natural gas consumption, the service and industrial sectors constitute a substantial contribution to greenhouse gas emissions and natural gas consumption in the built environment. At the same time, the large variety of natural gas-reliant applications presents significant challenges with regard to transitioning away from natural gas. This research will contribute to the literature by proposing a methodology to quantify natural gas consumption and non-space heating related natural gas consumption in the service and industrial sectors, as well as to identify possible low-carbon alternatives to natural gas applications. Additionally, this research will contribute to knowledge development on natural gas end-uses in the service and industrial sectors and on the possible alternative options to those natural gas end-uses.

1.5 Societal relevance

The findings of this research may be used by the municipality of Utrecht in the development of a heat plan and thereby contribute to achieving national climate targets in the built environment. Additionally, the methodology proposed in this research may be used by other municipalities in support of the development of their heat plan. Finally, an equitable distribution of the burdens of reducing greenhouse gas emissions across the building sector and society at large is considered essential to maintaining public support for emission reduction measures taken within the context of the natural gas transition. Attainment of sustainability goals in the service and industrial sectors, after much recent effort has principally targeted the residential sector, therefore contributes to maintaining public support for emission reduction measures and thereby contributes to the achieving of climate goals in the built environment as a whole.

2. Theoretical framework

This section sets out the theoretical classifications and approach used in this research. First an overview of natural gas consumption in the service and industrial sectors in the Netherlands is presented. This is followed by an overview of the service and industrial sectors in Utrecht. Finally, several approaches to analysing building energy usage as well as the approach used in this research are discussed.

1.1 Overview of the service and industrial sectors in the Netherlands

The BAG (Basic Administration for Buildings) contains information on building attributes (such as year of construction, useable floor area and ownership) for most buildings in the Netherlands, including the purpose of buildings listed in its database. Buildings may be assigned multiple purposes (referred to as functions) of which there are eleven in total (see table 5). Building purposes by themselves were found not to provide a sufficiently detailed level of categorisation for many applications (Olthof, 2012).

In January 2016, a study (Sipma & Rietkerk, 2016) commissioned by the Dutch Ministry of Infrastructure and Environment and performed by ECN in conjunction with Statistics Netherlands, was concluded that determined the average gas and electricity consumption per square meter of floor area for 24 different building types in different size categories in the services sector in the Netherlands. This was accomplished through an examination of the entire Dutch building stock by connecting several large databases of building information (including BAG) with data on amounts of natural gas supplied to individual gas connections (known as EAN-connections) as made available by grid operators. Resulting of Dutch privacy legislation, an extract from the resulting database is not able to be made available for this research. The typology has since been slightly revised (CBS, 2019f) and is shown in table 2 below, along with the associated natural gas intensities.

In the study the attribution of a building type to an individual building, or a portion of a building that is known by its own unique address, principally arises from the combination of the building's building purpose according to BAG and the NACE code registered to the address indicating the type of economic activity. Although other factors such as the name may be considered. For example, a place of residence in a building whose purpose is listed in BAG as 'Retail function', in combination with 'NACE 4722 - Stores in meat and meat products, game and poultry' would be categorised as 'Retail with cooling (Supermarket)'.

Although the average energy intensity is similar for many building types in the services sector (principally those building types that are unlikely to have substantial natural gas consumption associated with other end-uses than space heating), the distribution of energy intensities for all building types in the service sector in the Netherlands were found to be associated with considerable variation. Illustrated in fig. 2 below, for the population of supermarkets with an average natural gas intensity of 20,3 m^3/m^2, the 10^{th} and 90^{th} percentile values are 5,2 m^3/m^2 and 48,7 m^3/m^2, respectively.

Table 2: Building types and associated natural gas intensities in the Dutch services sector. Data from 2012. (CBS, 2019f)

#	Building type	Natural gas intensity (m^3/m^2) 0 to 250 m^2	250 to 500 m^2	500 to 1000 m^2
1	Recreation: swimming pool	62.3	48.7	48.6
2	Food & Accommodation: restaurant	37.4	33.1	26.5
3	Food & Accommodation: snackbar	38.1	28.7	24.3
4	Food & Accommodation: hotel	22.8	22.6	21.9
5	Education: secondary	.	.	18.2
6	Healthcare: home	18.5	19.2	17.3
7	Office: public	20.9	18.3	16.2
8	Education: tertiary	.	.	15.4
9	Education: primary	16.6	18.7	15.1
10	Food & Accommodation: bar	22.4	17.4	14.4
11	Healthcare: communal	17.6	15.8	14.3
12	Recreation: outdoor sports	16.8	15.9	14.0
13	Retail with cooling	18.7	17.2	13.7
14	Other: religion	18.4	15.7	13.6
15	Recreation: indoor sports	17.4	16.7	13.2
16	Healthcare: practice	17.4	14.8	13.0
17	Office: other	17.3	15.0	12.8
18	Motor vehicle repair services	16.3	12.1	12.1
19	Other: hair and beauty salon	20.2	13.8	11.3
20	Recreation: club	17.9	14.4	11.2
21	Wholesale with cooling	18.1	12.3	9.0
22	Wholesale without cooling	16.6	11.9	8.9
23	Retail without cooling	17.0	11.9	8.8
24	Motor vehicle companies	17.7	11.0	8.8

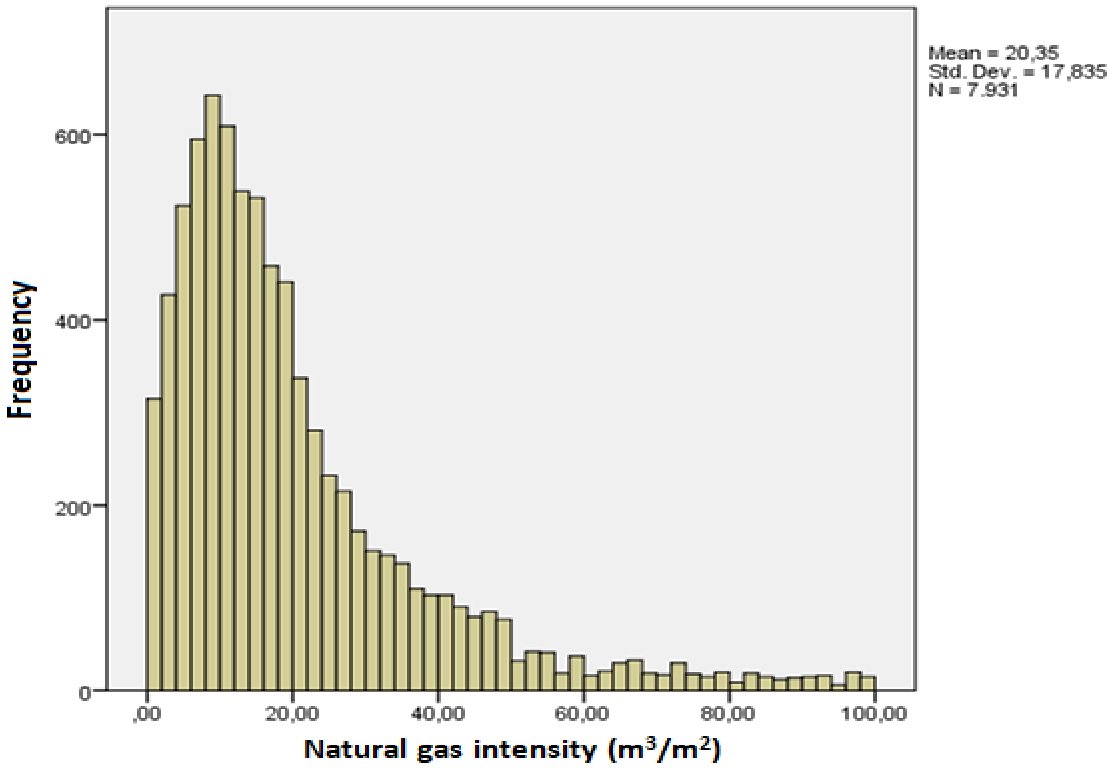

Figure 2: Histogram of the distribution of natural gas intensities among the population of supermarkets in the Netherlands. Data from 2012. (Sipma & Rietkerk, 2016)

With the exception of 12 industrial subsectors examined in (Sipma & Rietkerk, 2016), similar energy intensities for subsectors of the industrial sector are not known. The makeup of energy consumption from natural gas in subsectors of the industrial sector in the Netherlands is shown in table 3 below. As a measure of the scale of an individual subsector, the number of employees employed in each industrial subsector in the Netherlands is included in the right-most column. The services sector is included for completeness.

Table 3: Deliveries of natural gas and energy consumption from natural gas in industrial subsectors in the Netherlands. Data from 2016. (CBS, 2020a)

NACE code	Natural gas delivered		Final energy consumption	Net energy transformation	Non-energy use	Total energy consumption	Employees
	Mln m^3	(PJ)	PJ				×1000
A-U All economic activities	20.859	(660,2)					
A-U All economic activities (no energy sector)			360,5	138,9	96,2	595,6	
A Agriculture, forestry and fishing	3.981	(126,0)	50,1	75,7		125,9	97,5
01 Agriculture			50,1	75,7		125,9	94,7
02 Forestry and logging							1,5
03 Fishing and aquaculture							1,4
B Mining and quarrying	89	(2,8)					10,9
06 Extraction of crude petroleum & gas			X	X	X	X	3,7
08 Mining and quarrying (no oil & gas)			1,9			1,9	2,1
09 Mining support activities			X	X	X	X	5
091 Services for oil and gas extraction			X	X	X	X	.
099 Services for other mining			0			0	.
C Manufacturing	12.344	(390,7)					760,4
Industry (excl. energy (sector 19 & D))			177,2	59,3	96,2	332,7	.
10 Manufacture of food products			43,5	15		58,5	123,9
101 Slaughtering, processing of meat			2,5			2,5	15,9
102 Processing of fish			.			.	3,6
103 Processing of vegetables and fruit			5,8	1,5		7,4	10,2
104 Manufacture of edible oils and fats			2,4	4,7		7,1	2,5
105 Manufacture of dairy products			15,8	2,4		18,2	15,4
106 Grain milling and starch products			2,4	4,6		7,0	3,3
107 Manufacture of bakery products			.			.	40
108 Manufacture of other food			.			.	25,2
109 Manufacture of animal foods			2,9	-0,1		2,8	7,7
11 Manufacture of beverages			1,5	1,5		3	7,1
12 Manufacture of tobacco products			0,3			0,3	1,2
13 Manufacture of textiles			2,2			2,2	11,2
14 Manufacture of wearing apparel			0,1			0,1	2,2
15 Manufacture of leather and footwear			0,2			0,2	1,6
16 Manufacture of wood products			1,0			1,0	12,9
17 Manufacture of paper			5,5	8,9		14,4	16,9
18 Printing and reproduction			1,0			1,0	20,3
19 Manufacture of coke-oven and petroleum products			X	X	X	X	5,4
20 Manufacture of chemicals			69,1	31,3	96,2	196,6	44,6
201 Manufacture of basic chemicals			63,4	31,1	96,2	190,7	24,2
2011 Manufacture of industrial gases			6,3	10,4	19,5	36,1	.
2012 Manuf of dyes and pigments			0,9			0,9	.
2013 Manuf oth inorganic basic chem			7,1	1,4		8,4	2,4

NACE code	Natural gas delivered		Final energy consumption	Net energy transformation	Non-energy use	Total energy consumption	Employees
2014 Manuf organic basic chemicals			20,6	9,8	9,2	39,6	8,4
2015 Manufacture of fertilisers			23,3	3,8	67,5	94,7	1,8
202-206 Other chemical industry			5,7	0,2		5,9	0
21 Manufacture of pharmaceuticals			1,3	1,1		2,4	13
22 Manufacture rubber, plastic products			3,9			3,9	33,1
23 Manufacture of building materials			18,2	0,3		18,5	21,2
231 Manufacture of glass			7,2			7,2	.
233 Manuf of clay building materials			6,8	0,1		6,9	.
235 Manuf of cement, lime, plaster			.			.	.
236 Manuf of concrete etc, products			2,3	0,2		2,4	9,2
24 Manufacture of basic metals			12,4	1,1		13,6	19,5
25 Manufacture of metal products			5,4			5,4	87,5
26 Manufacture of electronic products			0,5			0,5	26,1
27 Manufacture of electric equipment			2,3			2,3	21,5
28 Manufacture of machinery n,e,c,			2,4			2,4	84,1
29 Manufacture of cars and trailers			1,3			1,3	21,3
30 Manufacture of other transport			0,7			0,7	17,3
31 Manufacture of furniture			1,0			1,0	17,6
32 Manufacture of other products			0,4			0,4	107,1
33 Repair and installation of machinery			0,8			0,8	44,1
D Energy generation & distribution		X	X	X	X	X	26,5
E Water supply and waste management	185	(5,9)	3,2	0,3		3,6	31,3
36 Water collection and distribution			0,1			0,1	5,3
37 Sewerage			0,2	0,5		0,7	3,8
38 Waste collection and treatment			2,9			2,9	20,1
39 Remediation, oth waste management			0	-0,1		-0,1	2,1
F Construction	130	(4,1)	4,1			4,1	317,3
G-S, U Services	4.130	(130,7)	125,6	3,5		129,1	

1.2 Overview of the service and industrial sectors in Utrecht

There are 6.284 buildings with a natural gas connection in Utrecht's service and industrial sectors, comprising a useable floor area of 6.264.983 m^2. Data on natural gas consumption in Utrecht is supplied to the Statistics Netherlands by grid operators and is available for main economic sectors collectively making up the agricultural, service and industrial sectors. However, information on natural gas consumption on the level of detailed economic subsectors is not available at the city or regional level. Data is available on energy consumption from natural gas in most subsectors of the industrial sector, excluding only those that deal with energy production, but only for the Netherlands as a whole. Further information on natural gas consumption in Utrecht, concerning the same data supplied by grid operators, is available at the geographic level for regions consisting of around 10-25 buildings known as a Postcode-6 or PC6-region, as well as well as for neighbourhoods known as Postcode-4 or PC4-regions. However, this does not allow attribution of natural gas consumption to economic activities.

