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The role of natural gas and its infrastructure in the energy transition in Switzerland

Simon Emilie

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Faculté des géosciences et de l'environnement
Institut de géographie et de durabilité

The role of natural gas and its infrastructure in the energy transition in Switzerland

Thèse de doctorat

présentée à la

Faculté des Géosciences et de l'environnement
de l'Université de Lausanne

pour l'obtention du grade de

Docteur en sciences de l'environnement

par

Emilie Simon
Maîtrise universitaire en sciences économiques
Université de Neuchâtel

Directrice de thèse
Sophie Swaton, Maître d'enseignement et de recherche à l'Université de Lausanne

Co-directeur de thèse
Stéphane Genoud, Professeur ordinaire à la HES-SO Valais-Wallis

Jury
Dominique Bourg, Professeur honoraire à l'Université de Lausanne
Massimiliano Capezzali, Professeur associé à la HEIG-VD
Sous la présidence de Marie-Elodie Perga, Professeure associée à l'Université de Lausanne

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Le Doyen de la Faculté des géosciences et de l'environnement autorise l'impression de la thèse de

Madame Emilie SIMON

Titulaire d'un
Master of Science en sciences économiques de l'Université de Neuchâtel

intitulée

THE ROLE OF NATURAL GAS AND ITS INFRASTRUCTURE IN THE ENERGY TRANSITION IN SWITZERLAND

Lausanne, le 17 octobre 2022

Pour le Doyen de la Faculté des géosciences et de l'environnement

Marie Elodie Perga

Professeure Marie-Elodie Perga

Résumé

Le rôle du gaz naturel et de ses infrastructures dans la transition énergétique en Suisse

Thèse de doctorat présentée par Emilie Simon à l'Institut de géographie et durabilité, Faculté des géosciences et de l'environnement, Université de Lausanne, Suisse

Augmentation de la température moyenne de l'air, réchauffement des océans, déclin régulier de la cryosphère, élévation accélérée du niveau de la mer et concentration croissante des gaz à effet de serre dans l'atmosphère : le changement climatique et l'influence de l'homme sur ce phénomène sont désormais sans équivoque. Notre système énergétique actuel, basé sur les énergies fossiles, est le principal responsable des émissions anthropiques mondiales. Il est donc crucial de commencer à construire un nouveau système énergétique sûr, capable de répondre à la demande d'énergie tout en tenant compte de la nécessité absolue de limiter le réchauffement climatique à un niveau acceptable. Cela implique une transition d'un système énergétique qui dépend fortement des combustibles fossiles tels que le charbon, le pétrole et le gaz naturel vers un système énergétique qui repose principalement sur les énergies renouvelables. L'objectif est clair, mais le chemin pour y parvenir n'est pas encore tracé. Comment orchestrer le déclin des combustibles fossiles ? Ayant la plus faible intensité de carbone de combustion des trois principales énergies fossiles, le gaz naturel est parfois présenté comme le combustible fossile de transition. Il est souvent décrit comme un compagnon des énergies renouvelables intermittentes, car il peut être une source bienvenue de flexibilité pour le système électrique. En outre, son infrastructure pourrait favoriser l'émergence de gaz renouvelables tels que le biométhane, le méthane de synthèse et l'hydrogène. Cette énergie doit-elle donc jouer un rôle particulier dans la transition énergétique ? En Suisse, le gaz naturel joue un rôle important dans son système énergétique. En effet, il représente 15% de la consommation finale d'énergie et son réseau s'étend sur 20'000 km. Alors que le pays s'est engagé à transformer son système énergétique afin d'atteindre la neutralité climatique d'ici 2050, quel sera le rôle du gaz naturel demain ? Est-il possible de mettre ses infrastructures au service de la transition énergétique ? L'objectif de cette thèse cumulative composée de trois articles différents est donc d'explorer quel rôle que le gaz naturel et ses infrastructures peuvent jouer dans la transition énergétique bas carbone en Suisse. Le premier article a adopté une approche qualitative et holistique afin d'explorer tous les aspects de cette question. Les deux plus grands défis liés à la transition énergétique en Suisse ont été identifiés. La mesure dans laquelle le gaz naturel et son infrastructure pourraient les résoudre a été mise en lumière. Le deuxième article a adopté une approche quantitative pour analyser l'implication du déploiement de l'un des rôles identifiés dans le premier article : L'utilisation de couplages chaleur-force alimentés au gaz naturel afin de produire de la chaleur et de l'électricité en hiver. Les résultats ont montré que le développement de cette solution peut réduire l'empreinte de gaz à effet de serre de l'électricité consommée en Suisse. Le troisième article a adopté une approche quantitative pour améliorer le modèle développé dans le deuxième article et pour analyser l'impact de l'arrêt de la centrale nucléaire de Mühleberg. L'article a également utilisé une approche qualitative pour identifier les barrières qui empêchent la pénétration des couplages chaleur-force en Suisse. Les résultats ont montré que ceux-ci sont confrontés à de nombreux obstacles. Tant qu'il n'y aura pas de définition claire d'une stratégie concernant cette technologie au niveau fédéral et cantonal, une réelle pénétration du marché semble compromise. Globalement, cette thèse contribue à une meilleure compréhension du rôle du gaz naturel et de ses infrastructures dans le contexte de la transition énergétique en Suisse.

Mots-clés : gaz naturel, Suisse, transition énergétique, gaz renouvelables, couplage chaleur-force, réchauffement climatique

Abstract

The role of natural gas and its infrastructure in the energy transition in Switzerland

PhD thesis submitted by Emilie Simon at the Institute of Geography and Sustainability, Faculty of Geosciences and Environment, University of Lausanne, Switzerland.

Rising average air temperature, warming of the oceans, steady decline of the cryosphere, accelerated sea-level rise and increasing concentration of greenhouse gases in the atmosphere: climate change and the influence of humans on this phenomenon are now unequivocal. Our current fossil-based energy system is the largest contributor to global anthropogenic emissions. It is therefore crucial to start building a new secure energy system capable of meeting energy demand while taking into account the absolute necessity of limiting global warming to acceptable levels. It implies a transition from an energy system that relies heavily on fossil fuels such as coal, oil and natural gas to an energy system that relies mainly on renewable energy. The objective is clear, but the path to get there has not yet been mapped out. How should the decline of fossil fuels be orchestrated? Having the lowest combustion carbon intensity of the three major fossil fuels, natural gas is sometimes presented as the transitional fossil fuel. It is often described as a companion to intermittent renewable energy as it can be a welcome source of flexibility for the power system. Moreover, its infrastructure might support the emergence of renewable gas such as biomethane, synthetic methane and hydrogen. Should this energy therefore play a special role in the energy transition? In Switzerland, natural gas plays an important role in its current energy system. Indeed, it accounts for 15% of final energy consumption and its network extends over 20,000 km. As the country is committed to transforming its energy system in order to achieve climate neutrality by 2050, what will be the role of natural gas tomorrow? Is it possible to put its infrastructures at the service of the energy transition? The aim of this cumulative thesis composed of three different papers is therefore to explore the role that natural gas and its infrastructure can play in the low-carbon energy transition in Switzerland. The first paper adopted a qualitative and holistic approach in order to explore all the aspect of this question. The two biggest challenges related to the Swiss energy transition were identified: Electricity supply in winter as well as the slow decarbonization of the buildings sector. The extent to which natural gas and its infrastructure could address them has been brought to light. The second paper adopted a quantitative approach to analyse the implication of the deployment of one of the roles identified in the first paper: Combined Heat and Power plants fuelled with natural gas as a power generation solution in winter. The results showed that the development of this solution can lower the GHG footprint of the electricity consumed in Switzerland. The third paper adopted quantitative approach to improve the model developed in the second paper and to analyse the impact of the decommissioning of the Mühleberg nuclear power plant. The paper also used a qualitative approach to identify the barriers hindering penetration of combined heat and power plant in

Switzerland. The results showed they are facing many obstacles. As long as there is no clear definition of a strategy regarding this technology at federal and cantonal level, a real market penetration seems compromised. Overall, this thesis contributes to a better understanding of the role of natural gas and its infrastructure within the Swiss energy transition context.

Keywords : natural gas, Switzerland, energy transition, renewable gases, combined heat and power, global warming

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J’aimerais ici exprimer ma profonde gratitude à toutes les personnes qui m’ont aidé à franchir toutes les étapes de cet incroyable périple.

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List of abbreviations

AR4	IPCC Fourth Assessment Report
AR5	IPCC Fifth Assessment Report
AR6	IPCC Sixth Assessment Report
BECCS	Biomass and bioenergy with carbon capture and storage
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
CH4	Methane
CHP	Combined heat and power plant
CO2	Carbon Dioxid
COP	Conference of Parties
CurPol	IPCC Illustrative pathways with outcomes under policies in place today
DAC	Direct air capture
EF	Emission factor
FAR	IPCC First Assessment Report
GHG	Greenhouse gas
GS	IPCC illustrative pathways with gradual strengthening of current policies
IMP	IPCC illustrative mitigation pathway
IP	IPCC illustrative pathway
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle analysis
LD	IPCC illustrative pathways with low demand
LUC	Land use change
ModAct	IPCC illustrative pathways with countries meeting their 2030 commitments
NDCs	Nationally Determined Contributions
Neg	IPCC illustrative pathways with extensive use of net-negative emissions
NG	Natural gas
Ren	IPCC illustrative pathways with high renewable
SAR	IPCC Second Assessment Report
SP	IPCC illustrative pathways with shifting development
SR1.5	IPCC Special Report on Global Warming of 1.5°C
SSP	IPCC shared socio-economic pathway
TAR	IPCC Third Assessment Report
UNFCC	United Nations Framework Convention on Climate Change
WG	IPCC Working Group

Chapter I : Introduction

Chapter I presents an overview of the dissertation in terms of context, objectives, research significance and scope of application.

A foreword from the author

The main objective of this dissertation was to answer the fascinating following research question: What role can natural gas and its infrastructure play in Switzerland's transition to a low-carbon energy system?

Why this research question?

Because, now more than ever, we need to build a new energy system that is secure, equitable, capable of meeting demand and, above all, capable of limiting global warming to acceptable levels. This implies a transition from a system based on fossil fuels to a system based mainly on renewables. But how do we orchestrate the decline of fossil fuels? How can we use them in the most appropriate way to build this new renewable energy system? This is a subject that is rarely discussed, although it is important to take a serious interest in it.

Why natural gas and not another fossil fuel? Because natural gas is the least dirty fossil fuel. But above all, because its consumption has required the construction of important infrastructures such as transport and distribution networks. This infrastructure is present on our territory and has required significant investment. Why not put this infrastructure at the service of the energy transition? I know that this subject is not unanimously accepted. I could tell by the eyebrows that were raised when I announced the topic of my doctoral thesis in discussions with my peers. So I hope that today, thanks to this dissertation, I will have succeeded in convincing more people of the relevance of this issue.

Why adopting a pragmatic research philosophy ?

This dissertation is rooted in a pragmatic research philosophy which aims at finding practical solution. Why this decision? Because an approach had to be found to reconcile the views of the different stakeholders involved in this research project. Indeed, this dissertation was born out of a particular context. Holdigaz, a company that includes natural gas distributors, decided to fund a doctoral thesis project to better understand the current context and to improve and transform the industry's knowledge. As a former Holdigaz employee, I decided to take up the challenge. For me, it was important to anchor this dissertation in the environmental sciences in order to give legitimacy to this research question. But it was also very important to stay close to the field and to adopt an applied research approach. This is why this thesis is co-directed by two professors from different universities, each contributing their expertise in each of these areas. Through this dissertation, I hope to have demonstrated that it is quite possible to produce a thesis that satisfies the needs of the private sector while maintaining its scientific rigour and quality.

The thesis in light of recent events

It is important to note that the elaboration of this dissertation took place before two major events that considerably changed the energy context of Switzerland and, consequently, the context and implications of this thesis. These events are, of course, the official recognition by the government of a possible winter electricity *shortage due to a reduced capacity of our neighbouring countries to export electricity to us as well as the Russian invasion of Ukraine. Today Switzerland faces the threat of a gas and electricity shortage for the winter of 2022-2023 and has to cope with energy prices that have reached unprecedented levels. Of course, these changes considerably the contributions of this thesis. For instance, the use of combined heat and power plant fuelled with natural gas to produce both power and heat is a feasible solution only if it is accompanied by natural gas saving measures in other areas. This context of energy scarcity shows us how necessary it is to discuss and plan how to use natural gas in the near future. Indeed, it requires upstream planning to ensure the most judicious use of this energy. Indeed, natural gas consumption must be reduced and used in specific contexts where it is the most efficient.*

1.1 Context

1.1.1 Transition to a low-carbon energy system

Rising average air temperature, warming of the oceans, steady decline of the cryosphere, accelerated sea-level rise and increasing concentration of greenhouse gases in the atmosphere: climate change and the influence of humans on this phenomenon are now unequivocal. This was reaffirmed in the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) published in 2021-2022. Today, these changes are already being felt in all regions of the world, as they have affected many extreme weather and climate events (IPCC, 2021). These extreme events have already had adverse effects on nature and humans. In an unrestricted future, the damage will increase and human and natural systems will not be able to adapt. Climate change requires urgent action as its extent and rate depends on short-term mitigation and adaptation measures (IPCC, 2022b). Indeed, global greenhouse gas (GHG) emissions must be reduced by 50% by 2030 compared to current levels if we want to limit the temperature increase to 1.5°C by the end of the century (IPCC, 2022b).

As the use of fossil fuels such as coal, oil and natural gas is the main source of GHG emissions, it is becoming indispensable to transform the energy systems of societies that rely heavily on them. An increasing number of countries have embarked on a transition to a low-carbon energy system. They have realized that it is necessary to build a secure energy system, capable of meeting energy demand while considering the absolute necessity of preserving the environment in order to mitigate climate change and the depletion of natural resources.

This is the case in Switzerland, which has developed the Energy Strategy 2050. This strategy is based on three pillars: reducing energy consumption and increasing energy efficiency, promoting renewable energies and phasing out nuclear energy (OFEN, 2013). Furthermore, following the ratification of the Paris Agreement on 6 October 2017, the Federal Council has developed a long-term climate strategy to reduce its net greenhouse gas (GHG) emissions to zero by 2050 (Conseil Fédéral, 2021a). Both the country’s energy and climate policies are geared toward a very sharp reduction, or even a complete halt, to fossil fuel consumption by 2050. The objective is clear, but the path to get there has not yet been mapped out. How can Switzerland build a new energy system that is secure, that preserve the environment and that is fair within the society in terms of accessibility and affordability ?

1.1.2 Role of natural gas and its infrastructure in the energy transition

When the countries of Europe began to sketch out plans for their energy future, natural gas was presented as the transitional fossil fuel and a golden age of natural gas was predicted for the coming years (IEA, 2011b). Indeed, having the lowest combustion carbon intensity of the three major fossil fuels (IPCC, 2006), it could replace other fossil fuels notably as a power generation solution. In addition, it can provide flexibility in power generation, a necessity alongside the deployment of intermittent renewable energy such as solar and wind (IEA, 2011b). Finally, because its consumption has required the construction of important infrastructures such as transport and distribution networks and important storage capacity. This infrastructure has required significant investment. It could be used to support the energy transition and support the emergence of renewable gas such as biomethane, synthetic methane and hydrogen.

However, so far the golden age of natural gas did not happen. At least, not as much as predicted. Why? Notably because the price of natural gas was not competitive with coal and because of geopolitical concerns about supply from Russia (Boersma & Jordaan, 2017). Indeed, in 2021, European natural gas consumption was 45% covered by imports from Russia (IEA, 2022). According to Boersma & Jordann (2017), natural gas and its infrastructure can still become an important cog in the wheel of the European energy transition with the development of renewable gas and the use of the gas infrastructure to store and transport renewable energy.

Today, in Switzerland, natural gas plays an important role in the current energy system. Indeed, it accounts for 15% (OFEN, 2020a) of final energy consumption and its network extends over 20,000 km (ASIG, 2021). In addition, the majority of the 100 companies active in this field are publicly owned. Finally, the industry has developed expertise in key areas such as storage, renewable gases, and power generation. What will its role be tomorrow? Is it possible to put its infrastructures at the service of the energy transition?

1.2 Research questions and objectives

This PhD project therefore aims to answer the following research question:

What role can natural gas and its infrastructure play in Switzerland's transition to a low-carbon energy system?

In order to answer this research question, the dissertation has the following research objectives:

1. Identify the roles presented in the scientific literature for natural gas and its infrastructure in the context of the decarbonization of the energy system

2. Present the official positions of the Confederation and the Swiss gas industry regarding the future of natural gas and its infrastructure

3. Identify the biggest challenges in the Swiss energy transition and how natural gas and its infrastructure could help addressing them

4. Assess how the deployment of combined heat and power plants fuelled with natural gas as a winter power generation solution can help the energy transition

5. Identify the barriers to the deployment of combined heat and power plants in Switzerland

In order to address these various empirically relevant topics, this thesis is presented as a cumulative one. Objectives 1, 2 and 3 are addressed in the first paper, objective 4 in the second and objective 4 and 5 in the third paper.

1.3 Scope of application

1.3.1 Organizational context of the dissertation

This PhD project is funded by Holdigaz, a holding company based in Vevey, Switzerland, which includes both natural gas distributors and companies operating in sectors directly or indirectly related to this activity. Holdigaz decided to finance a doctoral thesis project with the aim of better understanding the current context and improving and transforming the knowledge of the industry. This dissertation was written by Emilie Simon, a former employee of Holdigaz.

This dissertation is co-directed by two professors, Dr. Sophie Swaton from the University of Lausanne and Dr. Stéphane Genoud from the HES-SO Valais. Indeed, this thesis required two different fields of expertise: in the field of climate issues and sustainability and an expertise in the field of the energy market in Switzerland and an applied research philosophy.