A general overview of natural gas consumption in main economic sectors in Utrecht is shown below in table 4 and fig. 3. Energy generation and distribution (sector D) are the biggest consumers of natural gas, consuming approximately 490 million m^3 in 2017 or 85% of Utrecht's total natural gas consumption, and were omitted from the graph.

The useable floor area associated with a given economic sector can provide an indication of the measure of activity associated with that economic sector in Utrecht (Mulder & Groot, 2011) and hence provides an indication of whether the natural gas consumption was brought about by a high amount of activity of low energy intensity or, conversely, a low amount of activity of high energy intensity (Mulder & Groot, 2011). The useable floor area present in Utrecht per main economic sector is given on the next page in fig.4.

Table 4: Natural gas delivered to economic sectors in Utrecht in 2016 and associated natural gas intensities (CBS, 2019h)

	NACE code	Natural gas delivered (mln m^3)	In TJ	Gas intensity (m^3/m^2)
	A Agriculture, Forestry & Fishing	0,11	3,4	1,9
B-F Industry	B Mining & Quarrying	0,00	0,0	0,0
	C Manufacturing	20,90	661,4	66,3
	D Energy generation & distribution	*Approx. 490*	*15.508*	*28.779*
	E Waste & Water management	0,47	15,0	2,4
	F Construction	1,42	44,9	9,0
G-S, U Services	G Wholesale, Retail, Motor veh. repair	9,42	298,2	9,3
	H Transportation & Storage	1,83	57,8	8,0
	I Hotel & Food Service activities	5,40	170,8	15,6
	J Information & Communication	0,85	27,0	2,8
	K Financial & Insurance services	1,36	43,0	19,3
	L Renting, Buying & Selling Real Estate	2,11	66,9	49,5
	M Specialised business support services	2,29	72,6	5,2
	N Rental & Administrative services	1,59	50,4	6,9
	O Public Administration	2,37	75,0	26,8
	P Education	22,61	715,5	30,2
	Q Healthcare & Social work activities	19,47	616,4	23,7
	R Culture, Sports & Recreation	2,56	81,0	9,2
	S Other service activities	4,08	129,2	26,9

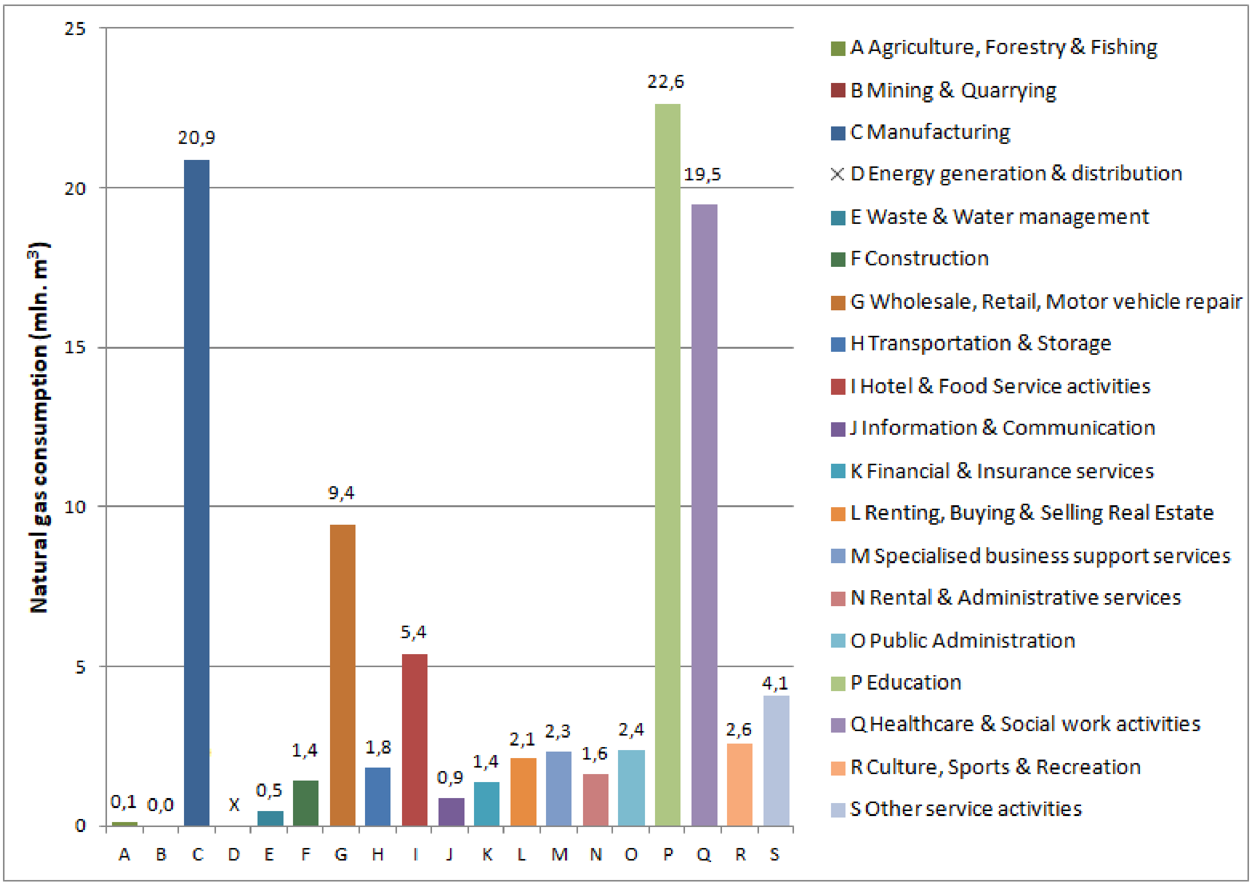

Figure 3: Natural gas consumption by economic sector in Utrecht in 2016 (CBS, 2019h)

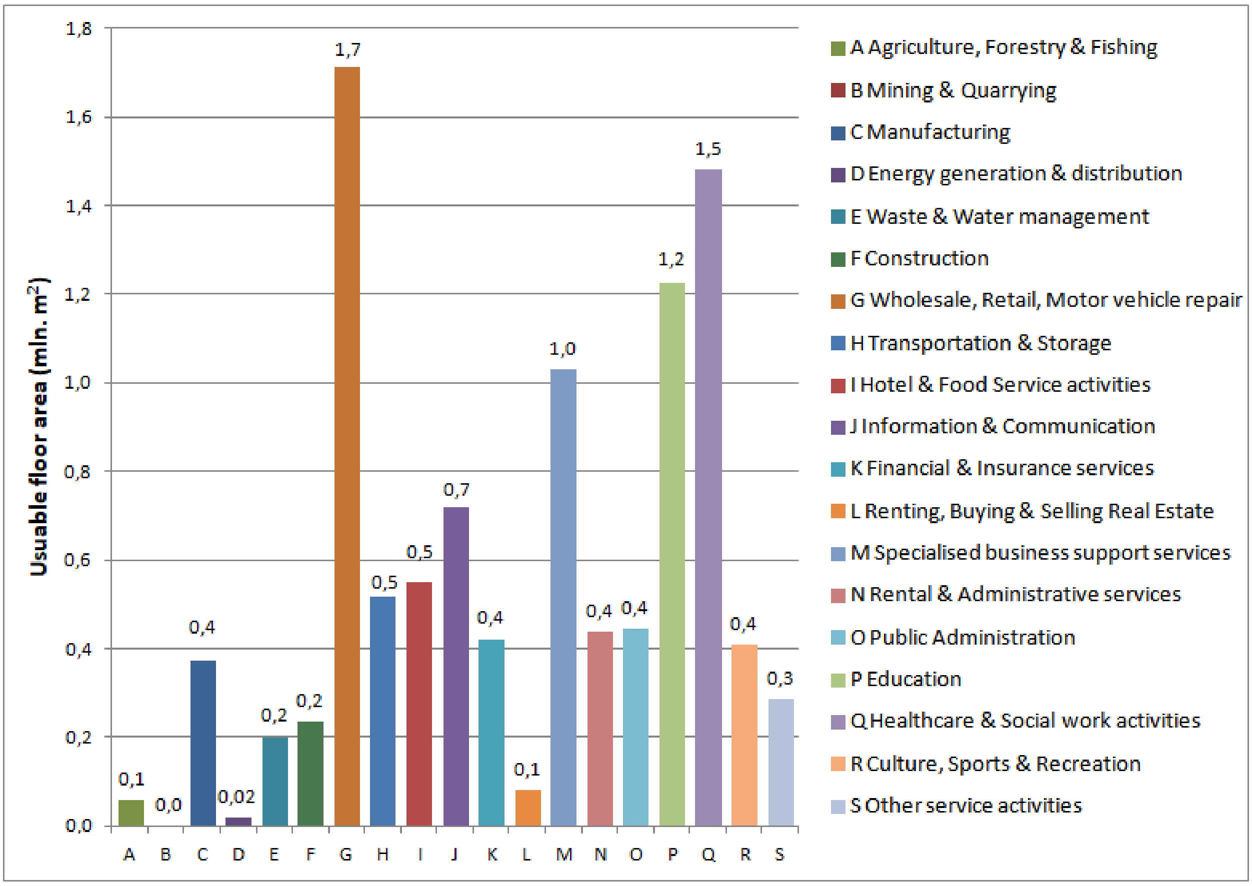

Figure 4: Useable Floor area per main economic sector in Utrecht in 2019 (PAR, 2019)

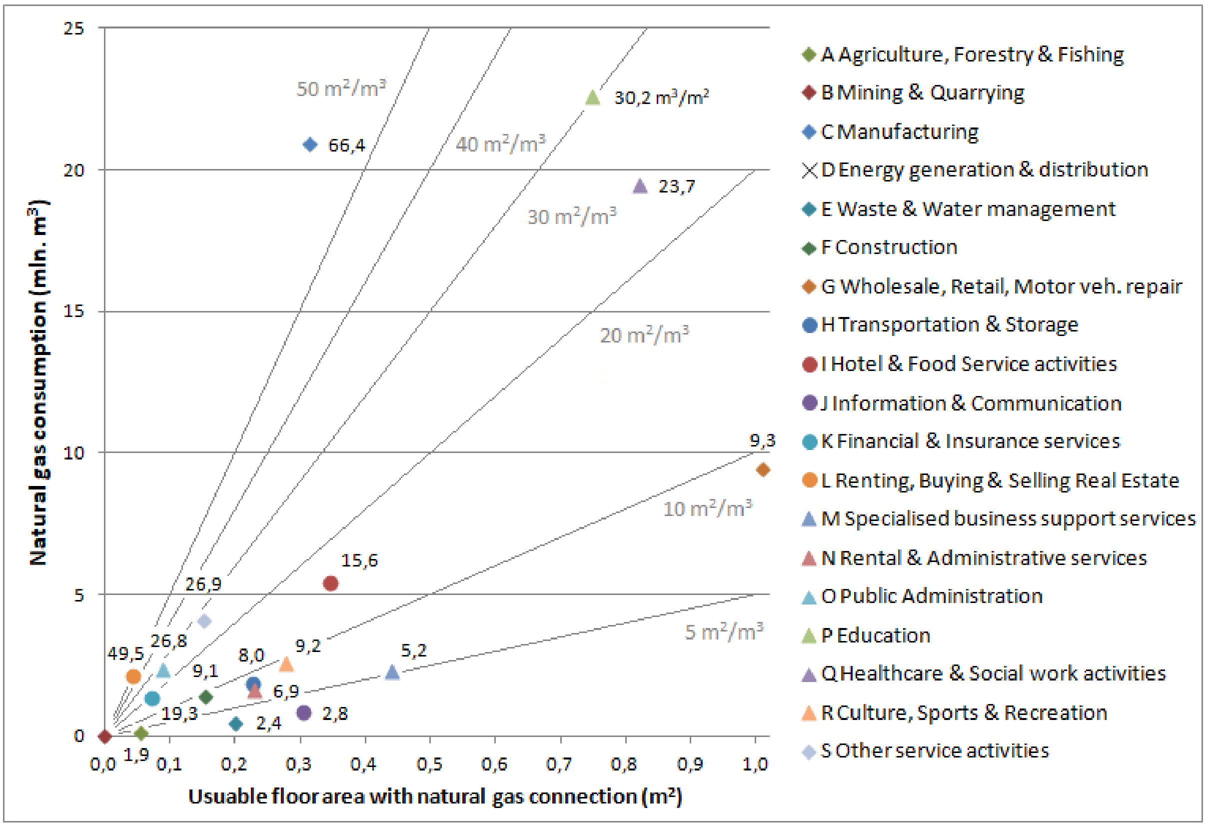

Figure 5: Natural gas consumption vs. floor area per economic sector, for buildings with a natural gas connection. Values shown in the graph area represent a sector's natural gas intensity (m^3/m^2).

By excluding buildings without natural gas connection and plotting natural gas consumption versus floor area (see fig. 5), it can be readily observed that sectors with a high level of natural gas consumption are not necessarily associated with a high level of energy intensity associated with the activities performed. The manufacturing sector, perhaps unsurprisingly, is associated with by far the highest energy intensity of the main economic sectors, even though it is one of three sectors associated with significant natural gas consumption. This is explained by the sector's substantially lower associated amount of floor area than the other two sectors.

The useable floor area for buildings associated with economic activity in the municipality of Utrecht delineated by primary building purpose is shown in table 5 below. In order to determine whether buildings in Utrecht are associated with economic activity and what type of economic activity, use was made of the PAR survey (Provincial Employment position Registry) and data known through the enforcement of environmental regulations. Buildings were considered to be part of Utrecht's service and industrial sector either if they were subject to the enforcement of environmental regulations or if the BAG indicated the building had a utility building purpose and the PAR survey indicated that at least one person was employed at that location.