1.3.2 Research approaches

This dissertation takes an applied research approach with the aim of bringing new knowledge to a limited problem (the energy transition and the natural gas industry in Switzerland) with results of practical relevance (Saunders et al., 2016).

Furthermore, the author wishes to adopt a trandisciplinary research strategy that crosses several disciplinary boundaries in order to create a holistic approach. This strategy also encourages the integration of knowledge from scientific and non-scientific stakeholders. Lang et al. (2012, p. 27) define transdisciplinarity as "a reflexive, integrative and methodological scientific principle that aims to solve societal problems [...] by differentiating and integrating knowledge from various bodies of scientific and societal knowledge".

In line with the previous two elements, the author of this thesis wishes to adopt a pragmatic research philosophy where "research starts with a problem and aims at a practical solution" and where "it is perfectly possible to work with different kinds of knowledge and methods" (Saunders et al., 2016, p. 143).

1.4 Thesis structure

As represented in Figure 1, the thesis is composed of four main chapters.

The first chapter, the present chapter, is the introduction. It presents an overview of the dissertation in terms of context, objectives, research significance and scope of application.

Chapter 2 presents the theoretical part on which I relied to elaborate the conceptual basis and the analysis grid that allowed me to develop the topics of the three articles of the empirical part. The subject of climate change and the transition to a low-carbon energy system is explored. Finally, the context of the energy transition in Switzerland is presented.

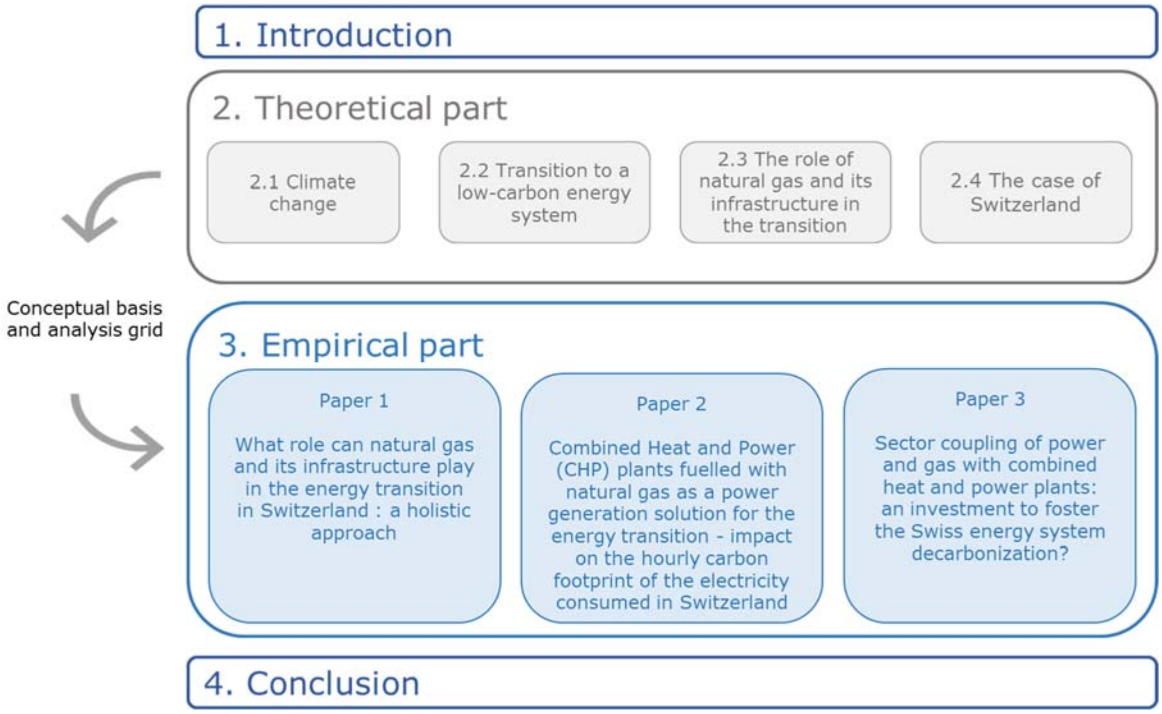

Figure 1: Structure of the thesis
Source: author

Chapter 3 presents the empirical part of the dissertation. It is composed of three different papers. Each paper is summarized in Table 1. The first paper adopts a qualitative and holistic approach to explore what role natural gas and its infrastructure can have in the Swiss energy transition. The second paper presents a new quantitative model to analyse the implication of the deployment of one of the roles identified in the first paper: Combined Heat and Power plants (CHP) fuelled with natural gas as a power generation solution for the energy transition. The third paper adopted quantitative approach to improve the model developed in the second paper and also a qualitative approach to identify the barriers hindering penetration of CHP in Switzerland.

Chapter 4 is the conclusion of the research. It summarizes the results, the theoretical contributions and the practical implications and points to the limitations of the research, and indicates some directions for future research.

Paper	**Author(s)**	**Motivation**	**Objective or research question**	**Methodology**	**Conference presentations and publication status**	**Contribution of the authors**
I. What role can natural gas and its infrastructure play in the energy transition : a holistic approach	Emilie Simon, Randolf Ramseyer, Stéphane Genoud	Empirical: Uncertainties regarding the future of natural gas and its infrastructure in the Swiss energy transition Theoretical: Lack of holistic and qualitative research on the role of natural gas in the energy transition in Switzerland	- What are the roles presented in the scientific literature for natural gas and its infrastructure in the context of a decarbonization of the energy system ? - What are the official positions of the Confederation and the Swiss gas industry regarding the future of natural gas and its infrastructure ? - What are the biggest challenges in the Swiss energy transition and how natural gas and its infrastructure could address them ?	Qualitative: research based on interviews	Not submitted yet	Emilie Simon: conceived the original idea, realized the literature review, designed the methodological framework, conducted interview, made the transcripts, analyzed data, wrote the article Randolf Ramseyer: helped designing interview guide and made the transcripts Stéphane Genoud: conceived the original idea and provided critical feedback
II. Combined Heat and Power plants fuelled with natural gas as a power generation solution for the energy transition – impact on the hourly carbon footprint of the electricity consumed in Switzerland	Emilie Simon, Francesco Maria Cimmino, Stéphane Genoud	*Empirical*: Power import dependency of Switzerland in Winter and potential solution with CHP fuelled with Natural gas *Theoretical*: The lack of a detailed approach (hourly and exchange with other countries) to assess carbon footprint of electricity in Switzerland	- What is the impact of the electricity inflows from neighbouring countries on the hourly carbon footprint of the electricity consumed in Switzerland ? -How the replacement of a part of the inflows from neighbouring by Combined Heat and Power (CHP) fuelled with natural gas impacts the hourly carbon footprint of the electricity consumed in Switzerland ?	Quantitative: research based on simulation	Accepted and presented at the The 1st IAEE Online Conference – Energy, Covid and climate change	Emilie Simon: conceived the original idea, realized the literature review, designed the methodological framework, developed the model, collected the data, wrote the code for the simulation, wrote the article Francesco Maria Cimmino: wrote the code for the simulation and provided critical feedback Stéphane Genoud: conceived the original idea and provided critical feedback
III. Sector coupling of power and gas with combined heat and power plants: an investment to foster the Swiss energy system decarbonization ?	Emilie Simon, Francesco Maria Cimmino, Stéphane Genoud	*Empirical:* Power import dependency of Switzerland in Winter and potential solution with CHP fuelled with Natural gas and low penetration of this technology *Theoretical:* The lack of research on the effect of the decommissioning of nuclear power plant on the hourly carbon footprint of Switzerland	- What effect the deployment of small CHP units fuelled with natural gas would have on the hourly carbon footprint of the electricity consumed in Switzerland ? - How this result would potentially change after the decommissioning of the Mühleberg nuclear power plant? - What are the economic, regulatory and policy barriers hindering penetration of CHP in Switzerland?	Quantitative: research based on simulation Qualitative: research based on interviews	Accepted and presented at the 10th FSR annual Conference – Infrastructure investment challenges : reconciling, carbonisation and digitalization	Emilie Simon: conceived the original idea, realized the literature review, designed the methodological framework, collected the data, developed the model, wrote the code for the simulation, conducted interview, made the transcirpts, analyzed data, wrote the article Francesco Maria Cimmino: wrote the code for the simulation and provided critical feedback Stéphane Genoud: conceived the original idea and provided critical feedback

Table 1 : General overview of the three papers
Source: author

1.5 References

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Chapter II : Theoretical part

Presents the theoretical part on which I relied to elaborate the conceptual basis and the analysis grid that allowed me to develop the topics of the three articles of the empirical part.

A foreword from the author

As stated earlier, it was important to me to anchor this dissertation in the environmental sciences. I wanted to root the concept of energy transition to the concept of transitioning to a carbon-neutral energy system. In order to do that, I had to start from the very basis. What is climate change ? What causes it ? Is there a scientific consensus about climate change ? Searching answers to those questions quickly led me to the Intergovernmental Panel on Climate Change Assessments (IPCC) Reports. Indeed, these reports reflect the scientific consensus on the issue of climate change. I then decided to take those assessment reports as the basis of my works. I wanted to know what the IPCC reports said about a future energy system compatible with 1.5°C or 2°C global warming by 2100. From there, I needed to put this thesis in the context of Switzerland and so I looked at its energy and climate policy. It is by setting this framework that I was then able to construct the three scientific articles of this thesis.

2.1 Climate change[1]

2.1.1 Definition

Rising average air temperature, warming of the oceans, steady decline of the cryosphere, accelerated sea-level rise and increasing concentration of greenhouse gases in the atmosphere: climate change and the influence of humans on this phenomenon are now unequivocal (IPCC, 2021).

But what is climate change? The United Nations Framework Convention on Climate Change defines climate change as "changes in climate which are attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which are in addition to natural climate variability observed over comparable time periods" (Nations Unies, 1992).

This convention therefore makes a distinction between climate change due to human activities altering the composition of the global atmosphere and natural climate variability. Indeed, climate change can be induced by processes intrinsic to the Earth such as change in the Earth's rotation axis or by external influences. In fact, different episodes of climate change have occurred throughout the Earth's geological history (IPCC, 2013b).

What alters the composition of the global atmosphere? The emissions of Greenhouse gas causes by human activities since the Industrial Revolution. The three principal greenhouse gases are: carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O). Each of these gases has a different greenhouse potential that can be compared using the Global Warming Potential (GWP) (see Table 2). GWP is a measure of how much energy is absorbed by a gas over 100 years or 20 years. This measure is relative to CO2, the most abundant GHG. In other words, CO2 has always a GWP of 1 as it is the reference. Methane, the main component of natural gas, absorb much more energy than CO2 (84 times more over 20 years and 28 times more over 100 years) but has a lifetime of 12.4 years, much shorter than CO2. Therefore, when analysing the impact of natural gas use in terms of climate change, it is important to take into account not only the CO2 emitted when it is burnt but also the methane released into the atmosphere (leakage) during its extraction, transport and consumption. This topic is discussed in more detail in the first scientific paper.

Name	Chemical Formula	Liftetime (years)	GWP 20-year	GWP 100-year
Carbon dioxide	CO_2		1	1
Methane	CH_4	12.4	84	28
Nitrious oxide	N_2O	121	264	265

Table 2: Lifetime and global warming potential of the three main GHGs

Source; adapted from (IPCC, 2013a): Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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[1] In this thesis the terms global warming and climate change have the same meaning and is therefore used interchangeably.

2.1.2 Chronology of scientific awareness of climate change

Before a scientific consensus was reached, several discoveries were made along the way to raising awareness of anthropogenic climate change (see Figure 2). It was Joseph Fournier who first described the greenhouse effect in 1824, allowing the earth to benefit from mild temperatures (Fourier, 1824). Thirty-six years later, John Tyndall's discovery of the heat-absorbing capacity of water vapour (H2O) and carbon dioxide (CO2) gave rise to the idea that changes in the proportion of these gases in the atmosphere can lead to variations in climate (Tyndall, 1861). In the late 19th century, Svante Augustus Arhenius was the first to link anthropogenic carbon emissions initiated by the Industrial Revolution with future global warming. With the first ever global warming model, he estimated that doubling CO2 in the atmosphere would cause a warming of about 5°C (Arrhenius, 1896). For almost 60 years, the results of various studies seemed to contradict Arhenius' theory. Indeed, behind this intuition, it remained to be proven that CO2 was increasing in the atmosphere, i.e. that the oceans or the biosphere were not capable of absorbing all the extra CO2 generated by human activity and that, finally, the increase in CO2 in the atmosphere was indeed causing global warming.

It was Charles Keeling who provided irrefutable proof of the inexorable rise in CO2 concentrations in the atmosphere. Indeed, between 1958 and 1960, by taking measurements in Antarctica and Hawaii, places that were not subject to disturbance, and thanks to new technical procedures, he succeeded in accurately measuring the evolution of CO2 in the atmosphere (Keeling, 1960).

It was in the 1980s that the link between CO2 and climate was proven. Indeed, by extracting ice cores in Antarctica, it was discovered that the evolution of CO2 was closely linked to glacial and interglacial periods (Lorius et al., 1985; Walker et al., 1981). Indeed, the CO2 curve closely followed the temperature curve.

In the following years, there was uncertainty as to the direction of causality between the evolution of CO2 in the atmosphere and temperature variations. Indeed, there was some evidence to suggest that the rise in temperature preceded the rise in CO2. Finally, new ice cores were able to show that these were positive feedback chains. For example, a slight change in the Earth's rotation axis caused a slight increase in temperature, which in turn caused the oceans to evaporate more CO2, thus increasing the initial warming, which in turn increased GHG emissions (Petit et al., 1999). In the past, GHGs have therefore been drivers of climate change, even if they were not necessarily the triggers (Shakun et al., 2012).

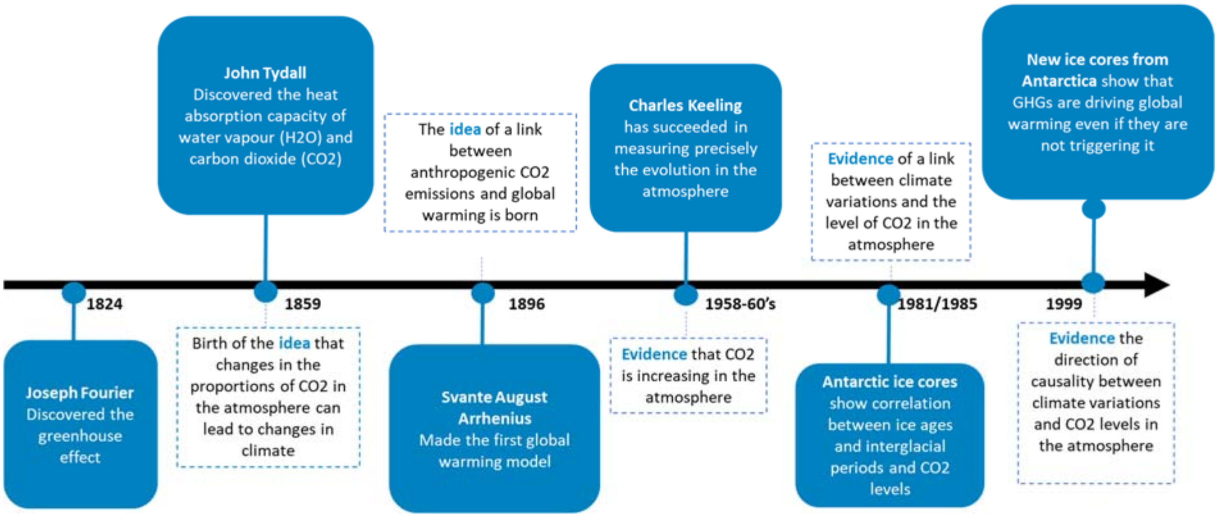

Figure 2 : Chronology of scientific awareness of climate change
Source: author

Today, there is a scientific consensus on anthropogenic global warming, not only among scientists with expertise in global warming (Anderegg et al., 2010; Doran & Kendall Zimmerman, 2009; Oreskes, 2004; Stenhouse et al., 2014; Verheggen et al., 2014, 2014) but also among scientists from other disciplines (Carlton et al., 2015).

This scientific consensus is also reflected in the publications of the Intergovernmental Panel on Climate Change (IPCC), founded by the World Meteorological Organisation and the United Nations Environment Programme in 1988. This organization is responsible for assessing the scientific, technical and socio-economic information on the current state of scientific knowledge on climate change and for identifying the elements of the scientific community's consensus. (*UN General Assembly Resolution 43/53, Protection of Global Climate for Present and Future Generations of Mankind*, 1988) Since then, the IPCC has published 6 assessment reports as well as several special reports and technical reports. Each of the IPCC assessments has been used as a basis for international negotiations on global warming, the main ones of which are presented in the following paragraph.