Table 5: Floor area by building purpose among buildings associated with economic activity in Utrecht

#	Primary building purpose (BAG)	Total floor area (m^2)	with natural gas connection
1	Conference function	1.213.165	73,3%
2	Education function	1.072.141	69,1%
3	Healthcare function	504.068	95,2%
4	Industry function	4.380.212	74,3%
5	Office function	421.602	80,7%
6	Other functions	12.469	93,9%
7	Overnight Stay function	38.284	90,7%
8	Prison function	16.437	100,0%
9	Retail function	120.300	67,9%
10	Residential function	501.809	75,4%
11	Sports function	33.897	81,8%
12	Unknown primary purpose	516.917	4,8%
	Total	**8.831.301**	**70,94%**

1.3 Theoretical approaches to assessing building energy performance

A wide variety of approaches and methodologies exist for assessing the energy performance of buildings based on the subject of study and the available data (Geraldi & Ghisi, 2020). A review of the literature was performed by Geraldi & Ghisi (2020) and two main approaches were identified in studies on the energy performance of buildings, one focussed on the building-level and one focussed on the stock-level (Geraldi & Ghisi, 2020).

The building-level approach is often employed in energy audit studies, zero energy building evaluations, assessment of energy saving measures and assessments of the performance gap between modelling estimates and actual energy use of a building (Geraldi & Ghisi, 2020). Building-level approaches focus on measuring the energy performance of one or a few buildings at the level of an individual building through on-site measurements at regular time intervals (Geraldi & Ghisi, 2020).

The stock-level approach is inspired by the field of epidemiology and considers a group of buildings as a population (Geraldi & Ghisi, 2020). It considers information such as size, type of use, construction year etc. and considers the variations in those attributes among buildings within the population (Geraldi & Ghisi, 2020). Stock-level approaches are typically employed in studies focussed on building regulations and directives, benchmarking and strategies to overcome climate change effects (Geraldi & Ghisi, 2020).

Within stock-level approaches two distinct definitions of the building stock can be distinguished, the type-based building stock and the geographic or geo-based building stock (Geraldi & Ghisi, 2020). The geo-based building stock considers all buildings within a geographic delimitation, while the type-based building stock defines a group comprised of buildings that share a purpose (Geraldi & Ghisi, 2020).

In non-residential buildings, the type of building use and the activities that take place within a building have a huge impact on the type, amount and end-use of energy needed (Pérez-Lombard et al., 2008) and the types of applications it is used for. However, there is no consensus on a universal classification of building types (Pérez-Lombard et al., 2008) and few sources offer data by typology, which makes for considerable difficulty in conducting a stock-level analysis.

This research will employ a stock-level approach with a type-based building stock to determine natural gas consumption and non-space heating related natural gas usage for building types and economic subsectors. To determine non-space heating related natural gas usage on a geographic basis a geo-based building stock will be used.

3. Methods

1.1 Introduction

Given the vast number of economic subsectors and building types present in the service and industrial sectors, a thorough examination of each for non-space heating related gas applications was precluded by the limited time available to this research. Therefore, it was desired to gain insight into which economic subsectors and which building types represent a substantial contribution to overall non-space heating related natural gas usage in Utrecht, so that these may be further investigated for the processes they harbour that bring about this gas usage.

It is likely that the greater the level of disaggregation and the greater the number of categories one employs for categorising buildings, the less will be the variation in natural gas end-uses within a given subsector or building type (Sipma, 2019b). It was thus desired to obtain data at a level sufficiently disaggregated so that the variation in natural gas end-uses within an economic sector or building type is low. However, the search for data on natural gas consumption at a detailed level was hampered by restrictions posed by privacy legislation and private concerns over sharing business sensitive information. Further complicating efforts is the fact that the process of relating individual buildings to natural gas connections currently being performed by the Statistics Netherlands, who posses special status according to privacy legislation, has not yet been completed for many sectors.

Therefore, a sequential approach was taken where use was made of data on natural gas consumption for specific buildings as available through the enforcement of environmental regulations whenever possible. Next, data on natural gas deliveries in Utrecht as made available by grid operators were used. As this data is subject to privacy legislation it is aggregated in various forms. In order to further disaggregate the data, estimations were made using the data that is available and key figures from the literature.

To answer the main research question, four sub-questions were formulated. The first sub-question was designed to gain insight into the amount of gas usage related to the performance of economic activities as opposed to space heating in Utrecht, as well as which economic subsectors and which building types are the largest contributors hereto. This gas usage is hereafter referred to as the *unexplained gas usage*. The second sub-question was designed to gain insight into the geographic distribution of the unexplained gas usage over neighbourhoods. The third sub-question was intended to gain insight into which applications for natural gas are responsible for this unexplained gas usage and what the relative contribution of these processes is to the overall amount of unexplained gas usage. Making use of these insights, the fourth sub-question was intended to establish the necessary boundary conditions for the functional performance of these processes and identify suggestions for alternatives. Consequently, these sub-questions allowed the main research question to be answered.

1.2 RQ 1: Unexplained gas usage among economic subsectors and building types

Data on natural gas delivered in Utrecht is made publicly available per main economic sector and per geographic region at the neighbourhood (PC4-region) and sub-neighbourhood level (PC6-region). In addition, data on natural gas consumption is known through the enforcement of environmental regulations (Wet Milieubeheer). An overview of data sources used in this research is shown in table 6 below.

Tabel 6: Overview of data sources used in this research

Data source	Data description	Use in this research	Data update frequency	Limitations
BAG database	Building characteristics linked to building address	Floor area, building purpose, building age and other building characteristics per address	Ad hoc	Contains no information on vacancies; Some building purposes missing/unknown
PAR survey	Employment and type of economic activity linked to building address	No. employees and 5-digit NACE code per address	Annual	Only available for Utrecht municipality
RVO (source)	Energy label linked to building address	Key figures in Vesta Mais model based on energy label; Selection of appropriate figures (FD_x) for known proc.	Ad hoc	~45% complete, some labels outdated
CBS (2019h) (source)	Natural gas consumption per main economic sector	Natural gas consumption at 1-digit NACE level	Annual	Utrecht region, data aggregated to the 1-digit NACE level
CBS (2019d) (source)	Residential & non-residential natural gas consumption (listed separately) per PC6 region	Service & industrial sector natural gas consumption per PC6 region equals non-residential gas consumption per PC6 region	Annual	Data omitted if < 5 connections per PC6 region or if a large user is present. % of records missing: • Residential: 17.5% • Non-resid.: 93.8% • Both missing: 15%
CBS (2019c) (source)	Non-residential electricity and natural gas consumption per PC4 region	Calculate unexplained natural gas consumption for PC4 regions	Annual	Data omitted on natural gas consumption for 3 out of 10 neighbourhoods in Utrecht
Municipality of Utrecht (restricted access)	Address-level natural gas consumption available through the enforcement of environmental regulations	Provides known natural gas consumption for some buildings including most large consumers	Depends on category of environmental relevance: Cat. 4,5: Annual Cat. 3: Biannual Cat. 1,2: After complaint only	Incomplete & out-of-date: Contains ~20% of records: ~4% on 2019, ~4% on 2018, ~4% on 2017, etc.
CBS (2019f) (source)	Natural gas intensities for building types in the services sector differentiated by	Primary building typology; natural gas intensities for 24 service sector building	One time research	Not all building types covered by typology; No differentiation by

Data source	Data description	Use in this research	Data update frequency	Limitations
	building size (revised typology)	types in different size categories		building age; Data from 2012
CBS (2019e) (source)	Natural gas intensities for building types in the services sector differentiated by building age & size (revised typology)	Service sector natural gas intensities for most building types in different size categories within age categories	One time research	6 of 24 revised typology building types omitted; Data from 2012
Sipma & Rietkerk (2016) (source)	Natural gas intensities for building types in the services sector (original typology)	Natural gas intensities for building types not covered by revised typology	One time research	Most industrial subsectors omitted; Data from 2012
CBS (2020a) (source)	Breakdown of energy consumption from natural gas in industrial subsectors in the Netherlands	Natural gas consumption in industrial subsectors at 2-4 digit NACE level	Annual	No energy sector; 5 of 50 Manufacturing (C) subsectors omitted
CBS (2020b) (source)	Employment, revenue and turnover in economic subsectors	No. employees in industrial subsectors at 2-4 digit NACE level	Annual	Sectors A, K, O, P, Q and R omitted
CBS (2019a) (source)	Number of jobs in December in economic subsectors	No. employees in subsectors omitted from CBS (2020b)	Annual	Data only available at 2-digit NACE level
CBS (2019b) (source)	Number of jobs in December in economic subsectors per municipality	Validation of PAR data on employment in Utrecht	Annual	Data only available at 1-digit NACE level
CBS (2019g) (source)	Amount of floor area and number of buildings per building type in the Netherland	Not used; Allows for determination of gas consumption per building type in the Netherlands	Unknown; Custom request (i.e. *maatwerkverzoek)*	Only includes services, excludes floor area for industrial subsectors

1.2.1 Data requirements and general approach

Service and industrial sector natural gas consumption in Utrecht at the level of main economic sectors, SI_{msec}, is related to natural gas consumption at the level of detailed economic subsectors or building types, $SI_{sec,msec}$, through:

$$[1] \quad SI_{msec} = \sum_{sec} (SI_{sec,msec})$$

If the total natural gas consumption at the level of detailed economic subsectors or building types in Utrecht, SI_{sec}, can be determined, the unexplained natural gas consumption, U_{sec}, can be obtained by subtracting an estimate of the natural gas consumption for space-heating and other known processes, i.e. the explained gas usage, E_{sec}:

$$[2] \quad U_{sec} = SI_{sec} - E_{sec}$$

The unexplained natural gas intensity, I^{u}_{sec}, can subsequently be obtained by dividing the unexplained natural gas consumption by its associated floor area: $I^{u}_{sec} = U_{sec}/A_{sec}$. In order to estimate the explained gas usage, E_{sec}, use was made of the procedure employed in the **Vesta Mais** model (Schepers & Leguijt, 2017; CE Delft, 2019) (see chapter 1.2.3).

In order to determine the unexplained natural gas intensity for detailed economic subsectors or building types, I^u_{sec}, it is thus required to determine the total natural gas consumption, SI_{sec}, the floor area, A_{sec}, and the explained natural gas consumption, E_{sec}, associated with the buildings i belonging to a given detailed economic subsector or building type sec. Furthermore, in order to determine quantities per economic subsector or building type a link must be established between buildings and their physical properties (e.g. age, floor area, building function) and types of economic activities performed within the building.

However, SI_{sec} cannot be determined without relying on some method of approximation. Data on natural gas deliveries per detailed economic subsector are not available at the municipal level. In order to determine the amount of natural gas consumption and the natural gas intensity for more detailed categories of economic activities, therefore, the available data on natural gas consumption per main economic sector had to be disaggregated to a more detailed level. As indicated in [11] and [12] below, this requires making some assumption, based on key figures from the literature and other data, with regard to the value of the unknown parameter $S_{sec,msec}$ that relates the available data on natural gas consumption at an aggregated level to natural gas consumption at the level of more detailed economic subsectors or building types.

There is, however, data available on the energy intensity per unit floor area for various building types in the services sector in the Netherlands and on the energy consumption and the size of economic subsectors of the industrial sector in the Netherlands, as well as data on the floor area of, and the economic activity performed in buildings in Utrecht. Use was therefore made of the available information on the relative energy intensity of various building types and economic subsectors in the Netherlands and the extent to which those building types and economic subsectors are present in Utrecht, to estimate the value of $S_{sec,msec}$ and allocate amounts of natural gas delivered to main economic sectors in Utrecht to the economic subsectors and building types that the main economic sectors consist of. An overview of the available and missing data is shown in table 7 below.

Table 7: Overview of available data and missing data requiring some method of approximation

Available data	Relevant parameter(s)	Source
Gas consumption per main economic sector (Utrecht)	SI_{msec}	CBS (2019h)
Gas consumption per PC4 region (Utrecht)	SI_{reg}	CBS (2019c)
Building properties per address	A_{sec}, E_{sec}	BAG
Detailed economic subsector per address	A_{sec}, E_{sec}	PAR
Natural gas intensity per building type and for some industrial subsectors	$I_{sec,msec}$	CBS (2019e);CBS (2019f); Sipma & Rietkerk (2016)
Gas consumption per industrial subsector (Netherlands)	$I_{sec,msec}$	CBS (2020a)
No. employees per industrial subsector (Netherlands)	$n_{sec,msec}$	CBS (2019a)

Missing data	Relevant parameter(s)	Approximation method
Gas consumption per detailed economic subsector (Utrecht)	$SI_{sec,msec}$	-
The share or fraction that gas consumption of a detailed economic subsector in Utrecht constitutes with respect to the main economic sector or PC4 region it is part of.	$S_{sec,msec}$ $S_{sec,reg}$	Apportionment based on the ratio of natural gas intensities and the amount of floor area/employees present in Utrecht

1.2.2 Building classification employed in this research

A type-based stock-level analysis was used, where all service and industrial buildings in Utrecht were assigned an economic subsector or building type based on the type of economic activity associated with the building. An indication of the economic activities performed in a building or place of residence was obtained based on a building's address through the Chamber of Commerce and sources such as the PAR survey. These record the economic subsector of the building's current occupant, to the extent that the data is up-to-date, by means of a NACE code. Buildings in the services sector were assigned one of 24 building types according to the typology developed by Statistics Netherlands and TNO as shown in table 2. This was done (see table 14 in appendix A) based on the NACE code linked to the building's address according to the methodology described in CBS (2016). For building types not covered by the revised typology, the original typology from Sipma & Rietkerk (2016) was used (see table 15 in appendix B), where a building type was assigned based on the NACE code linked to the building's address and the building's purpose as indicated in the BAG. Buildings in the industrial sector were categorised based on their associated NACE code as indicated in table 3.