2.1.3 The IPCC and international climate negotiations

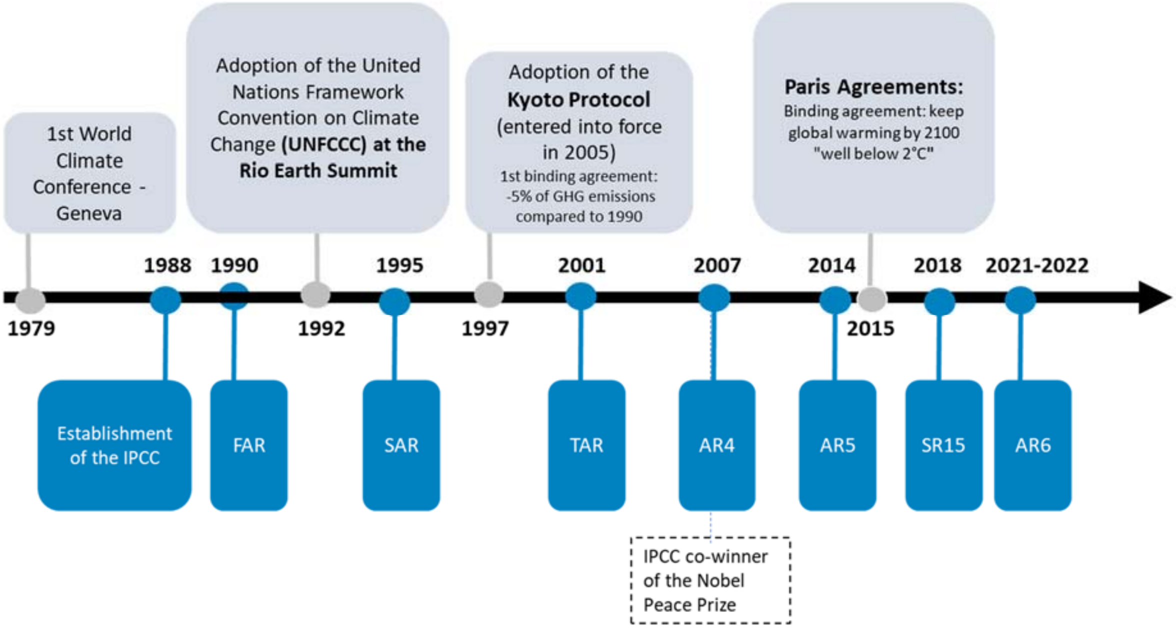

Figure 3 : IPCC and international climate negotiations
Source: author

2.1.3.1 First World Climate Conference and IPCC birth

The first World Climate Conference (WCC-1) in 1979 was the first international event to address the issue of global warming, demonstrating an awareness outside of scientific circles. At the end of the meeting, a declaration was written urging nations to take action to increase knowledge about climate and ultimately to predict and prevent climate change (OMM, 1979). It also gave rise to the World Climate Programme.

As mentioned earlier, the IPCC was established nine years later, in 1988. Indeed, at the 40th Session of the World Meteorological Organization, the Executive Council decided to establish the IPCC with the authorization of the United Nations Environment Programme. The IPCC was founded with the aim of preparing reports on all aspects of global warming and its impacts based on scientific and technical publications of widely recognized scientific value. The aim of these assessments is to transfer this knowledge to governments for consideration in the development of their environmental programmes (IPCC, 2004).

2.1.3.2 IPCC First Assessment Report and adoption of the UN Framework Conventions on Climate Change

The IPCC published its first assessment report (FAR) on 30 August 1990. In this report, the experts concluded that they were certain that GHG emissions from human activity were contributing to global warming. They also identified some uncertainties about the impact of this warming but appreciated that the impacts will be felt most severely in already vulnerable regions. They also presented various mitigation and adaptation measures for the short and long term. Finally, the report also included elements that could serve as a basis for an international convention on global warming (IPCC, 1990).

This first report was the basis for the negotiations that led to the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) at the Rio Earth Summit in 1992. The objective of this Convention is to "stabilize […] greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". (Nations Unies, 1992, p. 1). This convention requires signatory parties to adopt mitigation policies and measures and to report periodically. The Convention has been ratified by 197 countries and entered into force on 21 March 1994 (U.N.General Assembly, 1994). The signatories to this convention are called the Parties and meet annually at the Conferences of the Parties (COPs) to monitor and review the implementation of the UNFCCC.

2.1.3.3 IPCC Second Assessment Report and the Kyoto Protocol

The IPCC Second Assessment Report (SAR) was presented at the Second Conference of the Parties in Geneva (COP-2) in 1996. Among other things, the report highlighted the considerable progress in understanding climate change since the first report. Its synthesis report provided mitigation and adaptation measures that could be deployed to achieve the UNFCCC objective (IPCC, 1995).

The Kyoto Protocol was adopted at the third Conference of the Parties (COP-3) on 11 December 1997. This protocol commits industrialized countries to limit and reduce their greenhouse gas (GHG) emissions in accordance with the UNFCCC. It sets individual reduction targets to be achieved by 2008-2012 for 36 industrialized countries and the European Union. (United Nations Framework Convention on Climate Change (UNFCC), 1997)

2.1.3.4 IPCC 5th Assessment Report, the Paris Agreements and the 1.5°C Special Report

The IPCC Fifth Assessment Report (AR5) was published in 2014 (IPCC, 2013b). The publication of this report paved the way for negotiations on carbon emission reductions at the 21st Conference of the Parties (COP) in December 2015. These negotiations resulted in the Paris Agreement. In signing this agreement, Parties committed to containing "the increase in global average temperature to well below 2°C above pre-industrial levels and continuing action to limit the temperature increase to 1.5°C above pre-industrial levels" (art.1 United Nations Framework Convention on Climate Change (UNFCC), 2015). Each Party shall establish, communicate, and update its intended successive nationally determined contributions. Parties shall take domestic mitigation actions to achieve the targets of these contributions. To date, 189 of the 195 countries that signed the agreement have ratified it.

At the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC), the IPCC was asked to produce a special report on the consequences of a global warming of 1.5°C above pre-industrial levels. The IPCC accepted and published the results of this special report (SR1.5) in 2018 (IPCC, 2018). The experts concluded that limiting global warming to 1.5°C instead of 2°C or more would bring considerable benefits for human well-being, ecosystems and sustainable economic development. They believe that limiting global warming to 1.5°C is technically feasible according to the laws of physics. However, this would require profound changes in all aspects of society (energy system, land, urban infrastructure, transport, buildings and industrial systems). In his press release, UN Secretary-General Antonio Guterres called it a "deafening alarm" and said that "we must do what the science tells us to do before it is too late". He added that “a half of a degree of warming makes a world of difference” (Guterres, 2018). This IPCC report was considered the most important one published so far… until the sixth assessment report (AR6) in 2021-2022. Indeed, the AR6 presents a more worrying and urgent situation than the SR1.5. Since then, greenhouse gas emissions have continued to build up in the atmosphere. This time, the UN Secretariat General said in the press release of the report that « We are on a fast track to climate disaster » and “We are on the pathway to global warming of more than double the 1.5°C limited in Paris” (Guterres, 2022).

The content of this report is presented in the following paragraph.

2.1.4 The sixth IPCC assessment report

The three IPCC working groups contributing to the assessment reports (see Table 3) published their results for the sixth assessment cycle on 6 August 2021, 27 February 2022 and 4 April 2022 respectively.

Working group	**WG I**	**WG II**	**WG III**
What	**The physical Science Basis**	**Impacts, Adaptation and Vulnerability**	**Mitigation of Climate Change**
Definition	“Examines the physical science underpinning past, present, and future climate change”	“Assesses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequence of climate change and options for adapting to it”	“Focuses on climate change mitigation, assessing methods for reducing greenhouse gas emissions, and removing greenhouse gases from the atmosphere”

Table 3: The three IPCC working groups

Source; author. Definitions For Working Group 1 from IPCC. (n.d.-a). Working Group I — IPCC. The Intergovernmental Panel on Climate Change. Retrieved June 24, 2022, from https://www.ipcc.ch/working-group/wg1/

For Working Group 2 from : IPCC. (n.d.-b). Working Group II — IPCC. The Intergovernmental Panel on Climate Change. Retrieved June 24, 2022, from https://www.ipcc.ch/working-group/wg2/

For Working Group 3 from: IPCC. (n.d.-c). Working Group III — IPCC. The Intergovernmental Panel on Climate Change. Retrieved June 24, 2022, from https://www.ipcc.ch/working-group/wg3/

Main messages from WGI:

Today, global warming is an undeniable phenomenon. Indeed, in this report, the level of certainty that human activity is responsible for the warming observed since the mid-20th century has increased further, as the IPCC now considers the link between the two to be “unequivocal”. The experts also evaluate that the increase in greenhouse gas concentration due to human activity has probably contributed to an average global surface warming of between 0.8°C and 1.3°C over the period 1850-1900 to 2010-2019. It has not only affected temperatures but also phenomena such as decline of the cryosphere, sea-level rise, precipitation changes and changes in the land biosphere. They have occurred in a widespread and rapid manner. Furthermore, evidences of human influence on extreme events such as heat waves, heavy rainfall, droughts and tropical cyclones have also increased (IPCC, 2021).

Main messages from WGII:

These extreme events have already had adverse effects on nature and humans. Indeed, already today, 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change. In an unrestricted future, the damage will increase, and human and natural systems will not be able to adapt. Climate change requires urgent action as the extent and rate of global warming depends on short-term mitigation and adaptation measures (IPCC, 2022b).

Main messages from WGIII:

According to WGIII, global greenhouse gas (GHG) emissions must be reduced by 50% by 2030 compared to current levels if we want to limit the temperature increase to 1.5°C by the end of the century. What is of concern is the fact that, average annual emissions over the period 2010-2019 have never been higher in human history. But fortunately, experts say that there are solutions in all sectors and regions to achieve this goal and avoid the worst consequences (IPCC, 2022c).

2.1.4.1 The energy sector in the AR6

As illustrated in Figure 4, global energy system remains the largest contributor to global anthropogenic emissions in 2019. Indeed, it amounts to 20 GtCO2-eq which represents 34% of global 2019 emissions (IPCC, 2022a)[2]. The growth of energy systems CO2 emissions has slowed down from 2.3% (2000-2010) to 1% (2010-2019). The key drivers for this slowdown between 2010-2019 are declining energy intensities (energy per unit of GDP) and declining carbon intensity of energy (CO2 from fossil fuel combustion and industrial process). This observation is mainly due to fuel switching from coal to gas, reduction in coal usage and expansion of renewable energies (IPCC, 2022c). In regard of this dissertation, it is interesting to note that the switch from coal to natural gas has helped slow the growth of CO2 emissions from the global energy system. This "switch" role will be discussed further in the first scientific article.

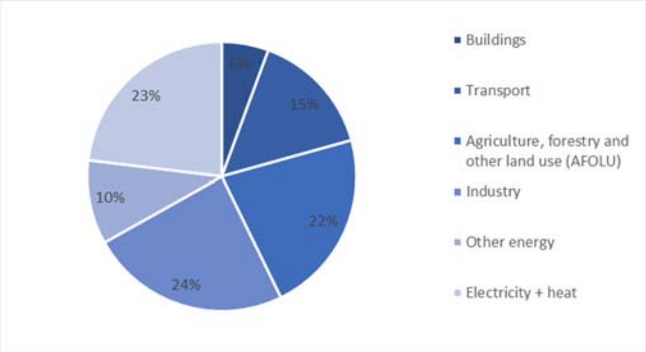

Figure 4: Anthropogenic emissions by sector in 2019

Source: author. Numbers from IPCC. (2022). Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.001.

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[2] 24% (14GtCO2-eq) from industry, 22% (13GtCO2-eq) from agriculture, forestry and other land use (AFOLU), 15% (8.7 GTCO2-eq) from transport and 6% (3.3 GtCO2-eq) from buildings

A new aspect presented in the report is the fact that the cumulative CO2 emissions projected from existing and currently planned fossil fuel infrastructure is higher than the cumulative CO2 emissions allowing global warming to be contained to 1.5°C. In other terms, it means that in order to limit global warming to 1.5°C, new coal installations without carbon capture and storage (CCS) should be cancelled and other existing fossil fuel-based power sector infrastructure should be decommissioned or reduced (use of CCS and or switch to low-carbon fuels) before the end of their lifetime (IPCC, 2022c). In the context of this thesis, this means that the construction of infrastructure solely dedicated to the energy carrier natural gas should be avoided. The use of existing infrastructure should be preferred and new infrastructure should be constructed with the aim of accommodating renewable or carbon neutral gases.

That new aspect has been explored using different scenarios. Indeed, composition of the future global energy system such as phasing-out of fossil fuel, future energy demand and the use of net negative emission are key elements used in the IPCC scenarios representing possible climate futures. The scenarios used in the AR6 are presented in the next section.

2.1.4.2 The AR6 Scenarios

In all its reports, the IPCC presented scenarios in order to represent possible climate futures. The IPCC did not develop those scenarios, they assessed and selected climate change scenarios elaborated by scientists around the world. The chosen scenarios have specific characteristics that represents some of the key findings of the assessment.

2.1.4.2.1 Shared Socio-economic Pathways (SSPs) from WGI

Among the literature of climate models, the working group I selected a set of five different illustrative climate scenarios. Those scenarios have differing end-of-century outcomes because they consider different socioeconomic assumptions driving the emissions and other forcing inputs but also different level of climate change mitigation. Those scenarios are called shared socio-economic pathways (SSP). The temperature outcomes of those five SSP’s are illustrated in Table 4. SSP1-1.9 and SSP 1-2.6 have respectively an outcome of global warming (best estimate) of less than 1.5°C degree and 2°C degree at the end of the century. Their CO2 emissions reach net zero around 2050. The three others (SSP 2-4.5, SSP3-7.0 and SSP5-8.5) exceed the two-degree limit with respectively 2.7°C, 3.6°C and 4.4°C rise in global air surface temperature by 2100.

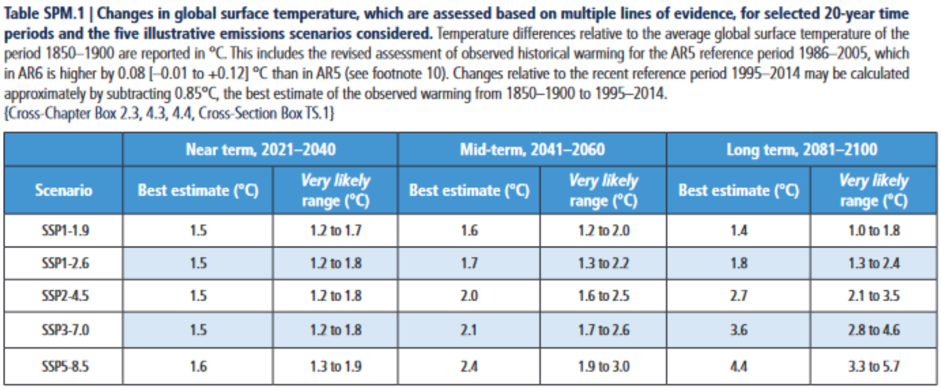

Table SPM.1 | Changes in global surface temperature, which are assessed based on multiple lines of evidence, for selected 20-year time periods and the five illustrative emissions scenarios considered. Temperature differences relative to the average global surface temperature of the period 1850–1900 are reported in °C. This includes the revised assessment of observed historical warming for the AR5 reference period 1986–2005, which in AR6 is higher by 0.08 [–0.01 to +0.12] °C than in AR5 (see footnote 10). Changes relative to the recent reference period 1995–2014 may be calculated approximately by subtracting 0.85°C, the best estimate of the observed warming from 1850–1900 to 1995–2014.
{Cross-Chapter Box 2.3, 4.3, 4.4, Cross-Section Box TS.1}

	Near term, 2021–2040		Mid-term, 2041–2060		Long term, 2081–2100	
Scenario	Best estimate (°C)	*Very likely* range (°C)	Best estimate (°C)	*Very likely* range (°C)	Best estimate (°C)	*Very likely* range (°C)
SSP1-1.9	1.5	1.2 to 1.7	1.6	1.2 to 2.0	1.4	1.0 to 1.8
SSP1-2.6	1.5	1.2 to 1.8	1.7	1.3 to 2.2	1.8	1.3 to 2.4
SSP2-4.5	1.5	1.2 to 1.8	2.0	1.6 to 2.5	2.7	2.1 to 3.5
SSP3-7.0	1.5	1.2 to 1.8	2.1	1.7 to 2.6	3.6	2.8 to 4.6
SSP5-8.5	1.6	1.3 to 1.9	2.4	1.9 to 3.0	4.4	3.3 to 5.7

Table 4: Five illustrative emissions scenarios
Table SPM.1 in IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY,USA, pp. 3–32, doi:10.1017/9781009157896.001.

Those scenarios are then used by complex earth system models to reproduce different aspects of climate change. An example is presented in Figure 5 where each scenarios have a different impact on global surface temperature change relative to 1850-1900, September Arctic sea area, global ocean surface pH and global mean sea-level change relative to 1900.

Human activities affect all the major climate system components, with some responding over decades and others over centuries

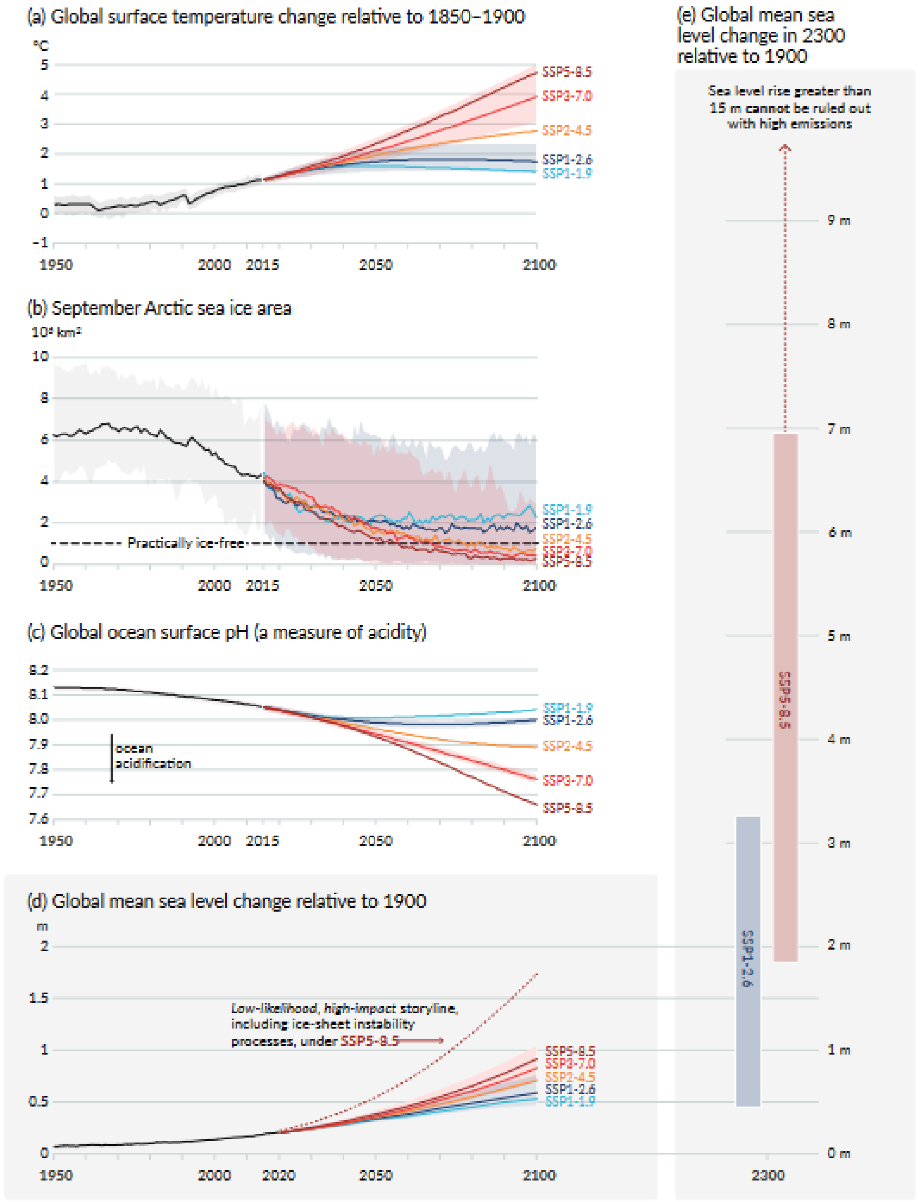

Figure SPM.8 | Selected indicators of global climate change under the five illustrative scenarios used in this Report

The projections for each of the five scenarios are shown in colour. Shades represent uncertainty ranges – more detail is provided for each panel below. The black curves represent the historical simulations (panels a, b, c) or the observations (panel d). Historical values are included in all graphs to provide context for the projected future changes.

Figure 5: Selected indicators of global climate change under the five illustrative scenarios Figure SPM.8 in IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY,USA, pp. 3−32, doi:10.1017/9781009157896.001.

2.1.4.2.2 The 7 illustrative (mitigation) pathways from WGIII

The working group III assessed thousands modelled emission pathways and scenarios submitted to the IPCC's Sixth Assessment Report database. Those scenarios, generated by integrated assessment models (IAMs), project evolution of GHG emissions based on assumption about future socio-economic conditions and related mitigation measures. Scenarios were then assigned to 8 climate scenario categories, labelled C1 through C8, ranging from a warming below 1.5°C to a warming above 4°C. Those assignments are based on the use of climate model emulators which provide only global average temperature changes (in contrast to SSPs from WGI which provide various aspects of climate change) (Chandrasekhar et al., s. d.).

In addition to those climate categories, five archetypes illustrative mitigation pathways (IMPs) were defined. Each of them representing different combinations of sectoral mitigation strategies consistent with a given warming level. They illustrate hypothetical future shaped by human choice. They help us reflecting on elements such as current policies, action to take to reach a specific temperature limit, the consequences of delay, etc (Pathak, et al., 2022).

Five of them represent important mitigation strategies that limit warming to below 2C or to 1.5C (see Table 5). Each of them present different feature such as a heavy reliance on renewables (ren), a strong energy demand reduction (LD), an extensive use of carbon dioxide removal (CDR), a broader sustainable development (SP) and a less rapid and gradual strengthening of near-term mitigation actions (GS). The two other illustrative pathways represent outcomes under policies in place today (CurPol) and outcomes if 2030 commitments are met but limited additional climate policies are enacted (Mod-Act) (IPCC, 2022c).

Climate category	**Description**	**Illustrative Pathways**	**SSPs**	**# scenarios**	**Cumulative CO2** (GtCO2 2020-2100, median*)	**Peak CO2 emissions** (median five-year interval*)	**Peak warming** (°C, 50% probability*)	**2100 warming** (°C, 50% probability*)
C1	Below 1.5C with no or limited overshoot	SP LD Ren	SSP1-1.9	97	320 [-210-570]	2020-2025 [2020-2025]	1.6 [1.4-1.6]	1.3 [1.1-1.5]
C2	Below 1.5C with high overshoot	Neg		133	400 [-90-620]	2020-2025 [2020-2030]	1.7 [1.5-1.8]	1.4 [1.2-1.5]
C3	Likely below 2C	GS	SSP1-2.6	311	800 [510-1140]	2020-2025 [2020-2030]	1.7 [1.6-1.8]	1.6 [1.5-1.8]
C4	Below 2C			159	1’160 [700-1490]	2020-2025 [2020-2030]	1.9 [1.7-2.0]	1.8 [1.5-2.0]
C5	Below 2.5C			212	1’780 [1’260-2’360]	2020-2025 [2020-2030]	2.2 [1.9-2.5]	2.1 [1.9-2.5]
C6	Below 3C	Mod-Act	SSP2–4.5	97	2’790 [2’440-3’520]	2030-2035 [2020-2090]	Does not peak by 2100	2.7 [2.4-2.9]
C7	Below 4C	Cur-Pol	SSP3–7.0	164	4’220 [3’160-5’000]	2085-2090 [2040-…]	Does not peak by 2100	3.5 [2.8-3.9]
C8	Above 4C		SSP5–8.5	29	5’600 [4’910-7’450]	2080-2085 [2070-…]	Does not peak by 2100	4.2 [3.7-5.0]
5th–95th percentile interval in square brackets								

Table 5: Characteristics of scenarios in each of the climate categories, including link between categories, illustrative pathways and SSPs

Source author: information from Table SPM1 in IPCC, 2022c: Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.001.Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.

Table 5 represents the different climate categories outcomes and the relationship with the illustrative pathways and the corresponding SSPs from WGI. It is interesting to point out that, for categories from C1 to C5, the median five-year interval at which CO2 emissions peak is 2020-2025. Another interesting aspect is that Mod-Act appears in the climate category "Below 3°C" and CurPol in the climate category "Below 4°C". In other words, the median value of the 97 scenarios illustrating outcomes where 2030 worldwide mitigation commitments are met is still 2.7°c of global warming by 2100. Furthermore, the median value of the 164 scenarios illustrating outcomes under policies in place today is 3.5°C of global warming by 2100.

The key characteristics in terms of energy system of each of the seven illustrative pathways are presented in Table 6 and illustrated in Figure 6. In three illustrative mitigation pathways limiting warming to below 1.5°C (Ren, LD and SP) we can observe a sharp reduction of emissions related to fossil fuel and a limited use of negative emissions. The slow fossil fuel phaseout of the scenarios Neg is balanced by the high use of BECCS (Bioenergy with carbon capture and storage) in order to still limit warming to below 1.5°C.

Illustrative pathways (Ips)		**Fossil-fuels phase out**	**Future energy demand**	**Carbon Dioxide Removal (CDR)**
CurPol	outcomes under policies in place today	fossil fuel remains important	high future energy demand	Limited deployment of LUC
ModAct	countries meet their 2030 commitments, but with little additional climate action	moving away from coal, growth of renewables	high future energy demand	limited deployment of BECCS and LUC
GS	gradual strengthening of current policies	slow fossil fuel phaseout	high future energy demand primarily met by renewables	fair amount DAC, BECCS and LUC
Neg	extensive use of net-negative emissions	slow fossil fuel phaseout	high future energy demand met primarily by renewables	relies heavily on BECCS
Ren	high renewable	rapid fossil fuel phaseout	moderate energy demand met primarily by renewables	limited deployment of BECCS and LUC
LD	low demand	rapid (the fastest) fossil fuel phaseout	low future energy demand	Limited deployment of LUC
SP	shifting development	rapid fossil fuel phaseout	low future energy demand	limited deployment of BECCS and LUC
LUC: land use change, BECCS: biomass & bioenergy with carbon capture and storage, DAC: direct air capture				

Table 6 : Key energy system characteristics of the seven illustrative pathways

Source: author. Information from IPCC. (2022a). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.

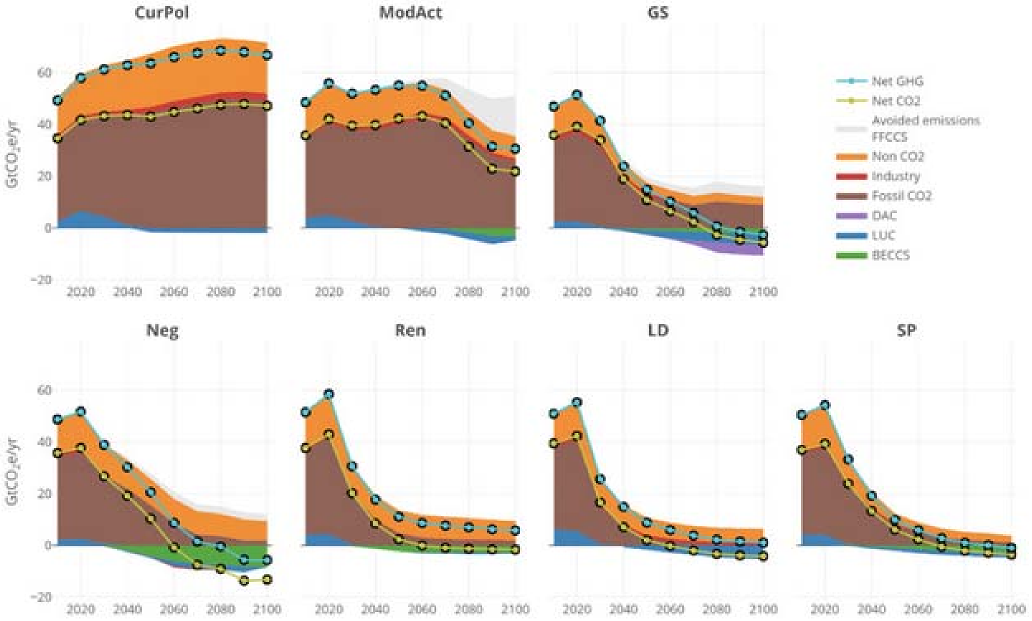

Figure 6: The residual fossil fuel and industry emissions, net land-use change, CDR, and non-CO2 2 emissions (using AR6 GWP100) for each of the seven illustrative pathways

Figure 3.7 in IPCC, 2022a: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.

Figure 7 illustrates the different primary energy use for the different illustrative mitigation pathways in 2020, 2050 and 2100. We can observe a total phase-out of coal in 2050 and 2100 for the three most stringent illustrative pathways (Ren, LD and SP). Oil and gas are still a little present in 2050 but we can observe a nearly total phase out in 2100. Concerning the Neg illustrative pathways, there is not a complete phase out either for gas and oil or coal both in 2050 and 2100.

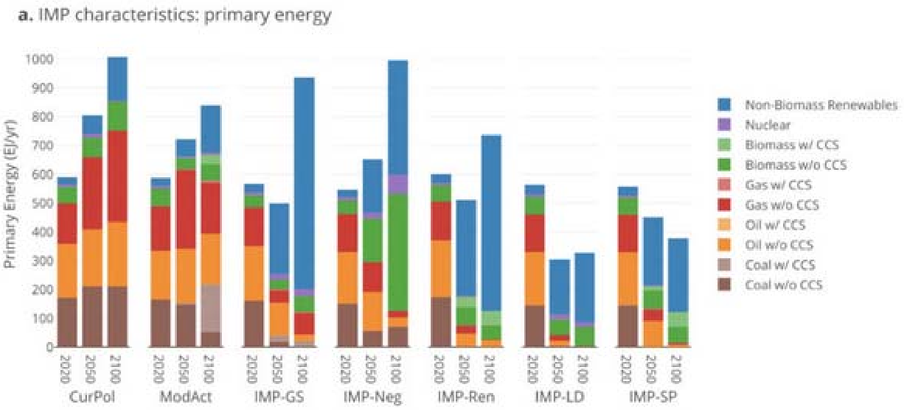

Figure 7: Primary energy use for the different Illustrative Pathways

Figure 3.16 in IPCC, 2022a: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.

2.1.5 Conclusion

In this chapter, the main international climate negotiations have been presented with their respective objectives. The way in which the IPCC assessment reports have been used as a basis for these negotiations has also been discussed. Finally, the content of the latest IPCC assessment report (AR6) was presented. This led to several observations important for the rest of the dissertation. First, the global energy system remains the largest contributor to global anthropogenic emissions. It is therefore crucial to transform the global energy systems in order to limit global warming. Second, the different scenarios of the AR6 allowed us to discover possible climate future depending on different future energy systems. We saw that current policies and 2030 international commitments scenarios are not sufficient to contain global warming to acceptable levels. Moreover, global greenhouse gas (GHG) emissions must be reduced by 50% by 2030 compared to current levels if we want to limit the temperature increase to 1.5°C by the end of the century. Therefore, more needs to be done to transform energy systems and it need to be done quickly. Regarding the use of fossil fuel in a carbon neutral future, the AR6 says that, with a limited used of carbon dioxide removal, a sharp reduction of their consumption by 2050 is necessary. However, in those scenarios oil and gas are still a little present in 2050 but we can observe a nearly total phase out in 2100. In addition, existing fossil fuel-based power sector infrastructure should be decommissioned or reduced (use of CCS and or switch to low-carbon fuels) before the end of their lifetime. Finally, another important aspect is the fact that the switch from coal to gas, as well as reduction in coal usage and expansion of renewables energies have slowed down the growth of energy systems CO2 emissions. This specific role, the switch from coal to gas is further discussed in the first scientific paper of this dissertation.

2.2 Transition to a low carbon energy-system

As stated earlier, an increasing number of countries have embarked on a transition to a low-carbon energy system. It means that they will need to transition from an energy system that relies heavily on fossil fuels such as coal, oil and natural gas to an energy system that relies mainly on renewable energy. Many energy transitions have occurred during the past. The first major being the transition from wood to fossil fuels during the Industrial Revolution. Most of these transitions have lasted over a long period of times (over a century or longer) (Solomon & Krishna, 2011). However, according to the last IPCC report (IPCC, 2022a), this century energy transition will need to be more rapid as emissions must be reduced by 50% by 2030 compared to current levels if we want to limit the temperature increase to 1.5°C by 2100. In addition, the new energy system will have to be secure, take into account the necessity of preserving the environment and be fair within the society in terms of accessibility and affordability. These three elements are known to be the three sides of the Energy Trilemma (see Figure 8). According to the World Energy Council (2021), each of these three elements are recognized as equally important for a country to reach prosperity and competitiveness. Countries around the world have different contexts in terms of natural resources, geography and socio-economic system. It is on these contexts that their energy system is currently built. Therefore, each country must find its own successful energy transition path (World Energy Council, 2021).

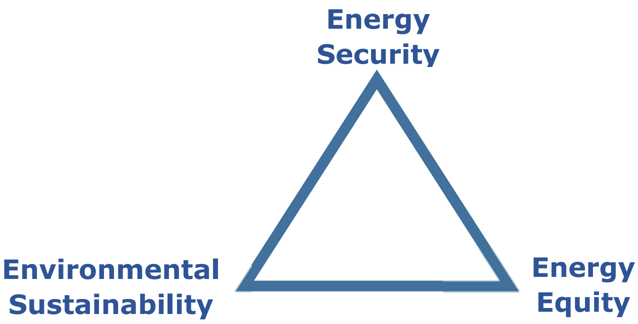

Figure 8: The Energy Trilemma
Source: author. Inspired from *(World Energy Council, 2021)*: *World Energy Council. (2021). World Energy Trilemma Index 2021. World Energy Council 2021. . Used by permission of the World Energy Council*

A final important aspect to mention when talking about energy transition is the link between energy consumption and GDP. Indeed, until now, economic growth has gone hand in hand with an increase in fossil fuel consumption. A great many studies have analysed this relationship in order to understand the direction of causality between these two elements (Menegaki, 2014). The transition to an energy system would therefore imply a decoupling of the two (Haberl et al., 2020) or even a degrowth (Kalimeris et al., 2014). The transformation of a country's energy system is therefore all the more complex because its economy was built on the consumption of fossil fuels.

2.3 The case of Switzerland

2.3.1 Global warming in Switzerland

Is Switzerland getting warmer? The answer is yes. Because of its latitude and distance from the oceans, the country is particularly affected by global warming. Indeed, while the global average is 1.1°C, the average annual temperature has risen by more than 2.1°C since measurements began in 1864 in Switzerland (MétéoSuisse, 2022). It is mainly during the last 10 years that this increase has manifested itself (see Figure 9). This increase in temperature is observed in all regions of the country (MétéoSuisse, 2020). The number of tropical days (temperature >= 30°C) has continuously increased in recent years, while the number of frost days (temperature <=0°C) has decreased considerably.