1.2.3 Calculation of gas demand for known processes in the Vesta Mais model

In the **Vesta Mais** model the functional energy demand (from electricity and natural gas) for several known processes is determined based on key figures and building properties as they are known through BAG (CE Delft, 2019). These processes include, among others: space heating, space cooling, warm tap water production and mechanical ventilation. Excluding processes associated only with electricity consumption, the functional energy demand from natural gas for space heating and the production of warm tap water for buildings in the service and industrial sectors is calculated on based on a building's floor area, its building purpose and its energy label, and the building's year of construction. To convert the functional energy demand from natural gas to final natural gas demand ('demand at the meter'), the model assumes (Schepers & Leguijt, 2017) that space heating occurs by means of a high-energy condensing boiler at an efficiency of 104% and production of warm tap water occurs at a boiler efficiency of 72%. In addition, the model takes account of pipe heat losses. The resulting formula for the final natural gas demand for known processes, E_{sec}, is given by:

$$[3] \quad E_{sec} = \sum_i \left(\frac{FD^{SH}_{bp,lab} * A_{i,bp,lab,sec} * PHL^{SH}}{\eta^{SH}} + \frac{FD^{WW}_{bp,lab} * A_{i,bp,lab,sec} * PHL^{WW}}{\eta^{WW}} \right)$$

Where:

$FD^{SH}_{bp,lab}$	= Functional natural gas demand per m^2 floor area for space heating (SH) as a function of building purpose (bp) and energy label (lab)
$FD^{WW}_{bp,lab}$	= Functional natural gas demand per m^2 floor area for warm tap water (WW) as a function of building purpose (bp) and energy label (lab)
$A_{i,bp,lab,sec}$	= Useable floor area for a given building (i) with building purpose (bp) and energy label (lab) associated with economic subsector or building type sec
PHL^{SH}	= 1,05; Pipe heat losses space heating
PHL^{WW}	= 1,10; Pipe heat losses warm tap water
η^{SH}	= 1,04; Conversion efficiency space heating
η^{WW}	= 0,72; Conversion efficiency warm tap water

1.2.4 Structure of available data and relationships between variables

Natural gas consumption at the level of detailed economic subsectors or building types, $SI_{sec,msec}$, is assumed to be some share, $S_{sec,msec}$, of the natural gas consumption of the main economic sector that the economic subsector or building type is part of:

$$[4] \quad SI_{sec,msec} = S_{sec,msec} * SI_{msec}$$

Linking data from the BAG and PAR, using the address i as a key variable, allowed for the determination of the amount of floor area, A_{sec}, associated with each economic subsector or building type in Utrecht, allowing for the explained gas usage, E_{sec}, to be determined as indicated in [3]. For a given economic subsector or building type, the unexplained natural gas usage, $U_{sec,msec}$, is given by the subsector's natural gas intensity, $I_{sec,msec}$, times its floor area, $A_{sec,msec}$, less the explained natural gas usage, $E_{sec,msec}$, of the buildings i associated with that economic subsector or building type:

$$[5] \quad U_{sec,msec} = I_{sec,msec} * A_{sec,msec} - E_{sec,msec} = SI_{sec,msec} - \sum_i (E_{i,sec,msec})$$

Given that privacy legislation prohibits linking data on natural gas deliveries directly to building addresses, the amount of natural gas usage per economic subsector or building type, $SI_{sec,msec}$, could not be determined directly. However, data is available on natural gas deliveries in Utrecht per main economic sector at the 1-digit NACE level (see table 4), SI_{msec}. This allowed for the determination of the unexplained gas usage, U_{msec}, at the 1-digit NACE level, by first considering the natural gas demand for space heating, E_{msec}, of the buildings i associated with a given main economic sector:

$$[6] \quad U_{msec} = SI_{msec} - \sum_i (E_{i,msec}) = I^{u}_{msec} * A_{msec}$$

The unexplained natural gas intensity at the 1-digit NACE level can subsequently be obtained by dividing by the floor area:

$$[7] \quad I^u_{msec} = \frac{U_{msec}}{A_{msec}} = \frac{SI_{msec} - \sum_i \left(E_{i,msec}\right)}{A_{msec}}$$

The unexplained gas usage at the 1-digit NACE level, U_{msec}, is related to the unexplained gas usage, $U_{sec,msec}$, and the unexplained natural gas intensity, $I^u_{sec,msec}$, at the level of more detailed economic subsectors and building types through:

$$[8] \quad U_{msec} = \sum_{sec} \left(I^u_{sec,msec} * A_{sec,msec}\right) = \sum_{sec} \left(U_{sec,msec}\right)$$

However, in order to further disaggregate the available data on natural gas deliveries per main economic sector and determine the unexplained gas usage, $U_{sec,msec}$, at the 2-, 3- or 4-digit NACE level through [5], it was required to know the natural gas intensity at the 2-, 3- or 4-digit NACE level in Utrecht, $I_{sec,msec}$. Data on $I_{sec,msec}$ is only available for building types in the services sector and only for the Netherlands as a whole. Data on $I_{sec,msec}$ is not available for industrial subsectors. Alternatively, $U_{sec,msec}$ may be determined by substituting [4] in [5], but in such case it is required to know the share $S_{sec,msec}$ that natural gas consumption of a given detailed economic subsector, $SI_{sec,msec}$, represents with respect to the total natural gas consumption, SI_{msec}, of the main economic sector it is part of:

$$[9] \quad U_{sec,msec} = S_{sec,msec} * SI_{msec} - \sum_i \left(E_{i,sec,,msec}\right)$$

The unexplained natural gas intensity is subsequently obtained by dividing by the floor area:

$$[10] \quad I^u_{sec,msec} = \frac{U_{sec,msec}}{A_{sec,msec}} = \frac{S_{sec,msec} * SI_{msec} - \sum_i \left(E_{i,sec,msec}\right)}{A_{sec,msec}}$$

Given that the share $S_{sec,msec}$ is not known, the natural gas consumption at the 1-digit NACE level could not be related to the unexplained gas intensity at the 2-, 3- or 4-digit NACE level based on data on natural gas deliveries per main economic sector in Utrecht, without making some assumption with regard to the share $S_{sec,msec}$.

In order to attribute amounts of natural gas delivered to Utrecht to economic subsectors and building types, use was therefore made of available data on the relative energy intensity of different economic subsectors and building types in the Netherlands as a whole.

Given the two main ways data on natural gas deliveries to Utrecht is made available, geographically and per economic sector, two approaches presented themselves: allocation of amounts of natural gas delivered per geographic region (see chapter 1.3.2) and allocation of amounts of natural gas delivered per main economic sector for Utrecht as a whole.

1.2.5 Allocation of amounts of natural gas delivered to main economic sectors

Allocation of amounts of natural gas delivered to main economic sectors in Utrecht occurred based on the ratio of energy intensities for building types and economic subsectors as they were known through prior research or were able to be determined based on publicly available information. Buildings for which the natural gas consumption was known through the enforcement of environmental regulations did not need to have amounts of natural gas allocated to them and had their associated amount of natural gas subtracted from the total for their respective main economic sector. In addition, the enforcement of environmental regulations yielded information on the energy intensity for several types of economic activities. These were used whenever possible and are shown in table 9, otherwise publicly available information was used. The energy intensities of building types in the services sector were obtained through an assessment of the Dutch national building stock of 2012 and are indicated in table 2. Wherever such data was available from CBS (2019e), use was made of values for energy intensities taking account of both the size and age category of a building with a given building type. Otherwise, values from CBS (2019f) taking account only of the building's size category were used. For building types not covered by the revised typology described in CBS (2016), values from Sipma & Rietkerk (2016) taking account of the building's size category were used. For economic subsectors in the industrial sector the natural gas intensity, $I_{sec,msec}$, was determined based on a subsector's total energy consumption from natural gas in the Netherlands as indicated in table 3, divided by its number of employees. Using this approach to substitute for the unknown parameter $S_{sec,msec}$ in [4], the amount of natural gas attributed to a given economic subsector in the industrial sector in Utrecht, $SI_{sec,msec}$, is given by:

$$[11] \quad SI_{sec,msec} = \frac{n_{sec,msec} * I_{sec,msec}}{\sum_{sec}\left(n_{sec,msec} * I_{sec,msec}\right)} * SI_{msec}$$

Where $n_{sec,msec}$ is the number of employees of a given economic subsector in Utrecht, SI_{msec} is the amount of natural gas delivered per main economic sector indicated in table 3, and $n_{sec,msec} * I_{sec,msec} / \sum_{sec}\left(n_{sec,msec} * I_{sec,msec}\right)$ is the allocation factor, $S_{sec,msec}$.

Likewise, the amount of natural gas attributed to a given building type in the services sector in Utrecht is given by:

$$[12] \quad SI_{sec,msec} = \frac{I_{sec,msec} * A_{sec,msec}}{\sum_{sec}\left(I_{sec,msec} * A_{sec,msec}\right)} * SI_{msec}$$

Where $A_{sec,msec}$ is the amount of floor area associated with the building type in Utrecht, SI_{msec} is the sum of natural gas delivered to sectors G-S, and $I_{sec,msec}$ is the building type's natural gas intensity indicated in table 2. The unexplained gas usage, $U_{sec,msec}$, and the unexplained gas intensity, $I^{u}_{sec,msec}$, were then obtained by considering the demand for space heating, $E_{sec,msec}$, of the buildings associated with a given economic subsector or building type in Utrecht as indicated in [10].

1.3 RQ 2: Unexplained gas usage among geographic regions

1.3.1 General approach

The results obtained in chapter 1.2.5 were used to determine the unexplained natural gas consumption and the unexplained natural gas intensity for geographic regions in Utrecht. The total natural gas consumption associated with a given economic subsector or building type within a given geographic region, $SI_{sec,reg}$, less the explained natural gas consumption associated with that economic subsector or building type in that geographic region, $E_{sec,reg}$, yields the unexplained natural gas consumption associated with a given economic subsector or building type within a given geographic region, $U_{sec,reg}$:

$$[13] \quad U_{sec,reg} = SI_{sec,reg} - E_{sec,reg}$$

Data on service and industrial natural gas consumption per geographic region, SI_{reg}, was taken from table CBS (2019c) on non-residential natural gas consumption per neighbourhood (PC4 region) in Utrecht. As data for neighbourhoods 1, 5 and 7 are omitted from the table, these were grouped as a single region. Its natural gas consumption (excluding the energy sector) was determined as the difference between the sum over main economic sectors (while excluding the energy sector) of the natural gas consumption per main economic sector in Utrecht obtained from table CBS (2019h), and the sum of natural gas consumption for the remaining PC4 regions:

$$[14] \quad SI_{reg\ 1+5+7} = \sum_{msec} (SI_{msec}) - SI_{D\ Energy} - \sum_{reg(ex.1,5,7)} (SI_{reg})$$

In order to determine $SI_{sec,reg}$ use made of the ratio between the energy intensity associated with the different economic subsectors and building types present in a PC4 region, along with the floor area, as indicated in [18] and [19] below.

1.3.2 Allocation of amounts of natural gas delivered to geographic (PC4) regions

In order to relate energy intensities in the industrial sector, expressed in terms of energy per employee, to energy intensities in the services sector, expressed in terms of energy per m^2 of floor area, the amount of natural gas delivered per economic subsector or building type in Utrecht obtained previously, $SI_{sec,msec}$, was divided by the amount of useable floor area associated with that economic subsector or building type in Utrecht. The set of energy intensities thusly obtained contains scaled versions of the original energy intensities from table 2 and scaled versions of the energy intensities in the industrial sector expressed in units of energy per m^2 floor area in the appropriate ratio to one another. Making use of these energy intensities, the amount of natural gas attributed to a given economic sub-sector or building type within a given PC4 region in Utrecht, $SI_{sec,reg}$, was determined by:

$$[15] \quad SI_{sec,reg} = \frac{I_{sec} * A_{sec,reg}}{\sum_{sec}\left(I_{sec} * A_{sec,reg}\right)} * SI_{reg}$$

Where $A_{sec,reg}$ is the amount of floor area associated with a given economic subsector or building type in a given PC4 region, SI_{reg} is the service and industrial sector natural gas consumption from table CBS (2019h), and $I_{sec} * A_{sec,reg} / \sum_{sec}\left(I_{sec,} * A_{sec,reg}\right)$ is the allocation factor, $S_{sec,reg}$. The unexplained gas usage and the unexplained gas intensity were then obtained by considering the demand for space heating, $E_{sec,reg}$, of the associated buildings.

This allocation procedure is equivalent to the 'top-down plus bottom-up' approach employed in (Arnoldussen et al., 2020), where the amount of natural gas consumption, $C_{sec,reg}$, associated with a given building type in a region was determined by:

$$[16] \quad C_{sec,reg} = I_{sec,reg} * A_{sec,reg} * \frac{C_{reg}}{\sum_{sec}(I_{sec,reg} * A_{sec,reg})}$$

And $C_{reg}/\sum_{sec}(I_{sec,reg} * A_{sec,reg})$ is the scaling factor. Buildings for which the natural gas consumption is known through the enforcement of environmental regulations did not need to have amounts of natural gas allocated to them and had their associated amount of natural gas subtracted from the total for their respective PC4 region.

1.3 RQ 3: Identifying end-uses responsible for unexplained gas usage

1.2.1 Method

Previous research (Segers et al., 2017) has indicated that coherent data on final energy consumption by type of end-use is not currently available from government agencies (e.g. the Ministry of Economic Affair and Climate Policy (EZK); the Netherlands Enterprise Agency (RVO)), research institutes (e.g. ECN part of TNO) or industrial organisations. Therefore, in order to collect the desired data interviews were conducted with companies belonging to subsectors or building types that represent an opportunity for achieving meaningful reductions in energy consumption from natural gas in the short term in the service and industrial sector in Utrecht. Three subsectors or building types were selected and queried for their end-uses of natural gas. For each subsector or building type selected, with the exception of one, three interviews were conducted. The subsectors or building types were selected according to the following criteria:

- The subsector or building type had among the highest natural gas intensities
- The subsector or building type contributed substantially to overall unexplained natural gas consumption in Utrecht.
- The subsector or building type was indicated by the literature to have viable decarbonisation options in the short term.

End-uses of natural gas were categorised based on the delineation of end-use categories adapted from Segers et al. (2017) as shown in table 8 below. In addition, companies were inquired about their total final energy consumption from natural gas, confidentially issues permitting, to serve as validation for results obtained previously. In order to mitigate the risk that the sample of companies selected for interviews is significantly unrepresentative of the population as a whole, the data on final energy consumption from natural gas obtained from interviews was compared to data on companies of the same subsector or building type as available through the enforcement of environmental regulations.