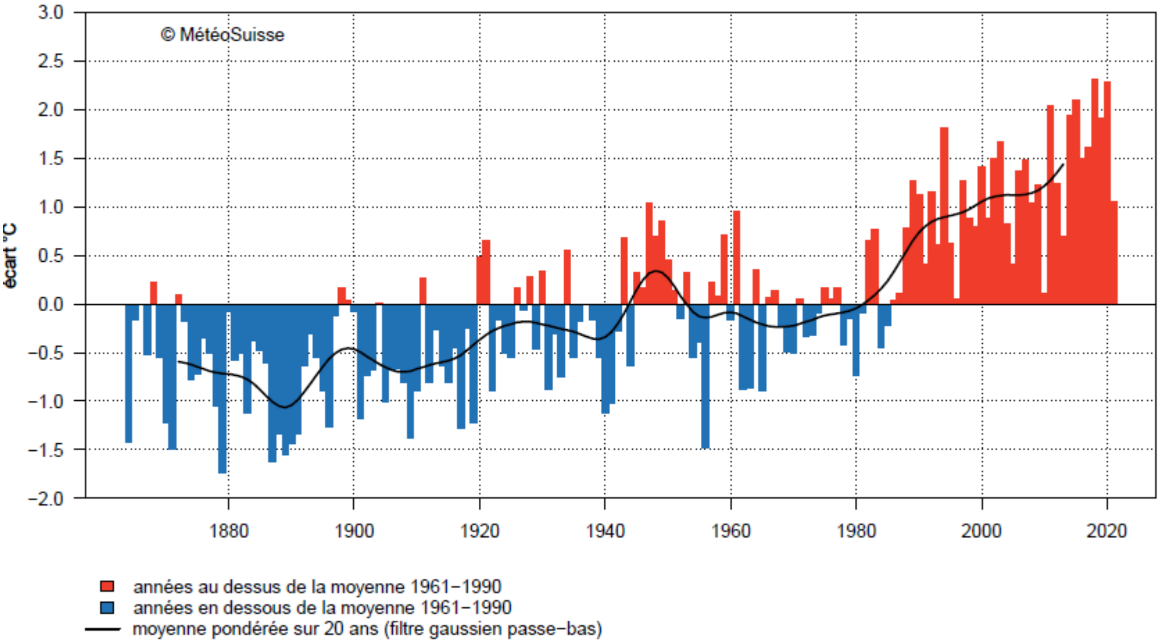

Figure 9 : Temperature in Switzerland 1864-2021
From MétéoSuisse, 2020 : Evolution de la température et des précipitations. https://www.meteosuisse.admin.ch/home/climat/changement-climatique-suisse/evolution-de-la-temperature-et-des-precipitations.html?filters=ths200m0_south_year_1864-smoother).

In a future where GHG emissions continue to rise unrestricted, Switzerland will have drier summers, heavier precipitation, more tropical days and winters with little snow (MétéoSuisse, 2020).

2.3.2 GHG emissions in Switzerland

What are the GHG emissions in Switzerland made up of? Mainly carbon dioxide (CO2) but also methane and nitrous oxide. According to the GHG emissions inventory, 79.1% of the 43.4 million tonnes of CO2 equivalents (CO2eq) emitted in 2020 were CO2. This was mainly due to the use of fossil fuels, but also to certain industrial processes. Methane (CH4) represents 10.6% of the GHGs emitted and comes mainly from agricultural activities and waste management, but also, to a lesser extent, from the natural gas network and from methanisation installations. Nitrous oxide (N2O), mainly linked to agricultural activities, represents 6.7% of GHG emissions and synthetic gases (HFCs, PFCs, SF6, NF3) 3.6%. The latter are mainly used as refrigerants and electrical insulators. Synthetic gases are the only ones whose emissions have increased considerably compared to the 1990 level. Indeed, the trend for the other three has been downwards since 1990 (OFEV, 2022).

Transport[3] and buildings are the two sectors with the largest share of GHG emissions. Indeed, they represented, respectively, 31.6% and 23.9% of emissions in 2020. Emissions from the building sector are related to households (16.4%) and services (7.5%). The rest of the emissions came from the industry sector (24.8%), agriculture (14.6%), synthetic gases (3.6%) and waste (1.6%). Figure 10 below shows the evolution of the emissions of the above-mentioned sectors from 1990

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[3] Excluding international air and sea transport

to 2020. A downward trend can be observed in the buildings (households + services), industry and transport sectors. It is also interesting to observe the impact of the coronavirus-related restriction measures, as emissions from the transport sector have decreased considerably between 2019 and 2020 (OFEV, 2022).

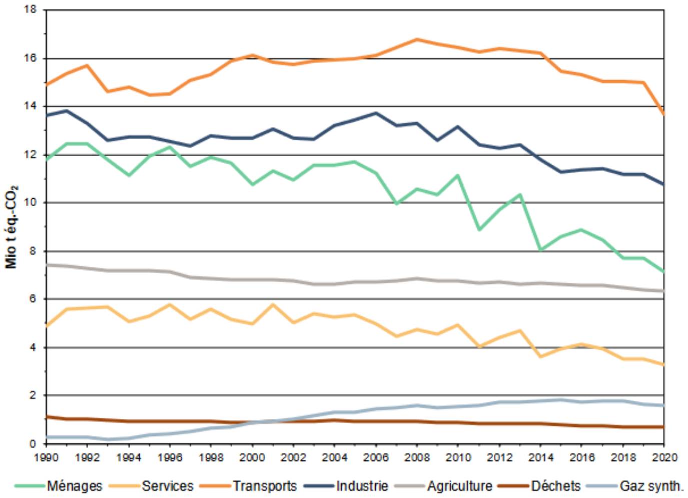

Figure 10: GHG emission trends by sector
Figure 2-2 in OFEV, 2022 : Indicateurs de l'évolution des émissions de gaz à effet de serre en Suisse. 1990-2020.

Swiss CO2, CH4 and N2O emissions have been slowly decreasing for several years and amounted to 43.4 million tonnes of CO2 equivalents (CO eq) in 2020 (53.97 in 1990). However, the 2020 figures should be taken with caution as GHG emissions were exceptionally low due to the slowdown in activity caused by the coronavirus pandemic and a less cold winter (OFEV, 2022).

On a per capita basis, this represents 5.0 tonnes of CO2e per inhabitant in 2020 (8.1 in 1990). This value is below average compared to other industrialized countries such as Germany, Great Britain and Italy. However, the picture changes when we take into account all the emissions for which the country is responsible (imports of goods) and not just those emitted on its territory. In fact, the country's greenhouse gas footprint (domestic emissions + imports - exports) amounted to 109 million tonnes of CO2e in 2019, or 13 tonnes of CO2e per capita. The share of emissions generated abroad amounted to 64% of the total (OFEV, 2022).

2.3.3 Swiss climate policy

Switzerland committed itself to reducing its greenhouse gas emissions at the international level by ratifying the Kyoto Protocol in 2003 (see Figure 11). The objective is to reduce its greenhouse gas emissions by 8% from 1990 levels between 2008 and 2012. At the national level, the country has included in the CO2 law a target to reduce its greenhouse gas emissions by 10% compared to 1990 by 2010. This law is the foundation of the country's climate policy. This first version of the law focused on measures to reduce emissions from fossil fuels. These first objectives (national and international) have been successfully achieved (OFEV, s. d.-a).

For the second commitment period of the Kyoto Protocol, Switzerland has committed to reduce its greenhouse gas emissions by 20% compared to 1990 by 2020. The country has set the same target in its second version of the CO2 law, but these reductions must be achieved exclusively within the country. Milder weather conditions in 2020 and the measures taken to contain the coronavirus pandemic have significantly reduced greenhouse gas emissions but have not been sufficient to meet the national target. However, the target for the second commitment period of the Kyoto Protocol was still reached thanks to the emission reductions achieved in the context of projects abroad (OFEV, s. d.-b).

By ratifying the Paris Agreement, Switzerland has committed to halve its greenhouse gas emissions by 2030 compared to their 1990 level. The country wanted to implement this objective through a total revision of the CO2 Act. However, the Swiss population rejected the revision of this law in the popular vote of June 13, 2021. Following this rejection, the Parliament adopted a transitional regulation that requires an additional reduction of 1.5% per year compared to 1990 for the period until 2024 (Conseil Fédéral, 2022). The Federal Council has put out for consultation a new draft law (Conseil Fédéral, 2021b).

The Paris Agreement also requires the Parties to develop climate strategies for 2050. To meet this requirement, the Federal Council adopted Switzerland's Long-term Climate Strategy on January 27, 2021. This strategy outlines the path to achieve the goal of climate neutrality by 2050 (Conseil Fédéral, 2021a).

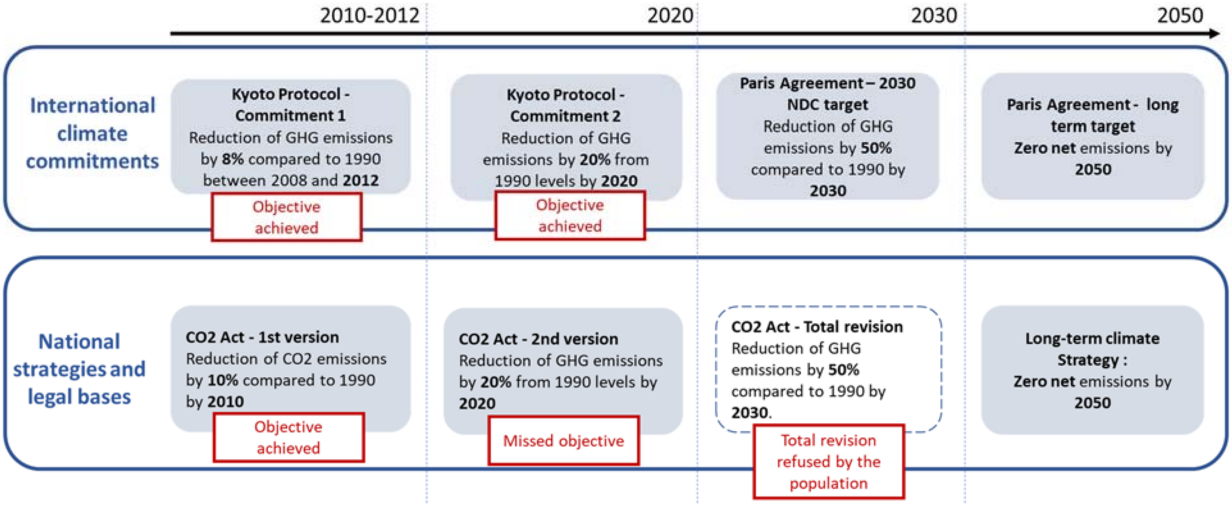

Figure 11: Swiss climate policy
Source: author

2.3.4 The Swiss energy system

2.3.4.1 Today

Today, the Swiss energy system relies heavily on the consumption of fossil fuels. In fact, the consumption of oil accounts for 43.4% of final energy consumption in 2021, natural gas 15.4% and coal 0.5%, i.e. a total of 59.3% (see Figure 12). Electricity represents 26.3% of final energy consumption and wood 5.8%. The rest of the consumption is covered by district heating (2.9%), industrial waste (1.5%) and other renewable energies (4.2%). (OFEN, 2022b)

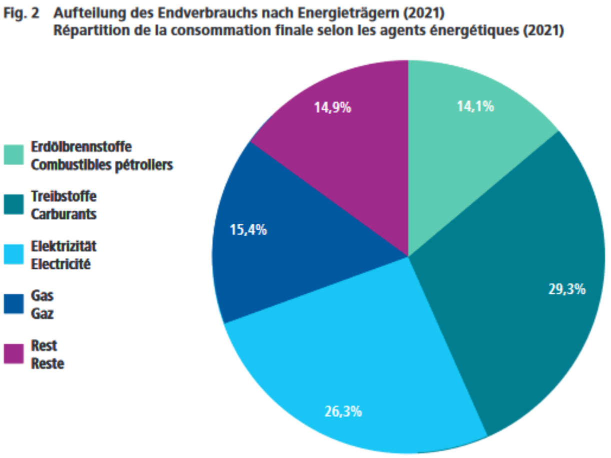

Figure 12: Final energy consumption by energetic agent
Figure 2 in OFEN, 2022b : Statistique Globale Suisse de l'énergie 2021

The Swiss power production is already almost CO2-free. Indeed, Switzerland's power production is mainly ensured by run-of-river and storage hydroelectric power plants (61.5%) and nuclear power plants (28.9%) (see Figure 13). The remainder is provided by renewable energies such as solar, wind and thermal power plants powered by renewable energies (7.7%) and the balance by conventional thermal power plants powered by fossil fuels (1.9%). (OFEN, 2022a). Switzerland still has four nuclear power plant reactors (Beznau 1 and 2, Gösgen and Leibstadt). The Mühleberg nuclear power plant was shut down in December 2019 and is being decommissioned (OFEN, 2022a).

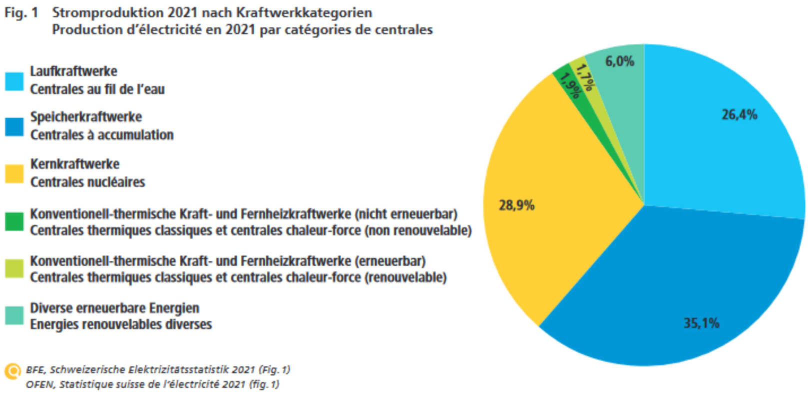

Figure 13 : Electricity generation by plant category
Figure 1 in OFEN, 2022a : Statistique Suisse de l'électricité 2021

Given the importance of fossil and fissile energy in Switzerland's energy supply, the country is highly dependent on foreign sources. In 2020, Switzerland was 72% dependent on foreign countries for its energy supply. (OFS, 2021). With regard to electricity, in 2021, Switzerland imported (31.5 billion kWh) more electricity than it exported (29.1 billion kWh). Imports took place mainly during the winter period, while exports during the summer period (OFEN, 2022a).

2.3.4.2 The Swiss trilemma Score

Switzerland achieves a score of 83.8/100 on the Energy Trilemma, which ranks it second (1^st^ place: Sweden, 3^rd^ place: Denmark). The World Energy Council, believes that Switzerland performs well in all three elements: energy security (66.3/100), environmental sustainability (88.2/100) and energy equity (98/100). This score is high thanks to past energy policies. However, current policy decisions will have an impact on the country's future score. Indeed, the World Energy Council expects a drop in the score for security of supply due to a dependence on electricity imports (World Energy Council, 2021).

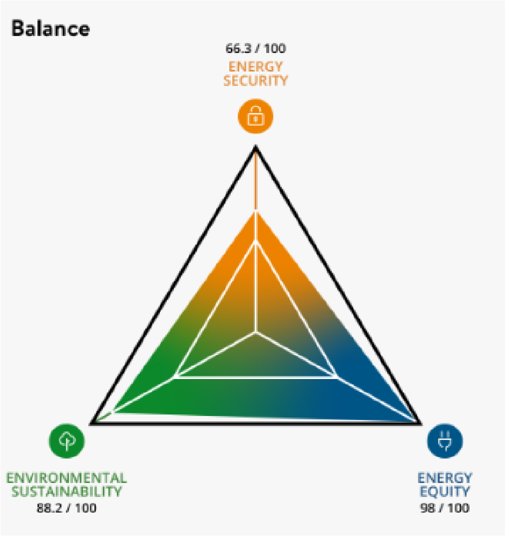

Figure 14: The Swiss Energy Trilemma Score
Figure 1 in World Energy Council, 2021 : Switzerland

2.3.4.3 Swiss Energy Policy : Energy Strategy 2050

In the wake of the Fukushima nuclear accident, Switzerland has committed itself to an energy transition through its Energy Strategy 2050. This strategy is based on three pillars: reducing energy consumption and increasing energy efficiency, promoting renewable energies and phasing out nuclear energy (OFEN, 2013). This last pillar means that the country will have to face the challenge of replacing nearly 30% of its domestic power generation (28.9% in 2021) (OFEN, 2022a) without putting at risk its climate mitigation policy. On 21 May 2017, the Swiss people accepted in a popular vote the revision of the Federal law on Energy (LEne) in connection with the Energy Strategy 2050. In this new Law on Energy, the following target values have been set:

- Electricity production from renewable energies (without hydropower): 4400 GWh in 2020 and 11400 GWh in 2035 (art. 2. al. 1)
- Electricity production from hydropower : 37400 GWh in 2035 (art. 2. al. 1)
- Average energy consumption per capita compared to 2000: -43% by 2035 (art. 3. al. 1)
- Average electricity consumption per capita compared to 2000: -13% by 2035 (OFEN, 2020b) (art. 3. al. 2)

In the energy strategy 2050, the topic of a potential special role for natural gas and its infrastructure has not been addressed. Indeed, no differentiation has been made between oil, gas or coal.

2.3.4.4 Tomorrow : Energy perspective 2050+

In 2020, the Swiss Federal Office of Energy published its Energy Outlook 2050+. These are scenarios for the development of the country's energy mix. These scenarios were developed with a view to the country's goal of carbon neutrality by 2050. The aim of these scenarios was to assess whether the climate objectives of carbon neutrality were compatible with the current energy strategy and whether they were technically feasible at affordable costs. This 2050+ energy perspective was used to develop Switzerland's long-term climate strategy. The results show that the country is able to transform its energy supply to achieve climate neutrality.

Zero Base Scenario
In the baseline scenario (Zero Base) for achieving carbon neutrality by 2050, a 98% reduction in fossil fuel consumption is expected by 2050. The country's energy autonomy would then be 75%, i.e. an increase by three of the current level. The remaining imported energy would mainly come from Europe and would consist of electricity, biogas, hydrogen and renewable fuels. The thermal consumption of buildings should be divided by 2 and the residual demand covered by the use of heat pumps (1.5 million) and district heating. The heavy traffic will be powered mainly by bioenergy and hydrogen. Biomass is used for process heat. 7 PJ of hydrogen is produced at the run-of-river power plant sites.

Electricity consumption is expected to increase by 11% compared to the current situation (see Figure 15). In a transitional phase, imports will be needed to cover the production that was generated by nuclear power (13 TWh). In the long term, this will be covered by hydroelectric power plants (53%), photovoltaic (40%) and other renewable energies. In 2050, Switzerland would have a balanced annual electricity import/export balance as it would export up to 9TWh in summer but import the same amount in winter (see Figure 16). This future energy system will have an increased need for a source of flexibility which will mainly be provided by hydroelectric storage power plants and demand-side management.