Table 8: Example questionnaire natural gas end-uses. Adapted from Segers et al. (2017)

Type of natural gas end-use	Natural gas consumption (m^3)
Total energy consumption from natural gas:	
Natural gas used for space heating:	
Natural gas used as feedstock for chemical processes	
Natural gas used for process heating, Total:	
Of which ... <200 degrees Celsius:	
200-500 degrees Celsius:	
500-1000 degrees Celsius:	
>1000 degrees Celsius:	
Other end-use(s): ...	
...	

1.2.2 Selection of sectors

In consultation with the municipality three sectors were selected for the conduction of interviews. The municipality indicated a preference that restaurants (56101) be investigated. In addition, two other sectors were selected: commercial laundries (9601) and swimming pools (93111). A fourth, the manufacture of metal products (25), was found not to have any non-space heating end-uses of natural gas (see chapter 4.4.1). The manufacture of metal products (25) sector was initially selected as the industrial sector with highest unexplained natural gas intensity and 10 companies from the sector were contacted. None, however, had any end-uses of natural gas other than for space heating, although some made use of bottled gas in the form of propane or acetylene. While the sector at the 2-digit NACE level is associated with substantial natural gas consumption in the Netherlands (see table 3) that allows for the possibility of non-space heating related sources of natural gas consumption, these may be present only in some subsectors at the 4-digit NACE level while not in others. As the companies contacted occupy the ‘general metalworking (2562)’ subsector that dominates the manufacture of metal products in Utrecht, it may be concluded that substantial consumption of natural gas for other purposes than space heating in this subsector is unlikely.

1.4 RQ 4: Identifying possible alternatives to non-space heating natural gas end-uses

Based on the information on natural gas end-uses obtained previously, a review of the literature was performed with the aim of generating an overview of the possible options to reduce energy consumption from natural gas in the subsectors or building types targeted. This took the form of a state-of-the-art literature review that was conducted for each of the three subsectors or building types selected in RQ3. Literature was found using the search terms “renewable energy” or “sustainability” combined with search terms denoting either the economic sector, such as “swimming pools” or “industrial laundries”, or the principal natural gas end use technology, such as “steam boiler” or “cooking stove”. Further relevant literature was subsequently obtained by means of the ‘snowballing procedure’ according to the guidelines set out in Wohlin (2014).

In order to support the identification of suitable low carbon alternatives, information was also collected during interviews regarding:

- Technical aspects of the processes identified
- Obstacles experienced by the company (e.g. financing, lack of information)
- Low-carbon options previously considered by the company, which, if any, were deemed viable and why.

Concurrently, making use of the information obtained from interviews, relevant industrial organisations were contacted to determine what information exits regarding possibilities for reducing natural gas consumption.

In addition, it was of interest to obtain some qualitative information from participating companies regarding their preferences on the role of government in relation to the natural gas transition, level of knowledge on alternative options, and degree of preparedness for the natural gas transition that may prove valuable in support of the implementation process. An attitude and perception survey was therefore be conducted. The questions are listed in appendix C.

4. Results & discussion

4.1 Unexplained gas usage among economic subsectors and building types

4.1.1 Data known through enforcement of environmental regulations

For certain buildings data was available through the enforcement of environmental regulations. These are shown in table 9 below. The natural gas intensity among service and industrial sector buildings was found to be highly variable and in some instances differed markedly from figures found in the literature. A few office buildings were found to have an extraordinarily large natural gas consumption, leading to an elevated natural gas intensity in some cases where economic activities were represented by only a few buildings in the dataset that is likely not representative of the entire sector. Notably, this includes 'Architects (NACE: 7111)' with 237 m^3/m^2 and 'Film production (5911)' with 63,6 m^3/m^2. Of the economic activities represented by a at least 5.000 m^2 of floor area, the economic activities with the highest natural gas intensities were 'Cleaning of clothes and textiles (9601)' (93,3 m^3/m^2), 'Swimming pools (93111)' (64,5 m^3/m^2), 'Fast-food restaurants (56102)' (49,8 m^3/m^2) and 'Wholesale of manufacturing supplies (4669)' (47,7 m^3/m^2).

4.1.2 Results for the services sector

The total unexplained natural gas consumption and the unexplained natural gas intensity for building types in the services sector are shown in figure 6 and table 10. Some combinations of building purpose and economic activity in the services sector were found not to fit any classification in the revised or the original typology. Two additional services sector categories were therefore devised to cover these remaining buildings: 'Other services' (containing police stations, fire departments, mail and courier services and transportation companies) and 'Cleaning of clothes and textiles' that denotes commercial laundries.

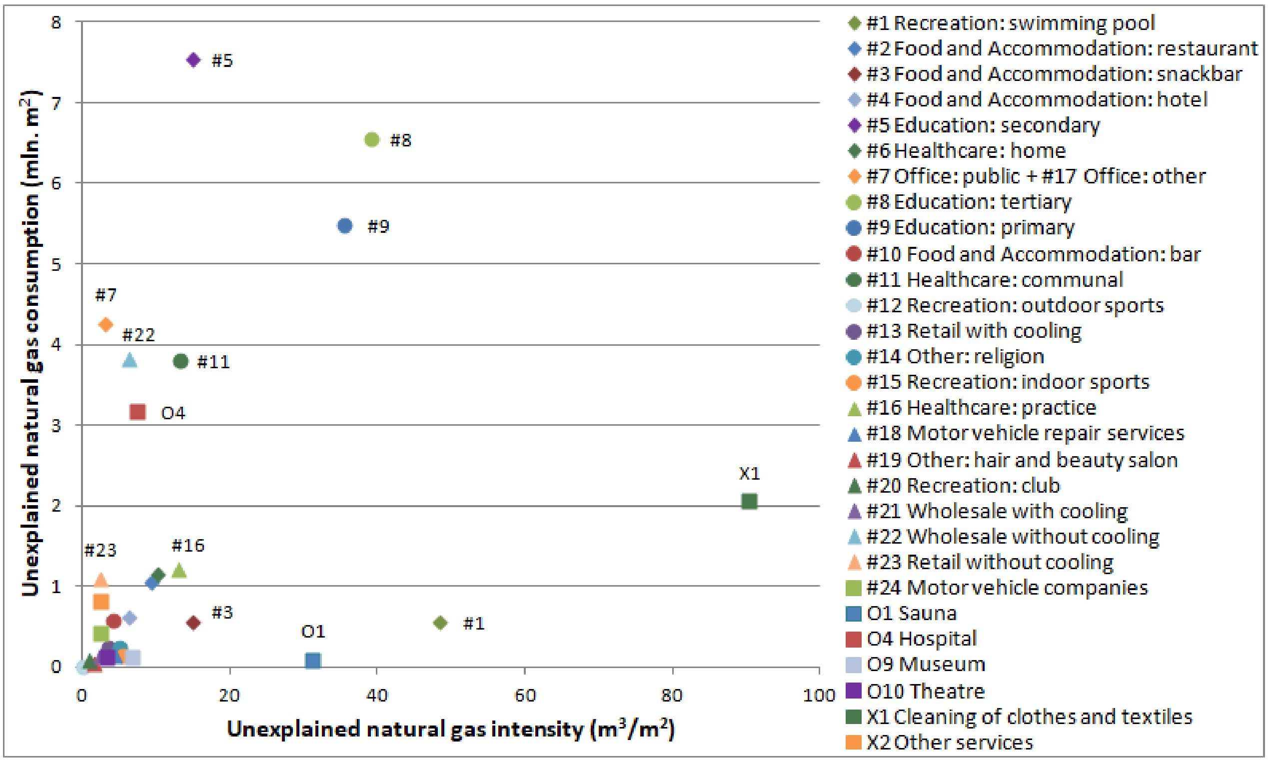

Figure 6: Unexplained natural gas consumption and unexplained natural gas intensity for building types in the services sector

Tabel 9: Natural gas consumption and intensity in economic sectors as known through the enforcement of environmental regulations

Sector	NACE code	Description	Number of entities	Natural gas consumption (x1000 m^2)	Floor area (x1000 m^2)	Natural gas intensity (m^3/m^2)
C	2511	Manufacture of metal structures and parts of structures	4	33	8,5	3,9
	2562	Machining	7	28	5,1	5,5
	3101	Interior construction and manufacture of business furniture	4	33	8,5	3,9
F Constr.	4120	Construction of residential and non-residential buildings	12	68	12,5	5,4
	4211	Construction of roads and motorways	4	79	9,2	8,6
	4321	Electrical installation	6	260	15,8	16,4
	4322	Plumbing and fitting; installation of sanitary fittings & air-conditioning	8	123	14,1	8,7
	4399	Other specialised construction activities	6	33	4,1	7,9
G Wholesale, Retail, Motor veh. repair	4511	Sale and repair of cars and light motor vehicles	62	673	77,3	8,7
	4519	Sale and repair of trucks, trailers and caravans	7	41	9,1	4,5
	4520	Specialised repair of motor vehicles	23	169	13,8	12,2
	4632	Wholesale of meat and meat products and of game and fowl (not live)	4	181	14,6	12,4
	4638	Wholesale of other food and of other raw materials for food	8	101	18,4	5,5
	4639	Non-specialised wholesale of food	4	76	8,5	8,9
	4646	Wholesale of pharmaceutical goods & medical instruments	7	271	27,6	9,8
	4649	Wholesale of other consumer goods (non-food)	6	37	4,3	8,7
	4651	Wholesale of computers, peripheral equipment and software	22	417	34,4	12,1
	4652	Wholesale of electronic and communication equipment and related parts	9	74	10,8	6,9
	4669	Wholesale of other machines, equipment and supplies for manufacturing	12	2.070	43,4	47,7
	4673	Wholesale of wood, sanitary equipment and construction materials	18	229	59,2	3,9
	4677	Wholesale of waste and scrap	4	21	3,2	6,7
	4690	Non-specialised wholesale	4	4,6	0,3	11,8
	4711	Supermarkets, department stores and similar non-specialised stores	22	235	28,8	8,2
	4722	Shops selling meat and meat products, game and poultry	7	35	2,4	14,6
	4729	Other specialised shops selling food	4	7,9	0,8	9,3
	4730	Petrol stations	5	15	1,9	7,5
	4752	Shops selling do-it-yourself articles	9	175	29,7	5,9
	4759	Shops selling furniture, articles for lighting and other household articles	9	135	61,7	2,2
	4764	Shops selling bicycles, sports and camping goods and boats	4	198	10,2	19,4
	4771	Shops selling clothes and clothing accessories: textile supermarkets	20	182	14,8	12,3
	4776	Shops selling flowers, plants, seeds, garden material & articles for pets	4	137	14,6	9,4
	4791	Retail sale via mail order and internet	19	24	3,8	6,3
	4799	Canvassing, street trade and other retail sale	4	3,7	0,4	8,5
H	4941	Freight transport by road (no removal services)	13	171	59,7	2,9
	5229	Forwarding agencies, ship brokers, charterers; weighing and measuring	4	13,4	5,4	2,5
	5320	Postal activities without universal service obligation and couriers	5	120	23,4	5,1
I Hotel & F.	5510	Hotels and similar accommodation	14	1.249	68,9	18,1
	56101	Restaurants	91	1.158	38,2	30,3
	56102	Fast-food restaurants, cafeterias, ice cream parlours etc.	29	410	8,2	49,8
	5621	Event catering	10	70	19,6	3,6
	5629	Canteens and industrial catering	40	514	40,6	12,7
	5630	Bars	22	186	10,7	17,3
J Information	5811	Book publishing	7	61	3,9	15,6
	5911	Motion picture and television programme production	11	155	2,4	63,6
	5912	Support activities for film & television programme production	4	14	1,3	10,5
	6201	Writing, producing and publishing of software	86	193	42,4	4,5
	6202	Computer consultancy activities	37	298	29,5	10,1
	6209	Other information technology and computer service activities	29	111	14,5	7,6
	6312	Web portals	13	49	3,7	13,2
K	6419	Other monetary intermediation	5	104	13,2	7,9
	6420	Financial holdings	7	14	2,2	6,1
	6619	Mortgage, credit and currency brokers, savings bank agencies etc.	6	0,5	0,2	3,1
	6622	Insurance agents	6	10	13,6	0,8
L	6810	Buying and selling of own real estate	4	0,8	0,1	5,7
	6820	Renting of real	16	46	8,4	5,5

Sector	NACE code	Description	Number of entities	Natural gas consumption (x1000 m³)	Floor area (x1000 m²)	Natural gas intensity (m³/m²)
	6831	Intermediation in buying, selling and renting real estate	9	6,8	0,8	8,3
M Specialised bus. services	6910	Legal activities	39	256	26,1	9,8
	6920	Accounting, tax consultancy, administration	23	254	17,3	14,6
	7022	Management en business consultancy (no public relations)	122	594	61,9	9,6
	7111	Architects	4	203	0,8	239,7
	7112	Engineers and other technical design and consultancy	41	538	70,1	7,7
	7219	Non-biotechnical research and development	11	625	56,3	11,1
	7311	Advertising agencies	36	213	25,2	8,5
	7320	Market research and public opinion polling	16	65	5,5	12,0
	7410	Industrial and fashion design	19	23	2,5	9,3
	7420	Photography and photo and film developing	4	2,6	0,7	3,6
	7430	Translators and interpreters	5	18	1,1	16,3
	7490	Other specialised business services	14	57	9,6	5,9
N Rental serv	7711	Renting and leasing of passenger cars and light motor vehicles	6	64	9,4	6,8
	7810	Employment placement agencies	19	245	37,9	6,5
	7820	Temporary employment agencies and job pools	27	133	8,6	15,4
	7911	Travel agencies	4	1,1	0,1	11,6
	8121	General cleaning of buildings	9	15	2,2	6,6
	8299	Other business support activities	4	25	2,4	10,5
O	8411	General public administration	10	707	108,1	6,5
	8424	Police	9	480	38,3	12,5
	8425	Fire brigades	4	41	10,0	4,1
P Education	8520	Primary and special education	58	1.154	94,4	12,2
	8531	General secondary education	6	162	27,0	6,0
	8532	Secondary vocational education and adult education	11	483	281,9	1,7
	8541	Post-secondary non-tertiary education	12	454	54,3	8,4
	8551	Sports and recreation education	4	18	2,5	7,3
	8552	Cultural education	7	56	5,2	10,6
	8559	Other education	29	233	22,1	10,6
Q Healthcare	8610	Hospitals including mental health and substance abuse hospitals	5	601	61,3	9,8
	8621	General medical practices	5	29	3,1	9,2
	8622	Specialist medical practices and outpatients' clinics (no dentistry)	20	100	6,8	14,8
	8623	Dental practices	7	12	3,1	4,0
	8691	Practices of midwives and paramedical practitioners	52	246	13,5	18,2
	8692	Other health care & support activities without accommodation	37	420	52,3	8,0
	8710	Residential nursing care	8	447	17,2	25,9
	8730	Residential and day care for the disabled and elderly	11	690	42,6	16,2
	8790	Social assistance with residential care to children and other persons	13	171	19,8	8,6
	8810	Social work activities without accommodation for the elderly & disabled	8	4,6	2,0	2,3
	8891	Child day-care centres	64	625	36,6	17,1
	8899	Social work and counselling, community activities	28	341	24,9	13,7
R Culture, sports, rec	9001	Performing arts	10	36	2,1	16,8
	9002	Support activities to performing arts	11	95	15,2	6,2
	9003	Writing and other artistic creation	17	28	1,2	22,8
	9004	Theatres and event halls	5	133	10,8	12,3
	9101	Lending of cultural goods and public archives	6	141	21,8	6,5
	9102	Museums and art galleries	5	138	15,2	9,0
	93111	Swimming pools	3	514	8,0	64,5
	9312	Outdoor sports	6	34	40,9	0,8
	9313	Fitness facilities	4	179	3,5	50,7
	9314	Indoor sports	5	212	10,6	20,0
S Other serv	9412	Professional membership organisations	15	66	10,2	6,4
	9420	Trade unions	4	219	21,0	10,4
	9499	Other interest and ideological organizations, hobby clubs	21	54	7,6	7,1
	9601	Cleaning of clothes and textiles	4	1.863	20,0	93,3
	9602	Hairdressing and beauty treatment	4	2,3	0,3	7,9
	9609	Other service activities	4	91	1,9	48,8

Tabel 10: Total, explained, unexplained gas consumption, floor area and unexplained gas intensity for building types in the services sector in Utrecht

#	Service sector building type	Building type natural gas consumption (1000 m³) $SI_{sec,msec}$	Explained natural gas consumption (1000 m³) $E_{sec,msec}$	Unexplained natural gas consumption (1000 m³) $U_{sec,msec}$	Floor area (1000 m²) $A_{sec,msec}$	Unexplained natural gas intensity (m³/m²) $I^{u}_{sec,msec}$
X1	Cleaning of clothes and textiles	2.159	104	2.055	23	90,2
#1	Recreation: swimming pool	666	112	553	11	48,5
#8	Education: tertiary	7.433	877	6.556	167	39,2
#9	Education: primary	6.462	974	5.489	155	35,5
O1	Sauna	123	30	93	3	31,1
#5	Education: secondary	8.769	1.230	7.538	500	15,1
#3	Food and Accommodation: snackbar	921	357	564	38	15,0
#11	Healthcare: communal	6.036	2.232	3.804	288	13,2
#16	Healthcare: practice	2.146	938	1.208	93	13,0
#6	Healthcare: home	2.216	1.060	1.155	113	10,2
#2	Food and Accommodation: restaurant	1.935	879	1.056	112	9,5
O4	Hospital	7.359	4.185	3.174	423	7,5
O9	Museum	144	13	131	19	6,8
#4	Food and Accommodation: hotel	1.428	808	620	97	6,4
#22	Wholesale without cooling	5.893	2.078	3.815	607	6,3
#15	Recreation: indoor sports	292	148	144	26	5,5
#14	Other: religion	611	372	240	47	5,1
O10	Theatre	149	52	97	21	4,7
#18	Motor vehicle repair services	306	154	153	35	4,3
#10	Food and Accommodation: bar	1.074	493	581	143	4,1
#13	Retail with cooling	583	330	253	71	3,6
#7	Office: public + #17 Office: other	11.412	7.157	4.255	1.383	3,1
X2	Other services	1.830	1.061	769	270	2,8
#21	Wholesale with cooling	276	139	137	53	2,6
#24	Motor vehicle companies	989	565	424	164	2,6
#23	Retail without cooling	2.645	1.551	1.094	453	2,4
#19	Other: hair and beauty salon	276	227	49	31	1,6
#20	Recreation: club	328	233	95	89	1,1
#12	Recreation: outdoor sports	41	34	7	54	0,1

The highest unexplained natural gas intensity was found among swimming pools and commercial laundries. The highest total amount of unexplained natural gas consumption was found among education buildings. This is likely a consequence of the fact that the education sector has the highest natural gas consumption among economic sectors in Utrecht, while its associated amount of floor area is comparatively limited. As the assessment of the natural gas demand for space heating and other known processes is linearly dependent on amount of floor area, the comparatively limited amount of education sector floor area constrains the estimate for the explained gas usage and results in a large difference between total and explained gas consumption.

This could possibly be explained by some education buildings in the municipality of Utrecht having a much higher natural gas demand for space heating per unit floor area relative to the natural gas demand for typical education buildings in the Netherlands that is relied upon by the Vesta Mais model. Notably, buildings with a large building volume relative to floor area would skew the results.

4.1.3 Results for the industrial sector

Figure 7 below and table 11 show the total unexplained natural gas consumption and the unexplained natural gas intensity for building types in the industrial sector. Total amounts of unexplained natural gas consumption per subsector in the industrial sector were lower than for the services sector. The highest unexplained natural gas intensity and unexplained natural gas consumption was found for the chemical manufacturing sector (20) (not shown in figure), followed by the manufacture of metal products (25), the manufacture of food products (10) and the manufacture of paper products (17). The result for the manufacture of chemicals is principally determined by a single plant with 271 employees. As the estimate for total building energy use in the industrial sector is based on the number of employees and a sector's total gas consumption in the Netherlands, the large number of employees leads to a very high estimate for total natural gas consumption on this location. Meanwhile the sector's limited floor area leads to a low estimate of the explained gas usage and consequently a large amount of unexplained natural consumption and a high unexplained natural gas intensity. The waste treatment and remediation sector's (39) unexplained natural gas consumption and unexplained natural gas intensity was found to be negative resulting of the fact that the sector is associated with negative natural gas usage (natural gas production) (see table 3).

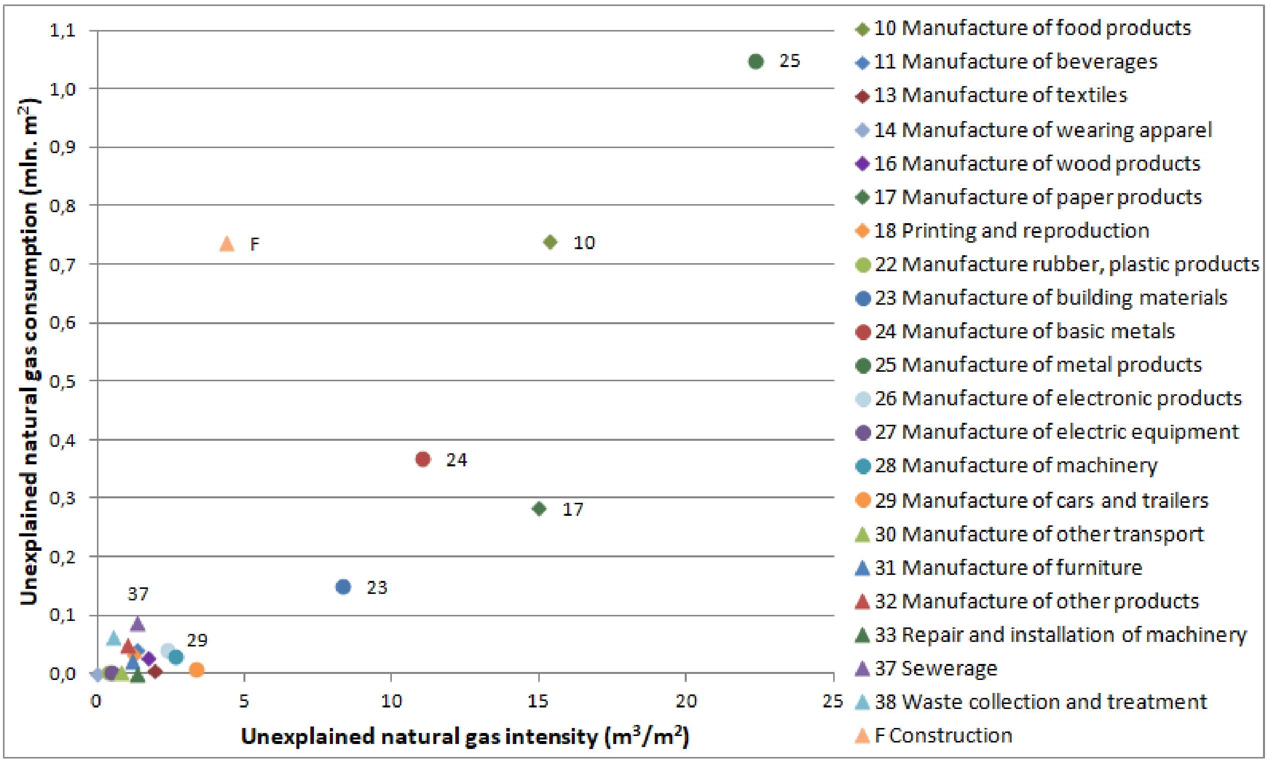

Figure 7: Unexplained natural gas consumption and unexplained natural gas intensity for building types in the industrial sector

Tabel 11: Total, explained, unexplained natural gas consumption, floor area and unexplained natural gas intensity for economic subsectors of the industrial sector in Utrecht

NACE code	Industrial subsector	Subsector natural gas consumption (1000 m^3) $SI_{sec,msec}$	Explained natural gas consumption (1000 m^3) $E_{sec,msec}$	Unexplained natural gas consumption (1000 m^3) $U_{sec,msec}$	Floor area (1000 m^2) $A_{sec,msec}$	Unexplained natural gas intensity (m^3/m^2) $I^u_{sec,msec}$
20	Manufacture of chemicals	12.780	22	12.758	5,0	2.574
25	Manufacture of metal products	1.151	102	1.050	35,4	29,6
10	Manufacture of food products	1.049	309	740	47,7	15,5
17	Manufacture of paper	429	145	284	18,9	15,1
24	Manufacture of basic metals	703	336	367	33	11,1
23	Manufacture of building materials	185	35	149	14,8	10,1
F	Construction	1.559	822	737	169,1	4,4
29	Manufacture of cars and trailers	27	18	9	2,6	3,3
28	Manufacture of machinery n.e.c.	61	31	29	10,9	2,7
26	Manufacture of electronic products	70	31	39	16,3	2,4
13	Manufacture of textiles	12	7	5	2,5	2,0
16	Manufacture of wood products	40	14	26	14,6	1,8
11	Manufacture of beverages	212	171	42	29,2	1,4
18	Printing and reproduction	84	53	31	22,5	1,4
37	Sewerage	139	52	87	64	1,4
31	Manufacture of furniture	55	34	21	17,4	1,2
22	Manufacture rubber, plastic products	10	7	3	2,4	1,1
32	Manufacture of other products	206	158	48	46,4	1,0
30	Manufacture of other transport	10	8	2	2,6	0,8
27	Manufacture of electric equipment	12	9	2	3,5	0,7
38	Waste collection and treatment	126	62	64	119,8	0,5
33	Repair and installation of machinery	9	9	0	7	0,1
14	Manufacture of wearing apparel	4	4	0	2	0,0
36	Water collection and distribution	121	121	0	14	0,0
12	Manufacture of tobacco products	0	0	0	0	0,0
15	Manufacture of leather and footwear	0	0	0	0	0,0
21	Manufacture of pharmaceuticals	0	0	0	0	0,0
39	Remediation, other waste management	-28	14	-42	2,8	-15,2

4.1.4 Discussion

The empirical results reported here must be interpreted with caution and a number of limitations should be borne in mind. Over the course of allocating amounts of natural gas delivered to main economic sectors to economic subsectors and building types several unknowns were encountered that required assumptions to be made. Statistics Netherlands categorizes buildings as either 'residential buildings' or 'businesses and other utility buildings' using several large databases, including BAG, Dataland, Locatus en ABR, as well as other criteria such as the name registered to the natural gas connection. Statistics Netherlands has indicated that this procedure allows some buildings with a residential building purpose to be classified as businesses. This procedure is therefore likely to result in a different population of buildings from the approach taken in this research, where use was made of the PAR survey and it was considered whether a building bears a utility building purpose according to BAG. As it is required to know the population of buildings (and their associated amount of floor area) responsible for the natural gas consumption per main economic sector as known through Statistics Netherlands, this represents a source of uncertainty. It was decided to include businesses that were known through the enforcement of environmental regulations, but that nevertheless had a residential building purpose, in the population.

The dataset included several instances of large agricultural buildings and workshop buildings in the construction sector with a large floor area that are unlikely to be heated. In some instances buildings were indicated by BAG to have since been demolished or indicated to have a floor area of 1 m^2 and it is possible that vacancies occurred mid-year, while in this research a building’s annual natural gas demand for space heating is assumed to be based on a full year of consumption.