Figure 6: Production d'électricité selon les technologies
Évolution de la production d'électricité annuelle selon les technologies dans le scénario ZÉRO base, variante stratégique «bilan annuel équilibré en 2050», en TWh

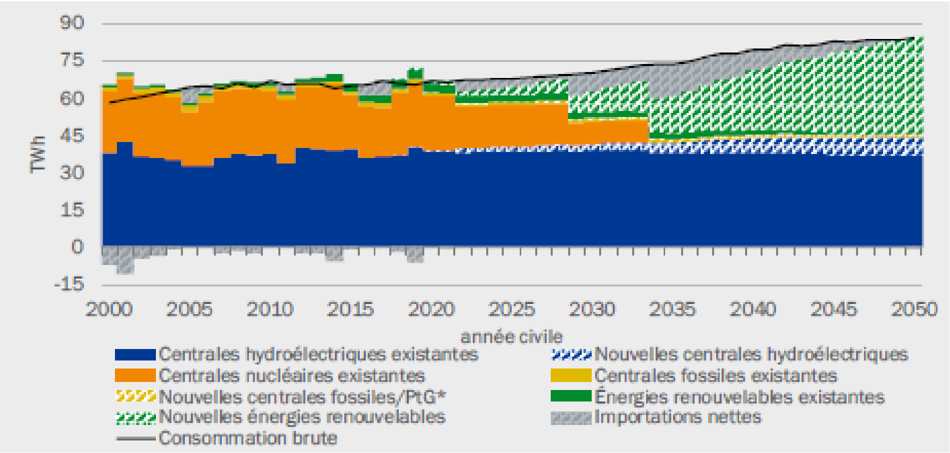

Figure 15: Evolution of electricity production (Zero Base scenario)
Figure 6 in (OFEN, 2020c): PERSPECTIVES ÉNERGÉTIQUES 2050+ RÉSUMÉ DES PRINCIPAUX RÉSULTATS

Figure 7: Bilan hiver/été
Évolution de la production brute d'électricité pendant le semestre d'hiver et d'été dans le scénario ZÉRO base, variante stratégique «bilan annuel équilibré en 2050», en TWh

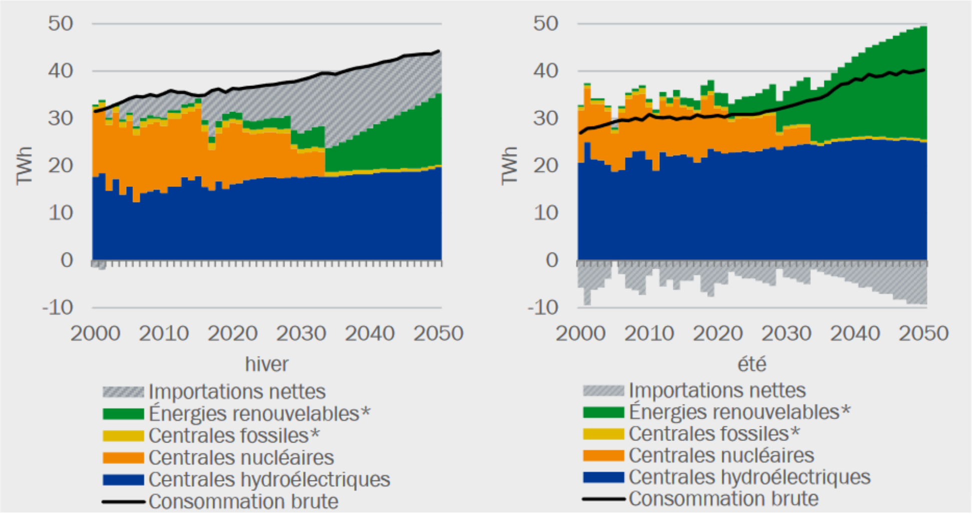

Figure 16: Evolution of electricity production in Winter and Summer (Zero Base scenario)
Figure 7 in (OFEN, 2020c): PERSPECTIVES ÉNERGÉTIQUES 2050+ RÉSUMÉ DES PRINCIPAUX RÉSULTATS

Scenarios Zero A, Zero B and Zero C

According to the results of the study, three variants can also be considered depending on technological developments (see Table 7). All of these variants also allow carbon neutrality to be achieved by 2050. The first variant, Zero A, considers a more intensive electrification of the energy system. Variant Zero B considers a more important role for biogas and syngas (power-to-gas/liquid/hydrogen). Finally, variant zero considers a more important use of heat networks and biofuels.

Zero Base	**Zero A**	**Zero B**	**Zero C**	**PEA** (Continuation of the current policy)
High level of energy efficiency, biomass potential fully exploited, high electrification, limited use of syngas and hydrogen.	Extended electrification of the energy system	Biogas and electricity-based gases play an important role as an energy agent, alongside electricity, in the energy system.	Heat networks and biogenic or electricity-based liquid fuels play an important role alongside electricity as energy sources in the energy system	Represents current energy and climate policy measures with a continuation of the technological development observed today.

Table 7: The different Energy Perspective 2050+ scenarios
Source : author. Defintions from (OFEN, 2020c): PERSPECTIVES ÉNERGÉTIQUES 2050+ RÉSUMÉ DES PRINCIPAUX RÉSULTATS

These variants have a different effect on the power import balance after the last nuclear power plant is shut down in 2034. Figure 17 compares the import balance of the different scenarios. This varies from 9 TWh for the zero B variant (biogas and syngas) to 14 TWh for the zero A variant (large electricity). All of the ZERO variants reach a balanced annual electricity import/export balance by 2050. In regard with this dissertation, it is interesting to point out the fact the that the scenario limiting the most the power import after the decommissioning of nuclear power plants is the scenario where biogas and syngas play an important role alongside electricity in the energy system.

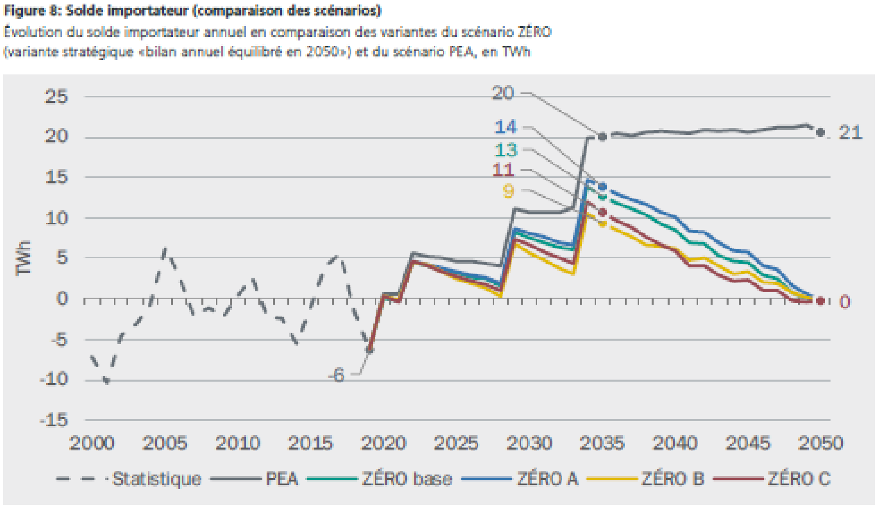

Figure 17: Import balance: comparison of scenarios
Figure 6 in (OFEN, 2020c): PERSPECTIVES ÉNERGÉTIQUES 2050+ RÉSUMÉ DES PRINCIPAUX RÉSULTATS

2.3.5 The Swiss gas industry

2.3.5.1 Natural gas

In 2020, final gas consumption in Switzerland was 34,833 GWh, which represents 15.1% of the country's final energy consumption. This proportion has changed slightly since it was 12% ten years ago (ASIG, 2022).

Natural gas is mainly used for heating purposes in households and services. These two sectors account for 42% and 22.2% of final consumption respectively. Its consumption is therefore strongly influenced by temperature. As illustrated in

Figure 18, the consumption of natural gas, and therefore its import, is much higher in winter than in summer. Natural gas is also used by industry (33.8%) for processes requiring steam, hot water, heat or cold. This consumption is rather constant over the year. Transport represents only 0.9% of the total consumption (ASIG, 2022).

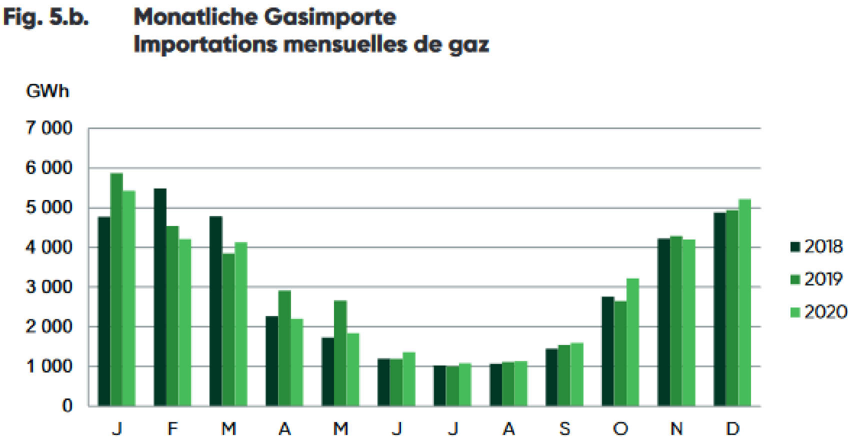

Figure 18: Natural gas imports over the months
Figure 5b in (ASIG, 2022): Association Suisse de l'Industrie Gazière Statistique 2021

Switzerland had 37 biogas plants that injected 418 GWh into the grid. This represents about 1% of the gas consumed in the country. Domestic biogas production has increased considerably, from only 64 GWh in 2010. Biogas sales amounted to 1456 GWh and were mainly covered by imports. When imports are taken into consideration, the share of biogas in the total gas consumed in Switzerland amounts to 4.2% (ASIG, 2022).

The industry has set voluntary targets for the share of renewable gas to be achieved. The first target is for 2030, by which time the share of renewable gas should be 30% of the domestic heating market. In 2040, this share should be 40% of the heating market. Finally, the gas industry aims to be supply neutral by 2050.

In 2020, natural gas imported into Switzerland came mainly from Russia (47%), Norway (24%), the European Union (19%) and Algeria (7%) (ASIG, 2022).

2.3.5.2 Natural gas infrastructure

Its pipeline network extends over 20,000 km. This is a value that has not changed in recent years. Three quarters of the Swiss population live in communities having access to the gas grid. The Swiss network is composed of two main levels of networks. The distribution network managed by about 100 local companies which supply natural gas to final consumers. The regional transmission network managed by four regional companies (Erdgas Ostschweiz, Gasverbund Mitelland, Erdgaz Zentralschweiz and Gaznat) which supply natural gas to local companies and industry. (Gasindustrie, s. d.).

In 2020, the amount of gas heating installations has decreased by about 2000 installations to 336'000. This is the first time that a decline has been observed. The number of combined heat and power plants has been decreasing for the last five years (ASIG, 2022).

Switzerland does not have any storage capacity on its territory, but has storage capacity abroad.

2.4 Conclusion

In this section, the Swiss context was presented. It shows that Switzerland is strongly impacted by global warming. The transport and buildings sectors are the main contributors to the country's GHG emissions. GHG emissions per capita within the country are rather low compared to other G20 countries. However, when GHG emissions from imported goods are taken into account, the balance sheet becomes much heavier. Indeed, about 2/3 of Switzerland's GHG emissions from consumption take place outside its territory. By signing the Paris Agreement, the country committed to reducing its emissions by 50% by 2030. However, the country has not yet succeeded in introducing this target in its CO2 law, as its draft law revision was rejected by the population in 2021.

The Swiss energy system is dependent on foreign countries for about ¾ of its energy. Despite this, Switzerland ranks among the top countries in the Energy Trilemma. However, the World Energy Council believes that Switzerland's dependence on imported electricity in winter will pose a threat to the country's security of energy supply in the future. Indeed, Switzerland has initiated a transformation of its energy system through the 2050 energy strategy. The country has committed itself to a gradual phase-out of nuclear power and will therefore have to replace around 30% of its electricity production. In the energy strategy 2050, the topic of a potential special role for natural gas and its infrastructure has not been addressed.

The Energy Outlook 2050+ has shown that it is possible to transform Switzerland's energy system to achieve carbon neutrality by 2050. It is technically feasible and affordable. To achieve this, for example, the thermal consumption of buildings will have to be halved. The closure of the last nuclear power plants is expected to generate a winter electricity import requirement of up to 14 TWh during a transitional phase. The scenario limiting the most the power import (9 TWh) after the decommissioning of nuclear power plants is the scenario where biogas and syngas play an important role alongside electricity in the energy system.

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Chapter III : Empirical part

Presents the empirical part of the dissertation. It is composed of three different papers.

A foreword from the author

Why a qualitative approach for the first article?

Because it is a very complex and sensitive research question. It was important to be able to address it as a whole and to anchor it in the reality of the Swiss context. I wanted to know what science had to say on the subject but not only that. I wanted to take the pulse of experts in the field of energy in Switzerland. Before starting this article, I was full of doubts. I was afraid to be confronted with actors who were sticking to their positions, each one anchored in their own reality. But I was really surprised to see how open-minded each of them was about this issue. Thanks to this, this first paper is a mine of information on this theme.

Why combined heat and power technology for the second and third article?

Because it is a proven technology that has been around for a long time. It can therefore be implemented on a large scale and quickly. Furthermore, it is a highly efficient energy conversion process with a high exergetic performance. Moreover, CHP can be fuelled with natural gas but also with renewable gases. It is therefore a simple technology that allows the coupling of electricity, gas and heat networks.

Paper I : What role can natural gas and its infrastructure play in the energy transition in Switzerland : a holistic approach

Simon, E., Ramseyer R, & Genoud, S. (2022, juillet). What role can natural gas and its infrastructure play in the energy transition in Switzerland : a holistic approach.

Abstract

Currently, natural gas plays an important role in the Swiss energy system. Indeed, it accounts for 15% (OFEN, 2020a) of final energy consumption and its network extends over 20,000 km (ASIG, 2021). As the country is committed to transforming its energy system in order to achieve climate neutrality by 2050, what will be the role of natural gas tomorrow? Is it possible to put its infrastructures at the service of the energy transition? In order to explore all the aspects of the question, we adopted a qualitative and holistic approach. We firstly realized a systematic literature review in order to identify the potential roles that natural gas and its infrastructure could take. Then, we transposed the roles identified in the literature to the Swiss context by looking at the official positions of the Confederation and the gas industry on this issue. Finally, in order to enrich these two visions, we conducted semi-structured interviews with 15 experts in the field of energy in Switzerland. We were able to identify the biggest challenges related to the Swiss energy transition: Electricity supply in winter as well as the slow decarbonization of the buildings sector. We also identified the extent to which natural gas and its infrastructure could address them. In the context of the Swiss energy transition, many issues remain to be clarified. A national strategy for the development of infrastructure and deployment of renewable gases, in particular hydrogen, is desired by most of our experts.

Key words

natural gas, energy transition, natural gas infrastructure, Switzerland, renewables gases, combined heat and power plant

1. Introduction

Currently, natural gas plays an important role in the Swiss energy system. Indeed, it accounts for 15% (OFEN, 2020a) of final energy consumption and its network extends over 20,000 km (ASIG, 2021). Moreover, the industry has developed expertise in key areas such as storage, renewable gases, and power generation. As the country is committed to transforming its energy system in order to achieve climate neutrality by 2050, what will be the role of natural gas tomorrow? Is it possible to put its infrastructures at the service of the energy transition?

Indeed, having the lowest combustion carbon intensity of the three major fossil fuels (IPCC, 2006), natural gas is often presented as the transitional fossil fuel. Indeed, it is often described as a companion to intermittent renewable energy as it can be a welcome source of flexibility for the power system. Moreover, its infrastructure might support the emergence of renewable gas such as biomethane, synthetic methane and hydrogen.

Determining the future role of natural gas and its infrastructure is a really complicated subject with lots of uncertainties. Most studies on the subject address only one or two aspects of the potential role of natural gas and its infrastructure. Therefore we wanted to adopt an integrative and qualitative approach in order to be able to grasp the problem in its entirety within the Swiss context. Our study aims at answering the following research questions:

1) What are the roles presented in the scientific literature for natural gas and its infrastructure in the context of a decarbonization of the energy system ?

2) What are the official positions of the Confederation and the Swiss gas industry regarding the future of natural gas and its infrastructure ?

3) What are the biggest challenges in the Swiss energy transition and how natural gas and its infrastructure could help addressing them ?

We developed a three-step methodology to answer this question (see Figure 19). Firstly, we realized a systematic literature review in order to identify the potential roles that natural gas and its infrastructure could take. Then, we transposed the roles identified in the literature to the Swiss context by looking at the official positions of the Confederation and the gas industry on this issue. Finally, in order to enrich these two visions, we conducted semi-structured interviews with 15 experts in the field of energy in Switzerland. It allowed us to identify the greatest challenges related to the Swiss energy transition and the extent to which natural gas and its infrastructure could address them. We also discussed the evolution of the gas infrastructure.

Figure 19 : the three parts of the research process
Source: author

The remainder of this paper is structured as follows: Section 2 presents the methodology. The results are then presented and discussed in Section 3. The paper concludes with section 4 with discussion and implication regarding the results.

2. Methodology

As stated earlier, we developed a four-step methodology to answer the research questions. For the systematic literature review (Figure 20), we used Web of Science database to access academic journals and conference proceedings. Searching "Natural gas", "energy transition", "bridge", "transition fuel" and "golden age" as keywords returned 136 results. We then filtered-out papers according to criteria presented in Figure 20. Finally, we add four papers specific to the Swiss context. The analysis of the 52 remaining papers allowed us to identify the potential roles that natural gas and its infrastructure could take. Then, we transposed the roles identified in the literature to the Swiss context by looking at the official positions of the Confederation and the gas industry on this issue.