Since in the Vesta Mais model the functional demand for space heating for utility buildings per m^2 of floor area is determined based on three building properties, its construction year, its energy label, and its building purpose according to BAG, a building’s possible reduced natural gas consumption per unit floor area resulting of larger building size is not taken into account. The functional demand’s dependence on building purpose also brings forth the issue of which building purpose is reflective of a building’s natural gas demand for space heating in the case the building has multiple building purposes. In instances where buildings had multiple building purposes the assignment of a primary building purpose seemed not to follow a consistent pattern. For example, of care homes that had a ‘residential’, ‘healthcare’ and ‘conference’ building purpose, instances could be found of each listed as primary building purpose, and motor vehicle repair buildings and garages bearing ‘industry’ and ‘office’ building purposes, could have either ‘industry’ or ‘office’ listed as primary building purpose. The figure determining a building's total natural gas intensity is similarly determined based on a limited number of building properties (the building’s size category, construction year and building type) and it is not likely that buildings having these properties in common share the same natural gas intensity as is assumed in the model. Consequently, total natural gas consumption may be overestimated for some buildings resulting in unexplained gas consumption that is not due to non-space heating gas end-uses.

In order to determine whether a building made use of the district heating system or relied on natural gas for space heating, use was made of data the municipality provided. In some cases this data conflicted with data on natural gas consumption as known through the enforcement of environmental regulations and it is an unknown which of the two data sources is correct in those instances.

This study contributes to the literature by serving as validation for results obtained earlier regarding the heterogeneity within building archetypes (Booth et al., 2012), and the obstacles presented by the lack of a universal classification of building archetypes (Pérez-Lombard et al., 2008), as well as by providing additional reference values that may prove useful in future benchmarking endeavours. Lastly, a method is proposed for assessing non-space heating related natural gas usage among economic subsectors and building types in the service and industrial sectors.

4.2 Unexplained gas usage among geographic regions

4.2.1 Results

Table 12 shows the total unexplained natural gas consumption and the unexplained natural gas intensity for PC4 regions in Utrecht. The unexplained natural gas consumption and the unexplained natural gas intensity was found to vary considerably across PC4 regions. The combination of PC4 regions 1, 5 and 7, home to the largest amount of floor area associated with economic activity, was found to have the highest unexplained natural gas consumption and the second highest natural gas intensity. PC4 region 10 'Vleuten-De Meern', home to considerably less floor area associated with economic activity, was found to have the highest unexplained natural gas intensity and the second highest unexplained natural gas consumption. The lowest unexplained natural gas consumption and the lowest unexplained natural gas intensity was found for PC4 region 08 'Zuidwest'.

Table 12: Total, explained, unexplained natural gas consumption, floor area and unexplained natural gas intensity for geographic regions in Utrecht

PC4 region	Region natural gas consumption (1000 m^3)	Explained natural gas consumption (1000 m^3)	Unexplained natural gas consumption (1000 m^3)	Floor area (1000 m^2)	Unexplained natural gas intensity (m^3/m^2)
	SI_{reg}	E_{reg}	U_{reg}	A_{reg}	I^u_{reg}
10 Vleuten-De Meern	13.839	3.472	10.367	666	15,6
01 West+05 Oost+07 Zuid	52.245	14.171	38.074	2.611	14,6
03 Overvecht	6.636	2.405	4.231	485	8,7
02 Noordwest	3.947	1.718	2.229	270	8,3
06 Binnenstad	7.191	3.355	3.836	699	5,5
04 Noordoost	3.231	1.887	1.344	273	4,9
09 Leidsche Rijn	3.876	2.155	1.721	478	3,6
08 Zuidwest	2.861	1.994	867	783	1,1
Total	**93.826**	**31.157**	**62.669**	**6.265**	**10,0**

4.2.1 Discussion

The results for the unexplained natural gas usage among geographic regions are subject to several limitations. First, the natural gas demand for space heating and other known processes was estimated through the procedure employed by the Vesta Mais model and is therefore subject to its limitations. Second, as the procedure used by Statistics Netherlands to classify buildings either as ‘residential buildings’ or ‘businesses and other utility buildings’ cannot be precisely replicated, the population of buildings whose combined natural gas consumption is given in the tables made available by Statistics Netherlands (CBS, 2019c; CBS, 2019d) cannot be determined with certainty. As estimating the natural gas demand for space heating and other known processes of the non-residential building population in Utrecht relies on knowing the size and number of buildings in the population, among other characteristics, this can affect the accuracy of the results. Third, discrepancies were encountered between data available through the enforcement of environmental regulations and data available through Statistics Netherlands on whether certain regions contained non-residential buildings that consumed natural gas. This study contributes to the literature by proposing a method for assessing the spatial distribution of non-space heating related natural gas usage in the service and industrial sectors.

4.3 End-uses responsible for unexplained gas usage and possible alternatives

4.3.1 Restaurants

4.3.1.1 Natural gas end-uses

Interviews were conducted at three restaurants. Company 1 was an Italian restaurant of 2377 m^2, Company 2 was a Dutch restaurant of 2014 m^2, and Company 3 was a Greek restaurant of 241 m^2. The companies reported that due to the increased workload resulting of the Covid-19 pandemic, they could not spare the time to make their natural gas consumption available for this research. Kitchen appliances were found to dominate non-space heating related natural gas end-uses:

- Company 1 was equipped with a 38 kW gas range (consisting of: 17.5 kW stove + 8.8 kW oven + 11.7 kW grill), a 15.5 kW gas deep fryer, and made use of natural gas for space heating and warm water production.
- Company 2 was equipped with two 17.8 KW gas stoves, a 21.0 kW gas stove, a 13 kW gas oven and a beer brewing installation powered by steam boiler with an operating pressure of 8 bar at a maximum temperature of 192 °C. Space heating was provided by the district heating system. It was indicated that the kitchen appliances were responsible for approximately 5-7% of natural gas consumption, with the remainder used by the brewing installation at around 80 m^3 of natural gas per batch.
- Company 3 was equipped with a 24.0 kW gas stove, a 9.5 kW gas oven and a 17.5 kW vertical gyros grill. In addition, use was made of natural gas for space heating and warm water production.

4.3.1.2 Sustainable alternatives to natural gas end-uses

The restaurant sector is in some ways similar to the residential sector in that the principal natural gas end-uses constitute space heating and kitchen appliances, although different energy demands may be associated. The search for alternatives to natural gas is thus primarily concerned with finding alternatives to natural gas-reliant kitchen equipment. For alternatives to the steam boiler used to power the beer brewing installation see chapter 4.3.2.2. Although many restaurants were interested in reducing their energy usage and improving the sustainability of their operation, overall awareness of the natural gas transition was found to be low with two restaurants not having seen any information regarding the natural gas transition. Two restaurants noted the difficulty of implementing energy efficiency measures to reduce their natural gas demand for space heating due to their building having a monumental building status. The costs of new appliances were indicated to be an important obstacle to moving away from natural gas. It is important to note that sustainable restaurant practices involve more than energy use alone and include sustainable buying practices and supply chain management. The literature on sustainable cooking is focussed on the adoption of clean cooking technologies and fuels in developing countries Pradhan et al., 2020; Precht, 2021; Singh, 2021. In Klijnsma, (2018) a plan was developed to supply the total energy demand of the village of Heeg by renewable energy source. In the study electric cooking appliances, specifically electric induction cookers were chosen as the preferred alternative to natural gas based cooking. Electric cooking when combined with renewable sources of electricity were indicated by the literature to be cost-competitive with other fuel alternatives (Lombardi et al., 2019), while being associated with only a moderate extra load on the electricity grid (Lombardi et al., 2019). The state-of-the-art in terms of energy efficient electric cooking methods is presented in Dilip et al. (2012).

4.3.2 Commercial laundries

4.3.2.1 Natural gas end-uses

The commercial laundry sector was found to be differentiated into several distinct market segments that specialized in different kinds of textiles, and, accordingly, made use of different process techniques and optimizations. These include:

- Retail laundries specializing in clothing
- Industrial laundries specializing in: Industrial work wear
- Hospitality (linen from hotels and restaurants)
- Healthcare (linen and uniforms for hospitals and care homes)
- Washroom services (mats, roll towels and sanitary napkins)

Interviews were conducted at three laundries, two retail laundries and one industrial laundry catering to the hospitality industry. The laundries' average natural gas consumption over 2018 and 2019 along with the estimated unexplained natural gas consumption is shown in table 13 below. None of the laundries made direct use of natural gas for space heating due to the excess heat produced by the installations.

- Laundry 1 is a retail laundry of 384 m^2 that uses heat from a steam boiler for drying and ironing. Steam is supplied at a pressure of 4 bar. In addition, the laundry is equipped with a 400 litre condensing boiler to supply hot water for washing.
- Laundry 2 is a retail laundry of 70 m^2 that uses heat from a steam boiler for washing, drying and ironing. Steam is supplied at a pressure of 6 bar.
- Laundry 3 is an industrial laundry of 12.881 m^2 that uses heat from a 6 MW steam boiler for ironing and to operate twenty-five 250 kW dryers. Steam is supplied at a pressure of 12 bar and a temperature of 190 °C. Washing occurs at 80 °C. The system was highly optimised with various waste heat recovery system incorporated throughout the installation. The company indicated it was able to use 98.6% of the energy content of natural gas as useable energy.

Tabel 13: Actual natural gas consumption versus estimated unexplained natural gas consumption

	Floor area (m^2)	Natural gas consumption (m^3)	Unexplained natural gas consumption (m^3)	Natural gas intensity (m^3/m^2)	Unexplained natural gas intensity (m^3/m^2)
Laundry 1	384 m2	17.431	38.771	45,4	101,0
Laundry 2	70 m2	10.195	6.629	145,6	94,7
Laundry 3	1.2881 m2	2.010.337	1.659.213	156,1	128,8

4.3.2.2 Sustainable alternatives to natural gas end-uses

As the primary natural gas end-uses in the commercial laundry sector concern the production of steam by means of a steam boiler for drying and ironing, as well as the production of hot water in the case of small and medium-sized laundries, these processes must either be electrified in order to substitute the use of natural gas (Bühler et al., 2019) or else alternative renewable energy sources must be found (Ribeiro et al., 2020; Thellufsen et al., 2019).

Supplying high temperature industrial process heat in a renewable fashion has been identified as a challenge in improving industry sustainability (Ribeiro et al., 2020). The literature on improving sustainability in the commercial laundry sector principally emphasizes the importance of reducing the use of water, energy, as well as detergents and other chemicals (Cotton et al., 2020; Hloch & Bohnen, 2009; Klemes & Varbanov, 2013; Máša et al., 2013; Petek et al., 2016). The main approaches cited to achieve this end are the use of heat recovery systems (Bobák et al., 2012; Conde, 1997; Máša et al., 2013; Valenti et al., 2019; Wilk et al., 2017), software-driven energy and water management systems (Bobák et al., 2011; Fijan et al., 2008; Furlan, 2021; Yandri et al., 2020), energy efficient technologies such as tumble dryers and continuous tunnel washers (Bengtsson et al., 2014; Conde, 1997; Yadav & Moon, 2008), and the use of solar energy for the pre-heating of water (Buchet et al., 2012; Cottret & Menichetti, 2010; Farjana et al., 2018; Lima et al., 2015). The importance of integrating renewable energy sources for the production of industrial process heat is cited in Buchet et al. (2012), Petek et al. (2016), and Ribeiro et al. (2020).

Máša et al. (2013) has emphasized that for environmentally friendly technologies to be successfully developed and implemented, it is critical to consider the following three aspects of any technology: energy efficiency, environmental impact and financial aspects. Recent research has shown (Bühler et al., 2019, 2020; Zühlsdorf et al., 2019) that electrification of industrial processes through the integration of high-temperature heat pumps and electric heaters is possible and may be economically viable. Zühlsdorf et al. (2019) has assessed the state-of-the-art of high-temperature heat pumps and found that heat pumps for the supply of process heat of up to 280°C are technically and economically feasible. Bühler et al. (2019) analyzed electrification strategies based on electric boilers and high-temperature heat pumps in the case of a milk powder production factory and found that such an approach could be competitive with natural gas based systems under certain predictions for future energy prices. Bühler et al. (2020) investigated the electrification of an industrial laundry in Denmark based on centralised and decentralised heat pumps and found the approach to be technically feasible, although not economically feasible under currently predicted energy prices up to 2030.

Ribeiro et al. (2020) studied the uptake of Solar Heat for Industrial Process (SHIP) technologies and found that the lack of a general policy framework for renewable process heat and the lack of financial support schemes were the biggest obstacles to adoption. The state-of-the-art of SHIP technologies covering a temperature range of up to 400°C is presented in Cottret & Menichetti (2010) and Horta (2015). Several instances of woody biomass-based steam boilers used to supply steam for industrial laundries are documented. These include a 2.4 MW steam boiler based on wood residues to power a hospital laundry in Wejherowo, Poland (Chwieduk, 2000), a pellet-based steam boiler supplying 3 000 kg/h of steam at 11 bar to a hospitality laundry in Madrid, Spain (Aresol Group, 2012a), and a woodchip-based steam boiler supplying 2 000 kg/h of steam at 11 bar to a hospitality laundry in Palma de Mallorca, Spain (Aresol Group, 2012b). Buchet et al. (2012) and Nastasi et al. (2018) have highlighted the potential of Power to Gas (P2G) options as a way of integrating renewable energy sources for the supply of industrial process heat.

Finally, there exist off-site options for the production of process heat in the case of large industrial laundries, as these currently often rely on a nearby thermal power plant for the supply of hot water (Petek et al., 2016). Nyambura (2016) investigated the case of a geothermal heated laundry and established its feasibility. Barbarelli et al. (2020) propose a small-scale CHP plant (100 kW) fuelled by biomass to supply heat and power to industrial laundries, hospitals, food industries, or other users. It relies on a micro gas turbine to perform the topping cycle combined with a newly developed steam micro turbine to perform the bottoming cycle. Thellufsen et al. (2019) used modelling to investigate the potential of utilising industrial waste heat through implementation of a district heating system and found such an approach to be cost-effective given a sufficient density of heat consumers.