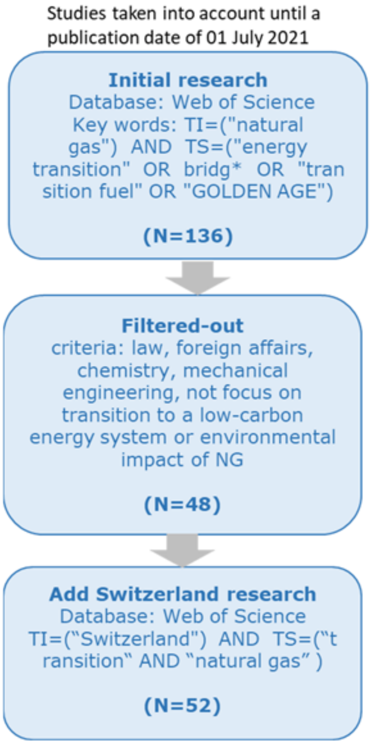

Figure 20: Systematic literature review
Source: author

Finally, semi-structured, in-depth individual interviews were conducted between June and September 2021 with fifteen Swiss energy experts. Interviews were conducted in French[4] and took place via video conference and face-to-face. Then, a thematic analysis based on the transcription of the audio recording was performed. It allowed us to identify the biggest challenges related to the energy transition in Switzerland and the extent to which natural gas and its infrastructure could address them. We also discussed the evolution of the gas infrastructure.

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[4] The quotations in the results section have been translated in English

Sample
2 politicians
5 federal, cantonal and municipal representatives
4 energy supply company managers
2 energy modelling scientists
2 members of security commission

Table 8 : sample

Methodological limitations

This study includes the perspectives of energy experts. Responses may be biased based on the participants' knowledge and their individual perspectives. As a result, their answer may not be representative. Indeed, a different sample could have led to slightly different results. This study being qualitative, the results are not generalizable and are limited to the Swiss context.

3. Results

3.1 Peer-reviewed literature

Compared to other fossil fuels, natural gas has some environmental advantages (lower carbon intensity and few fine particle emissions) and is a welcome source of flexibility with the development of intermittent renewable energy. This is why natural gas is often presented as the transition fuel, a bridge from the global fossil fuel energy system to a full renewable energy system (Delborne et al., 2020). Some authors assumed that this role could lead to an increase in natural gas demand for the next decades leading to a "golden age of natural gas" (Gillessen et al., 2019; Hauser et al., 2019; IEA, 2011a; Paltsev et al., 2011). However, there has been an intense debate among scientists about the legitimacy of natural gas in this "transition fuel" role. Indeed, determining the future role of natural gas is really complicated (Gürsan, 2019; McGlade et al., 2018). Through our literature review, we have therefore sought to identify the potential roles that natural gas and its infrastructure could take, the benefits presented by the proponents of transition fuel and the concerns presented by its detractors. The results of our analysis are synthesized in Table 9.

Role	Expected benefit	Concerns
Replacement of other fossil fuels (coal, oil)	Rapid GHG and other pollutants reduction	Unconventional gas Methane leakage Short vs long-term global warming potential of methane Delays in deployment of renewable energy Carbon lock-in Security of supply of natural gas
Compensation for the intermittency of variable renewable energies	Ensure flexibility of the energy system and its adequacy (security of supply)	
Promotion of the production, transport and storage of renewable and/or low-carbon gases	Favorize the development of renewable/low-carbon gases	Limited potential Blending, repurposing, or new hydrogen infrastructure

Table 9 : Roles of natural gas and its infrastructure identified in the scientific literature
Source: author

3.1.1 Role 1: Replacement of other fossil fuels – the switch from the use of coal/oil to natural gas

The first role that natural gas can play in the energy transition is to replace other fossil fuels. The role most often mentioned in the literature is that of using natural gas instead of coal for electricity production. The expected benefits of this switch are a direct reduction of greenhouse-gas emissions and an improvement of air quality (Gillingham & Huang, 2019). The improvement of the air quality through the abatement of Particulate Matter (PM) with the switch from coal to gas is a measure appreciated and supported by the population (Kim et al., 2018). Most of the studies have analysed the advantage and the drawback of this switch in the context of the USA and its shale gas boom (Healey & Jaccard, 2016; Paltsev et al., 2011). There, the switch contributed to important reduction of greenhouse gas emissions from electricity production (Cathles et al., 2012; Feng et al., 2016; Kotchen & Mansur, 2016; J. C. Peters, 2017). For some authors, it would reduce greenhouse gas emissions while increasing economic growth and security of supply (Aguilera & Aguilera, 2012). The switch also lead to an overall fall of power production carbon emissions in the UK (Wilson & Staffell, 2018) and in Iran (Hafeznia et al., 2017). According, to Wilson and Staffel (2018), switching from coal to gas in the power sector worldwide using only already existing infrastructure could buy precious time to slow the growth in cumulative carbon emissions. However, in general, switching to natural gas is not a sufficient measure on its own to achieve stringent climate objectives, it must be accompanied by other measures such as the development of renewable energies (Davis & Shearer, 2014; Hafeznia et al., 2017; IEA, 2011a; Paltsev et al., 2011; Wang-Helmreich & Lochner, 2012) or high carbon tax (Gillingham & Huang, 2019; Healey & Jaccard, 2016). Moreover, the benefit of the switch will also depend on the chosen technology to do so (Davis & Shearer, 2014; Hausfather, 2015). For instance, if the deployment of natural gas will be done alongside the use of carbon capture and storage (CCS) (Babaee & Loughlin, 2018; Das et al., 2021; McGlade et al., 2018). Moreover, this role of the switch is relevant in very high carbon energy systems such as in Iran (Hafeznia et al., 2017), China (Qin et al., 2018), India (Das et al., 2021) or Southeast Asia (Mohammad et al., 2021) and is less relevant in an already low carbon energy system (Hausfather, 2015; McGlade et al., 2018; Stephenson et al., 2012).

Switching is not only limited to electricity generation, but can also take place in other sectors. For instance, the switch from petrol engines to natural gas engines in Germany (Wang-Helmreich & Lochner, 2012) would result in significant emission reductions. In the UK and France, the switch to LNG for trucks will only have climate benefits if the efficiency of LNG vehicles is improved or biomethane is used (Langshaw et al., 2020; Ravigne & Da Costa, 2021). Switching from coal to gas in the residential sector would allow China to reduce its GHG emissions but also to improve air quality (Qin et al., 2018).

Methane leakage

Methane (CH4), the main component of natural gas, has a short atmospheric lifetime but it also has a high global warming potential (i.e. warming impact compared to CO2). In other terms, it is a much stronger greenhouse gas than CO2 but for a shorter period of time. In order to reach a carbon-neutral future, it is crucial to reduce both CO2 and CH4 emission in parallel. This is the reason why, to evaluate the lifecycle emissions of natural gas, one should not only consider the amount of GHG that are directly emitted as natural gas is burned but also fugitive methane emissions or leaks that occur during its extraction, transmission, storage and distribution(Fu et al., 2021). It is essential to quantify accurately those fugitive CH4 emissions from the natural gas system as, depending of its scope, the climate benefits of the switch from coal to gas could be offset (Stephenson et al., 2012). For some authors, it could even reverse the climate impact mitigation (Howarth, 2014; Howarth et al., 2011). For others it is unlikely that methane leakage would strongly undermine the climate benefits of the switch from coal to gas (Levi, 2013). Or that extremely high leakage rate (between 5.2% and 9.9%) are necessary for natural gas to become a greater mean forcing than coal (Hausfather, 2015). Finally, some think that fugitive emission associated with unconventional gas are overestimated by some studies (Cathles et al., 2012). Indeed, methane leakage abatement measures have been implemented since and many gas companies set the objective to reduce the leakage rate below 1% (Schneising et al., 2020). However, it seems that those objectives are, yet, far from being reached everywhere (Safaei et al., 2015; Schneising et al., 2020). Indeed, there are high differences of rate of fugitive emissions between world region or even between different field within the same region (Schneising et al., 2020). In this debate, an important aspect is the kind of natural gas analysed. Indeed, unconventional gas (tight gas, shale gas and coalbed methane) has a higher methane leakage rate than conventional natural gas (Howarth, 2014; Howarth et al., 2011). In addition, extraction (fracking) of unconventional gas can cause environmental damage and can have health impact through water contamination (Stephenson et al., 2012). It seems that, people did not feel that "the benefits of fracking outweigh its risks" and are concerns about methane leaks (Hazboun & Boudet, 2021, p. 1).

Opponents agree on one thing: there is not enough data on these fugitive emissions and further empirical data and investigation is necessary (Cathles et al., 2012; Howarth, 2014; Howarth et al., 2011; Levi, 2013; Safaei et al., 2015; Schneising et al., 2020; Stephenson et al., 2012). For Stephenson et al. (2012, p. 454), the degree of uncertainty regarding methane leakage is so high that even "the best available studies remain limited in their ability to inform responsible energy policy".

Short versus long term global warming potential of methane

Another aspect of the debate among scientists is the time horizon used to express the global warming potential of methane. Indeed, as stated earlier, CH4 is a much stronger greenhouse gas than CO2 but for a shorter period of time. The climate benefits of switching from coal to natural gas therefore will change greatly depending on the time horizon chosen for the analysis (20, 100 or 500 years) (J. C. Peters, 2017; Safaei et al., 2015; Zhang et al., 2016). Indeed, with a GWP calculated with a time horizon of 20 years, the warming impact of methane is 86 times higher than that of CO2, whereas it is 34 times higher than that of CO2 with a time horizon of 100 years (IPCC, 2006). For some authors, adopting a 20-year time horizon is essential given the need for action by 2030 to limit global warming to an acceptable level (Howarth, 2014; Howarth et al., 2011). For others, this short-term approach is not enough justified (Cathles et al., 2012).

Delays in adoption of renewable energy and carbon lock-in

Another concern regarding this transition role is the fact that it could redirect investments from renewable energy or low carbon technologies to natural gas infrastructure and causes delay in the adoption of renewable energies (Hausfather, 2015; Zhang et al., 2016). Indeed, inexpensive natural gas can compete against renewable energy. For instance, in Brazil, without proper policies, natural gas power plant could exceed hydropower power production capacities in a near future which would drive the country away from its climate objective (Vahl & Filho, 2015).

Those investments in natural gas infrastructure could lead in a carbon lock-in where the use of natural gas is extended. It can create barriers for the deployment of near-zero carbon technologies (Hausfather, 2015; Stephenson et al., 2012; Vahl & Filho, 2015; Wang-Helmreich & Lochner, 2012; Zhang et al., 2016). This could lead to a trap as investments conversion technologies can be used for 30 years and infrastructure more than 50 years (Brauers et al., 2021; Safari et al., 2019; Woollacott, 2020). According to Scharf et al. (2021), energy systems targeting high GHG abatement level without the use of GHG emission sequestration options will have to make a complete natural gas phase out in the long run.

As a result, the short-term benefit of the switch from coal to natural gas can be offset if it causes delays in the adoption of renewables energies or other low-carbon technologies and a carbon lock-in (Hausfather, 2015; Zhang et al., 2016). For instance, Brauers et al. (2021) think that the construction of Liquified Natural Gas import terminals in Germany could complicate and decelerate the energy transition.

This is the reason why making the distinction between utilizing existing gas infrastructure and investing in additional capacity is important. Indeed, for Wilson & Staffel, (2018) to ensure the climate benefit of the switch from coal to natural gas for power generation, spare generation and fuel supply-chain capacity must already exist. In the USA, even if the switch from coal to gas in the power generation has considerably lower GHG emissions, further investments in this area would not lead to substantial GHG abatement (Woollacott, 2020). For Gillessen et al. (2019), to avoid lock-in, further transmission grid expansion should be prevented and transmission and storage capacity should be uses for low-carbon/renewable gases.

Depending on all the elements mentioned above (methane leakage, time horizon of the analysis and carbon lock-in) "natural gas can be seen as a potential bridge fuel or a distraction" (J. C. Peters, 2017).

Security of supply of natural gas

The last concern is about the security of supply of natural gas and potential supply shortage. For instance, in Europe, the natural gas market is evolving rapidly, and international relations are affected by tensions. According to Kosowski and Kosowska (2021), clarity is missing in Europe regarding who is responsible for the security of supply in the gas sector. That could considerably shorten the transitional role of natural gas in Europe. Another concern in Germany is that, in some region, the potential increase demand of natural gas for power generation could cause interruption of supply and threaten the local heat production (Hauser et al., 2019). Natural gas shortage is also a concern in China. Indeed, there, the imbalance between supply and demand is likely to increase further over the next decades. The natural gas shortage that occurred in the winter of 2017 could therefore happen again (S. Wang et al., 2020).

3.1.2 - Role 2: Compensation for the intermittency of variable renewable energies

The second role identified in the literature is the compensation for the intermittent and stochastic nature of variable renewable energies. The quick ramping ability of natural gas generators offers a welcome flexibility complementing power production from intermittent and stochastic renewable sources (Holz et al., 2016; Neumann & von Hirschhausen, 2015; Vahl & Filho, 2015). In addition to flexibility, natural gas can ensure the adequacy (security of supply) of a highly renewable energy system especially in winter. For instance, natural gas and its infrastructure can play a welcome role in what the Germans call the "Dunkelsflaute", a long period in winter during which there is no electricity generation from wind and solar. Moreover, temperatures are low during those events and cause an increase in heat demand (Hauser et al., 2019). The coupling of the electricity and natural gas sector is welcome in such cases. For instance, combined heat and power plant fuelled with natural gas connected to district heating could help provide both power and heat lacking during those events (Hauser et al., 2019). In this role, Holz et al. (2016) imagine two possible futures. The first one is a situation where natural gas has a back-up role. Each MW of intermittent renewables is matched by a MW of natural gas. This is to ensure that the security of supply of the electricity system. The second is a situation where natural gas accompanies the growth of renewables temporarily then declines as renewables become self-sufficient with the use of storage technology). In conclusion, with the adequate technologies and policies, natural gas might help deploying renewable energy sources rather than acting against them (Davis & Shearer, 2014).

3.1.3 - Role 3: Promotion of the production, transport and storage of renewable and/or low-carbon gases

The last role is the promotion of renewable and/or low-carbon gases production, transport and storage. Indeed, today, renewable/low carbon gas such as biomethane, hydrogen or synthetic methane (see Figure 21) are already being produced, transported, and consumed through the natural gas grid infrastructure. It represents only a tiny part of the gas consumed today but it can grow in the future. Natural gas might therefore help enable a transition to long-term use of renewable/low-carbon gases (Burke & Zhu, 2015; Ogden et al., 2018; Scharf et al., 2021; Tlili et al., 2019). For instance, the power to gas process is considered an important process to store renewable electricity. In addition, gas grid can transport higher volumes of energy than can power transmission grid (Safari et al., 2019). Finally, For Burk & Zhu (2015), using natural gas can also help improve public acceptance toward hydrogen.

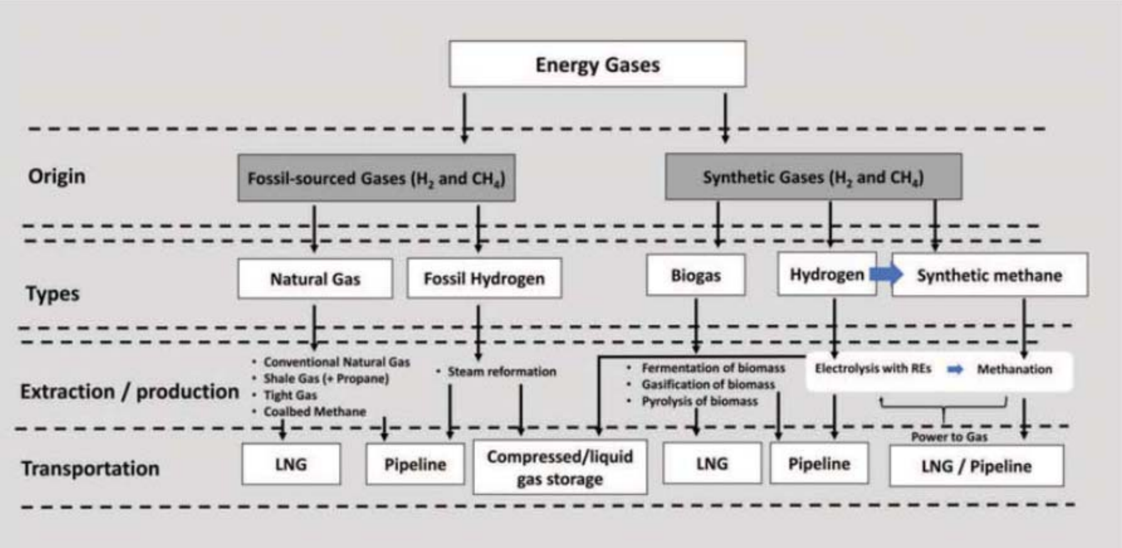

Figure 21 : Overview of different gases
Figure 1 in Von Hirschhausen et al., 2021 : Fossil Natural Gas Exit—A New Narrative for the European Energy Transformation Toward Decarbonization. In ECONOMICS OF ENERGY & ENVIRONMENTAL POLICY (Vol. 10, Issue 2, pp. 115–131). INT ASSOC ENERGY ECONOMICS.