4.3.3 Swimming pools

4.3.3.1 Natural gas end-uses

Although several swimming pools in Utrecht were indicated by the dataset to have a natural gas connection, all but one swimming pool in Utrecht turned out to have since been disconnected from the natural gas grid, as indicated the municipalities swimming pool maintenance expert, and are presently powered by the district heating system. An interview was conducted at the sole remaining swimming pool in the municipality of Utrecht still relying on natural gas. The swimming pool had a floor area of 3.447 m^2 and had an annual natural gas consumption of 152.052 m^3 (44,1 m^3/m^2) in 2018. This matched exactly with the data as known through the enforcement of environmental regulations, although its natural gas intensity was somewhat lower than indicated by the literature (55,6 m^3/m^2 for swimming pools in the size category 2.500-5.000 m^2). The pool water is kept at 30-31 °C through the use of counter-flow heat exchangers. The process fluid (water) enters the heat exchanger at a temperature of 65 °C and leaves at a temperature of 60 °C. Heat exchange occurs between the pool water, the ambient air and the pipes carrying the process fluid that run throughout the facility. As these heat flows are sufficient to keep the ambient air at the appropriate temperature, no direct use was made of natural gas for space heating.

4.3.3.2 Sustainable alternatives to natural gas end-uses

Swimming pools are highly energy intensive facilities (Buonomano et al., 2015; Jordaan & Narayanan, 2019; Li et al., 2021; Marín et al., 2019; Zuccari et al., 2017), and as such have been the focus of research since the 1960s (Czarnecki, 1963; Root, 1960) with the aim of reducing energy and operational costs. The aim of reducing greenhouse gas emissions from the building sector has since brought extra focus to swimming pool energy consumption and heating technologies given that sports facilities are one of the categories of buildings associated with the largest energy demand, and swimming pools have the highest energy demand among sports facilities (Jordaan & Narayanan, 2019; Li et al., 2021; Mousia & Dimoudi, 2015). Mousia & Dimoudi (2015) found that most swimming pools still rely on conventional heating technologies, in the form of oil and gas fired boilers, to supply their heat demand. Therefore, in order to substitute the use of natural gas and other fossil fuels alternative heating technologies are required.

In order to reduce swimming pool energy use and optimise the design and operation of swimming pool heating systems, it is essential that heat flows and losses within the facility are able to be accurately modelled (Li et al., 2021). As such, a considerable portion of the literature is devoted to the development of heat transfer models that are able to accurately capture heat losses due to evaporation (Hanssen & Mathisen, 1990; Shah, 2012, 2014, 2018; Smith et al., 1994), convection (Lam & Chan, 2001; Ruiz & Martinez, 2010; Woolley et al., 2010), conduction (Buonomano et al., 2015), radiation (Govaer & Zami, 1981), and the refilling of pool water (Buonomano et al., 2015), as well as heat gained due to solar irradiation (Lam & Chan, 2001; Wu et al., 2009). Li et al. (2021) have noted that most of the heat transfer models proposed fail to take into account several factors that can have a material effect on the real energy savings achieved. These include temperature variations across different regions of the pool due to building shading and heat gain due to the number and activity of swimmers in the pool that affect the optimal control and operation of heating systems.

In the literature passive and active heating techniques are differentiated (Katsaprakakis, 2015). Passive heating techniques revolve around the use of thermal-insulation covers of various materials. Single-layer (Czarnecki, 1963), inflated double-layer (Czarnecki, 1963; Root, 1960) and air-bubble (Francey & Golding, 1981; Szeicz & McMonagle, 1983) covers are distinguished in the literature, made of either transparant or opaque material. The performance of transparent and opaque covers was compared in Francey & Golding (1981) and Szeicz & McMonagle (1983) and it was found that opaque covers are more effective at night, while transparent covers are more effective during the day due to their ability to trap incoming solar radiation.

Active swimming pool heating technologies include solar collectors (Aboushi & Raed, 2015; Buonomano et al., 2015; Jordaan & Narayanan, 2019; Zhao et al., 2018), heat pumps (Lam &

Chan, 2001; Sun et al., 2011), waste heat recovery (Borge et al., 2011; Kuyumcu et al., 2016; Oró et al., 2018; Stastny et al., 2014), geothermal (Barbato et al., 2018), biomass heaters (Katsaprakakis, 2015), phase change material (PCM) storage (Li et al., 2018, 2020), and cogeneration systems (Facão & Oliveira, 2006).

Aboushi & Raed (2015) evaluated the thermal performance and life cycle energy cost of a solar heating system based on evacuated tube collecters and found the system resulted in an energy reduction of 75% under a payback period of less than a year. Buonomano et al. (2015) used modelling to asses the economic and energy performance of a flat-plate photovoltaic thermal (PV/T) solar collector system for a swimming pool in Naples, Italy and found use of the system lead to a remarkable improvement in the energy performance of the pool, while financial incentives were required to achieve economic viability. Jordaan & Narayanan (2019) developed a mathematical model of a swimming pool in Queensland, Australia to study the implementation of flat-plate solar collectors, evacuated tube collectors, a photovoltaic direct heating system and electric heat pumps. They found the evacuated tube collector system to be the most feasible and photovoltaic direct heating to be the least effective. Zhao et al. (2018) studied whether solar collectors could be operated at lower flow conditions in order to minimize pump energy and found a pump energy reduction of 60% and at optimal mass flow rate of 0.016 kg/(s*m^2) per unit collector area.

Lam & Chan (2001) investigated the use of a heat pump system for a 35 m^2 outdoor hotel swimming pool in Hong Kong and found that an energy cost saving of 75% could be achieved over a 10 year life cycle compared to conventional electric or gas-fired boilers. Sun et al. (2011) studied a system based on a new heat pump dihumidifier that could be used either to recover latent heat from moist indoor air or use outdoor air to heat indoor air and swimming pool water. The system was found to have a payback period of 1.1 year and have good energy and economic performance. Several instances of the use of heat pumps to recover waste heat from nearby facilities are also documented. Borge et al. (2011) analysed heat pumps used to cool residential buildings, while using swimming pools as a heat sink. Kuyumcu et al. (2016) examined the performance of a heat pump based swimming pool heating system utilising waste heat from a nearby ice rink cooling system. Oró et al. (2018) did the same, but waste heat from a neaby datacenter was used instead, while Stastny et al. (2014) relied on heat from an engine room. Modest energy and cost savings were found in each instance, although it is emphasized that the relevant subsystems must be sized appropriately for optimal performance.

Barbato et al. (2018) conducted a feasibility study on a geothermal plant to heat a 25 m by 17 m swimming pool in the volcanically active area of Campi Flegrei, Italy. The project was found to be economically feasible, although the payback period was long at 15.4 years. Katsaprakakis (2015) investigated a hybrid heating system based on biomass heaters in combination with solar collectors and a system using only biomass heaters and compared their operational costs to the use of conventional diesel oil fueled boilers. It was found that a significant reduction in operational costs could be achieved, although this was partly the result of the high diesel oil prices, and that the payback period was under five years. (Facão & Oliveira, 2006) proposed a system based on heat pipe solar collectors supplemented by a natural gas boiler for the cogeneration of heat and electricity. The system produced 6 MW of electrictity and 110 kW of heat at an average annual system efficiency of 85% with a relatively low collector area of 10 m^2 to 20 m^2. Despite relatively high intial investment costs the economic performance was found to be considerable. Li et al. (2018, 2020) proposed the use of PCM storage tanks in combination with heat pumps to shift electricity load to off-peak hours. Heat pumps would be used during off-peak hours to raise the temperature of the storage tanks to 60°C. The PCM storage tanks would then be used to heat the pool water to the appropriate temperature. The system was found to be technically and economically viable.

5. Conclusion & recommendations

In order to reduce and displace process-related natural gas use in commercial and industrial applications, the most significant sources of process-related natural gas use in the service and industrial sectors must be identified, electrification must occur, or else alternative renewable energy sources must be found. Herein the reduction of energy use is paramount in order to reduce the load that renewables have to bear. To identify contributions to process-related natural gas consumption by different economic subsectors and support the development of policies to displace natural gas it may be useful to establish an energy end-use profile of common economic subsectors.

In this research an attempt at benchmarking was performed to determine the energy per end-use (process or non-process) in different subsectors of the service and industrial sectors in Utrecht by means of information on the relative energy intensity of different categories of buildings and the Vesta Mais model's procedure to forecast building energy demand for space heating. It was found that swimming pools and commercial laundries had significant process-related natural gas usage among service sector building categories, and the food industry, manufacture of basic metals, paper and building materials sector could make use of process-related natural gas among industrial subsectors. The neighbourhood Vleuten-de-Meern was found most likely to harbour substantial process-related gas usage among geographic regions. However, these result must be interpreted with caution as the forecasting of building energy demand based on building characteristics is complex and the use of low-resolution input data has been cited before as a barrier to obtaining accurate results (Jaber et al., 2003). Notably, the lack of data on the energy intensity of industrial subsectors proved troublesome as is evidenced from the industrial subsector 'manufacture of metal products' obtaining a high process-related gas usage in the results, while the enforcement of environmental regulations indicated a very low intensity of natural gas use and telephone interviews confirmed no gas was being used for other purposes than space heating.

Industrial process heat was identified as a prominent source of process-related natural gas use in the service and industrial sectors. Specifically, the use of steam boilers for the production of super-heated steam was encountered in the commercial laundry sector for the purpose of drying and ironing and in the restaurant sector for the purpose of beer brewing. The use of natural gas fired boilers for the production hot water (65 °C-80 °C) was encountered in the case of swimming pools and small commercial laundries.

Several measures to reduce the energy demand for process heat as well as options to integrate renewable energy sources for the production of industrial process heat are described in the chapters on sustainable alternatives to natural gas end-uses. These include various solar applications (flat-plate collectors, evacuated tube collectors, photovoltaic direct heating, hybrid PV/T), heat pumps, geothermal, biomass heaters, PCM thermal energy storage, waste heat recovery and Power-to-Gas options.

As several renewable energy sources are likely to be constrained for the foreseeable future (e.g. biomass, geothermal) (Ribeiro et al., 2020), the electrification of industrial processes requiring heat along with reducing industrial energy demand for heat must be a priority. However, it has been noted that in order to successfully implement renewable energy technologies and energy efficiency measures, an individual, tailor-made approach is crucial (Máša et al., 2013) as achieving optimal energetic and economic performance often requires possible adjustments to the process, the design of the technology and the design of its components (Zühlsdorf et al., 2019). Furthermore, it has been suggested that those making recommendations regarding energy efficient solutions must possess sufficient technical and financial expert knowledge, knowledge of local industries and the energy policy of local governments and that this knowledge may only be obtained in close cooperation with technology manufacturers and business operators (Máša et al., 2013).

It is therefore recommended that a large number of energy audits be conducted to identify possible energy efficiency and renewable energy options for process-related natural gas users. Furthermore, the lack of a general policy framework and financial support schemes for renewable industrial process heat have been cited as barriers to adoption of alternatives (Ribeiro et al., 2020), while interviewees indicated that current policies incentivise the use of natural gas based appliances. As industrial process heat is likely to constitute a major component of process-related natural gas use in the service and industrial sectors, it is therefore recommended that a general policy framework for the implementation of renewable heat in developed.

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7. Appendices

Appendix A – Building type allocation for building types covered by revised typology

Table 14: Building type allocation for building types covered by revised typology (CBS, 2016)

#	Building type	NACE code(s)
1	Retail with cooling	47.11, 47.21-47.24, 47.81
2	Retail without cooling	45.32, 45.402, 47.19, 47.25, 47.26, 47.4-47.7, 47.82, 47.89, 47.9
3	Wholesale with cooling	46.3
4	Wholesale without cooling	45.31, 45.40.1, 46.1, 46.2, 46.4-46.7, 46.9
5	Motor vehicle companies	45.1
6	Motor vehicle repair services	45.2
7	Food and Accommodation: bar	56.3
8	Food and Accommodation: restaurant	56.101
9	Food and Accommodation: snackbar	56.102, 56.103
10	Food and Accommodation: hotel	55.1
11	Office: public	84.1, 84.21, 84.231, 84.3
12	Office: other	64-66, 69, 70, 71.1, 72.2, 73, 74.3, 74.9, 77.4, 78, 80, 82.1, 82.2 of 82.91
13	Education: primary	85.2
14	Education: secondary	85.31
15	Education: MBO	85.32
16	Healthcare: communal	88.9
17	Healthcare: practice	86.2, 86.9 (ex. 86.924)
18	Healthcare: home	87
19	Recreation: club	90.01-90.03
20	Recreation: indoor sports	93.112, 93.13, 93.14
21	Recreation: swimming pool	93.11.1, 93.15.1
22	Recreation: outdoor sports	93.113, 93.12, 93.152
23	Other: hair and beauty salon	96.02
24	Other: religion	94.911

Appendix B – Building types according to original typology

Table 14: Building types and associated average natural gas intensities in the Dutch services sector. Subdivision into size categories not shown in table. Data from 2012. (Sipma & Rietkerk, 2016)

#	Building type	Gas intensity (m^3/m^2)
1	Sauna	57
2	Swimming pool	39
3	Café / restaurant	29
4	Hospital	27
5	Hotel	22
6	Accommodation with overnight stay (Nursing homes)	18
7	Accommodation without overnight stay (Day care)	18
8	Medical practice	17
9	Museum	13
10	Theatre	13
11	Retail with cooling (Supermarket)	13
12	Office	13
13	Motor vehicle repair	13
14	Sports accommodation, inside	12
15	Primary school	12
16	Tertiary education / University	11
17	Retail without cooling	11
18	Garage / showroom	11
19	Sports accommodation, outside	10
20	Secondary school	10
21	Wholesale with cooling	9
22	Holiday park	8
23	Wholesale without cooling	7
24	Data centre	6

Appendix C – Questions attitude survey

- Would you describe your attitude towards the natural gas transition as positive or negative?
- How do you feel about your level of knowledge regarding the natural gas transition that is relevant to your business?
- How is sustainability incorporated into your business? What actions has your business taken regarding sustainability?
- How do you believe the transition away from natural gas will influence the competitiveness of business? Do you believe it will have a positive influence/negative influence on the competiveness of your business?
- Have you considered any alternatives to natural gas? Which alternatives have you considered? Do you think any synergies are possible? If so, which?
- What do you perceive to be the biggest obstacles for your business to move away from natural gas? What could the municipality do to address these obstacles?
- What role would you prefer for the municipality to perform during the natural gas transition? What should the municipality do? What should the municipality not do?