Blending into the existing grid, adapting the gas grid or creating a new dedicated grid

A major concern regarding this role is to know what to do with the existing natural gas grid infrastructure to support the development of renewable/low carbon gases. For instance, there are three main options for transporting hydrogen through pipelines. The first is to inject the produced hydrogen directly into the gas network, in parallel with natural gas. This is called blending and the proportion of hydrogen supported by the grid can go from 5 to 15% (Ogden et al., 2018). The second is to convert the gas infrastructure to be used solely for hydrogen. This is called "repurposing". Finally, the last option is to build infrastructure dedicated solely to hydrogen (Ogden et al., 2018; Tlili et al., 2019). For instance, Ogden et al. (2018) concluded that a dedicated renewable hydrogen system would be necessary in the case of hydrogen for fuel cell vehicles.

Limited potential

Another concern is that the development potential of these gases is rather limited. For instance, the Power-to-Gas process to produce synthetic methane from renewable power suffer high energy conversion loss as it has an efficiency around 13%. Direct consumption of renewable power should therefore be prioritized. It makes sense to convert renewable power to hydrogen when production exceeds demand. However, it is difficult for PtG-facilities to be run economically only on excess electricity from renewable energies (von Hirschhausen et al., 2021).

3.1.4 Technology

As stated earlier, the future role of natural gas and its infrastructure in the energy system will greatly depend on the deployment of specific technologies. Carbon capture and storage (CCS) seems to be a key element regarding that question. For some authors, natural gas is unlikely to act as "cost-effective bridge" without carbon capture and storage (Babaee & Loughlin, 2018; Das et al., 2021; McGlade et al., 2018)

Another technology that is often mentioned is the use of combine-heat and power plant to produce both power and heat (Hauser et al., 2019; Safari et al., 2019). It is presented as the "most efficient, flexible, and cost-effective low-carbon solution, distributed generation (DG)". It empowers energy final consumers, foster economic growth and reduce GHG emissions from heat and power production. It can also help balancing renewables and support energy security (Safari et al., 2019).

Finally, the role of natural gas and its infrastructure in the energy transition will greatly depend on the development of power-to-gas (Safari et al., 2019).

3.2 Official positions of the Confederation and the gas industry

The purpose of this section is to link the elements identified in the review of the scientific literature and the documents published on the subject of the role of natural gas and its infrastructure in the energy transition in Switzerland. For each of the roles identified above, we have sought to identify the opinion on the issue from the Confederation and the gas industry. The results are summarized in Table 10.

Confederation's view
At the federal level, the SFOE (2019) published a paper in 2019 on the future role of natural gas and its infrastructure in Switzerland's energy supply. This rather brief document summarizes the SFOE's assessments of this area. It represents the official discourse at the country level.

According to the SFOE, natural gas should be used "where it is economically expedient for the security of energy supply and climate protection and where the use of renewable energies would entail disproportionate costs" (OFEN, 2019, p. 6 [Own traduction]). In the short-term (5-10 years), the use of natural gas remains important and it still makes sense in building. Compared to other fossil fuels, it will be the winning substitution fuel. However, in the long run natural gas consumption will have to be reduced considerably (-45% to -85% by 2050) and the remaining demand will have to be covered as much as possible by renewable gases. Indeed, in the medium and long term, natural gas and renewable gases must be used "effectively and judiciously", mainly in industry and commerce for the production of high-temperature process heat, in heavy traffic and long-distance transport and to cover the peak loads of district heating as well as combined-heat and power plants. However, according to the paper, natural gas will not be needed to stabilize the electricity grid. In fact, Switzerland already has "more flexibility than it needs" (OFEN, 2019, p. 6 [Own traduction]). This is in the form of power reserves, storage and pumped storage power plants and demand-side management.

The SFOE considers the potential for the production of renewable biogas and synthetic gas (synthetic methane and hydrogen) to be limited. The biomethane sustainable potential is estimated to be 3.5 TWh (without wood biomass). Wood gasification and the production of hydrogen/synthetic methane using power-to-gas (P2G) technologies would increase the potential for renewable gas production. However, both processes are very expensive and hardly profitable. Finally, the mechanism of guarantees of origin allowing the import of biomethane and synthetic methane and hydrogen is being set up. However, the capacity to supply such gas from the EU might be limited.

Given the expected decline in natural gas consumption, the profitability of gas networks will probably also decline. The high-pressure gas network (<5bars) will probably remain important in the future. Indeed, it mainly serves large consumers (industry and crafts), dual-purpose power plants, etc.). On the other hand, the profitability of distribution networks will be drastically reduced. As a result, "investment in new gas networks that would compete with heating networks should be avoided" and decommissioning of some gas pipelines should be considered.

Swiss gas industry's view

The Swiss Gas Industry Association has published a document entitled "2020 Theses of the Swiss Gas Industry" in which it sets out its views on the role of natural gas and its infrastructure in the Swiss energy transition. The industry's vision is not so far removed from that of the Federal Office of Energy. The subject on which their opinions differ most is the role of compensating for the intermittency of renewable energies. In contrast to the SFOE, the gas industry believes that the gas industry is essential to the country's security of supply and that it would allow seasonal storage. With regard to renewable gases, the gas industry believes that the potential for imports from neighbouring countries will be significant. They are also considering the possibility of using blue hydrogen as a non-renewable low carbon gas something that was not envisaged by the Confederation. In addition, the industry has set voluntary targets for the share of renewable gas to be achieved. The first target is for 2030, by which time the share of renewable gas should be 30% of the domestic heating market. In 2040, this share should be 40% of the heating market. Finally, the gas industry aims to be supply neutral by 2050.

Confédération Title: Rôle future du gaz et de l'infrastructure gazière dans l'approvisionnement énergétique de la Suisse Author : OFEN Year : 2019	**Gas industry** Titre: Thèses 2020 de l'Industrie gazière Suisse Author : ASIG Year : 2020

1st role: replacement of other fossil fuels
- No switch
- "Use of natural gas where it is economically expedient for the security of energy supply and climate protection and where the use of renewable energies would entail disproportionate costs"
- gas consumption: -45% to -85% by 2050
- residual LT demand:
  - high temperature industrial process
  - heavy traffic and long-distance
  - peak loads of district heating
  - CHP plants
  ➔ covered as much as possible by renewable gases
	1st role: replacement of other fossil fuels
	- high temperature industrial process
	- mobility
	- heat: neighbourhoods placed under the protection of the architectural heritage AND regions with no renewable heat source easy to operate with following technologies:
	  - CHP plants
	  - gas heat pump
	  - gas and solar heating
	  - hybrid heating
	- peak load of district heating.

2nd role: Compensation for the intermittency of variable renewable energies - no need for gas flexibility: Switzerland already has "more flexibility than it needs"	**2nd role: Compensation for the intermittency of variable renewable energies** - "fundamental to security of supply" - Seasonal storage
3rd role: Promotion of the production, transport and storage of renewable and/or low-carbon gases - Biomethane, green hydrogen and synthetic methane: limited indigenous production potential and limited import potential from Europe - P2G: high energy conversion loss, limited profitability - P2G2P: in direct competition with storage and pumped-storage power plants, no gas storage in Switzerland for the medium to long term	**3rd role: Promotion of the production, transport and storage of renewable and/or low-carbon gases** - Blue hydrogen, green hydrogen transported by tanker, dedicated hydrogen grid or blending - High importation potential Objectives of the industry : - 2030 : 30% renewable gases in the gas heat market - 2040: 50% renewable gases in the gas heat market - 2050: climate neutral gas supply
Infrastructure - High-pressure network remains important - Distribution network: avoid investment, consider decommissioning	**Infrastructure** - Distribution network: avoid investment, consider decommissioning - Need to develop storage capacity

Table 10 : Official positions of the Confederation and the gas industry
Source: author

3.3. Results of the semi-directif interviews

We sought to identify the biggest challenges related to the Swiss energy transition and the extent to which natural gas and its infrastructure could address them.

3.3.1 Electricity supply in winter, one of the biggest challenges of the energy transition in Switzerland

Faced with a likely increase in electricity demand, supply is not keeping up

When discussing the energy transition in Switzerland with our sample of experts, one element kept coming up as one of the biggest challenges of this transition: ensuring electricity supply in winter. This was a concern that was widely shared by the interviewees. They all anticipated an increase in electricity demand linked to the electrification of building heating and mobility, increased digitalization of society and also an increase in population. And in the face of this growing demand, respondents believe that there will be a lack of supply. Indeed, one of the three pillars of Switzerland's 2050 energy strategy is the phasing out of nuclear power. Today, Switzerland's nuclear power plants provide about 40% of the country's electricity supply. The Federal Council is counting on increased energy efficiency and the development of renewable energies to guarantee security of supply following the shutdown of these plants. However, even with the effective implementation of these two measures, periods such as "kalte Dunkleflaute", windless and cloudy winter days with an increased demand for electricity due to low temperatures, are of concern to some of the interviewees.

Public opposition slows down the development of winter electricity generation capacity

In addition, the deployment of wind energy in Switzerland is encountering a lot of opposition from the population and is developing very slowly, if at all. "This is a pity because wind energy is very complementary to solar photovoltaic energy, which is currently developing at a good pace in the country". This opposition does not only concern wind turbines. Experts believe that every infrastructure project (dam, geothermal, high-voltage line, etc.) in Switzerland is confronted with this problem. In the words of one respondent: "The (energy) transition is not a technical problem but a problem of social acceptance". For this reason, some of them believe that the scenarios of the Federal Office of Energy's "Perspectives énergétiques 2050+" are too optimistic regarding the deployment of renewable energies. "Today, it is almost impossible to build an industrial infrastructure. The only thing we can do is put solar panels on the roofs. And that doesn't solve the problem of supply in winter".

Increasing dependence on electricity imports from neighbouring countries in winter is a risk for the country

Switzerland is already unable to cover its electricity demand during the winter months and is dependent on imports from its neighbouring countries. The respondents believe that this winter dependence could pose a serious supply risk for the country in the future. Indeed, the countries surrounding Switzerland are facing the same challenges related to the decarbonization of their energy system and will therefore have limited export capacity. Respondents believe that this risk has been further exacerbated by the end of the institutional framework agreements with the European Union. In the words of one respondent: "The biggest challenge is the lack of electricity in winter and Switzerland's dependence on foreign countries. I think this is a time bomb. It is a subject that is underestimated and today there are no credible answers in the short or medium term.” For another, the idea that a country would suddenly want to keep its energy to itself and stop exporting is not completely "far-fetched". It is something "serious that can be done in 3 seconds". The point at which it will become a real problem is difficult to estimate. According to the respondents, it could happen tomorrow or decades from now. In some cantons, attempts are already being made to improve resilience and to raise awareness among critical actors so that they can cope with a possible blackout or shortage. According to one respondent, this awareness-raising is difficult to achieve because the people concerned find it difficult to envisage such an eventuality. This vision, in which the risk of an electricity shortage seems to be increasing, is not shared by all the respondents, since one of them considers that there is no alarming situation at present and not in the medium term either.

Identified solution to this potential winter electricity shortage: Exploiting more of the country's hydroelectric potential

Hydropower, which has long been the backbone of Switzerland's electricity supply, is the solution presented as one of the main answers to this problem. Indeed, exploiting the country's hydropower potential further seems to be the main focus of the Confederation. This takes the form of increasing the capacity of existing dams but mainly through the creation of new dams. According to some respondents, this would be by far the most efficient solution. Moreover, these infrastructure developments would not only provide winter power generation capacity, but would also serve for flood protection and the supply of irrigation or drinking water. However, the fear shared by many respondents is the timeframe for the deployment of such hydropower infrastructure. According to one of them: "If it's there (the new hydroelectric infrastructures) in 2040, we can be happy". Some stakeholders believe that we should not rely solely on this solution. The supply must be diversified as much as possible. "We must remain open [...] Any innovation, any possibility of securing our supplies are welcome". According to one of the respondents, there is not "one good solution, but many solutions" to this problem.

Identified solution to this potential winter electricity shortage: extension of the operation of nuclear power plants

Another response to the lack of electricity production in winter identified by our respondents is the extension of the operation of nuclear power plants. Indeed, the certainty of the effective shutdown of nuclear power plants seems to be shaking among several of our respondents. In fact, according to one of them, "For the past few weeks, we have felt the return of the nuclear lobby. Can we decarbonize by closing the nuclear door?” Indeed, Switzerland is planning a gradual withdrawal from nuclear power. There are no deadlines for the shutdown of these plants, they will be operated as long as their safety is ensured. According to one of our respondents, "We can invest to ensure the safety of these installations [...]. Personally, I think they will last because it (the development of renewable energy) is not going fast enough". Some of them believe that they could remain active beyond 2040. One of the six Swiss reactors, Mühleberg, was shut down in December 2019 by the operator for economic reasons. According to one of the interviewees, the decommissioning of this plant and its costs will help to advance the debate on the fate of the other reactors.

The intermediate role of natural gas in the energy transition

It is a view shared by all respondents, there is no doubt that natural gas consumption must, and will, drastically decrease by 2050. In the words of one of our respondents, "It makes perfect sense and is consistent if carbon neutrality is to be achieved”. However, respondents agree that natural gas is difficult to replace in specific uses such as high-temperature industrial processes, in synergy with renewable energies, as a complement to district heating or for heavy and long-distance transport. These are uses "in which natural gas can express its full energy potential". Natural gas will therefore act as an intermediate solution and will be predominant over other fossil fuels. According to them, it could be "a tool for managing the intermittency of renewable energies by using an infrastructure that is already there". In the long term, all respondents agree that the residual demand will have to be covered as much as possible by renewable gases.

Natural gas-fired combined heat and power as a transitional solution to winter power shortages

The use of natural gas-fired combined heat and power plants that produce both heat and electricity in winter is a potential solution to the problem of the lack of electricity in winter. Indeed, a project is currently being studied where heat and power couplings would be financed by a common fund in order to operate them only when necessary. In addition, according to two of our respondents, the positioning of CHPs at certain critical locations in cities such as water treatment plants or at the level of water distribution would make it possible to produce electricity and operate these key infrastructures in the event of a blackout. However, they agreed that in order to fulfil its full potential for this role in the event of a blackout, further studies would still need to be carried out to confirm the ability of the gas infrastructure to operate under these conditions. For one respondent, given that 50% of Switzerland's natural gas supply comes from Russia, using it to strengthen the country's security of supply "is like leaning on a crutch that is unstable and wobbly". For another, the risks of natural gas supply seem much lower than for electricity. "We can always import natural gas”.

Gas storage in rock cavities to improve security of supply

A project for the storage of natural gas in rock cavities is currently being studied in Switzerland. Today, Switzerland does not have any seasonal natural gas storage capacity on its territory. Respondents believe that this storage capacity would therefore improve the security of supply of natural gas initially. In addition, in the long term, it could help to absorb excess electricity from photovoltaic plants and wind farms in the form of hydrogen or renewable methane thanks to the power-to-gas process. It could thus provide a welcome response to the problem of electricity shortages in winter. Indeed, according to one respondent, "molecular storage is the only way to shift summer production for consumption in winter". Another advantage of this form of storage is that it is underground. It is therefore not detrimental to the landscape. Despite this, most respondents believe that, like any infrastructure project in Switzerland, the development of this storage will probably encounter opposition and its deployment could only take place in a timeframe of 10-20 years.

Biomethane, syngas and hydrogen as a long-term solution

As mentioned above, natural gas consumption will have to decrease over time and the remaining demand will have to be met by renewable gases. In general, respondents recognize their value and the key role that these renewable gases will have to play in the Swiss energy transition. With regard to biogas, most respondents believe that it is a valuable resource that should be exploited to the full. They recognize the great efforts that have been made by the gas industry in recent years to exploit it. However, they are all aware of the limited potential of this resource. For some, on the contrary, the potential of synthetic gases and hydrogen (wood gasification and gases from the power-to-gas process) seems more promising. For others, the potential of power-to-gas is really limited by its efficiency. Others are of the opinion that when there is too much electricity production, the efficiency issue becomes less important. For many, the legitimacy of power-to-gas will therefore lie in the existence of surplus electricity. One of our experts believes that "from the moment we have to get out of nuclear energy, we will have all the difficulties in the world to do it just to ensure the supply of electricity. I don't see how we can take up the challenge of creating surplus electricity to make syngas at the same time”. This opinion is not shared by all, since many believe that in the long term this surplus will be present.

Concerning the power-to-gas process, the interviewees had divergent opinions regarding the output to be favoured. Indeed, the power-to-gas process makes it possible to produce hydrogen by electrolysis of water. It is also possible, by combining this hydrogen with CO2 via the methanation process, to generate synthetic methane. For some, hydrogen is not easily stored, it needs to be compressed or large volumes to contain it. According to one of them, gaseous storage in rock cavities "costs three times as much for the same amount of energy if it is in hydrogen". For others, the additional costs involved in the methanation stage limit the potential of synthetic methane.

Finally, the use of blue hydrogen, hydrogen produced from natural gas, is not so much discussed in Switzerland. In the words of one respondent: "using carbon capture and storage to enable the use of natural gas in the long term is not an objective supported by the Confederation". However, this decarbonized, but non-renewable gas seems to be an integral part of the EU strategy. The import and consumption of this type of gas in Switzerland will not be prohibited in principle. Part of our sample believes that the issue of deploying carbon capture and storage (CCS) or negative emission technologies should be further explored in Switzerland and that an official position of the Confederation should be taken.

3.3.2 The other challenge of the energy transition in Switzerland: the slow decarbonization of the buildings sector

A quarter of Switzerland's CO2 emissions are generated by the building sector. It is therefore a key sector for achieving carbon neutrality by 2050. The strategies mentioned to decarbonize the building sector are the reduction of heat needs thanks to the improvement of the building envelope, the replacement of fossil boilers by renewable solutions such as heat pumps, wood or the deployment of distance heating supplied mainly by renewable energies or waste heat. However, for many of the respondents, the energy renovation of buildings is not going fast enough. "The objective in buildings is clear: to drastically reduce fossil (energy) consumption. But it is going to be more complicated and take longer than we thought". Most of them feel that the renovation rates are not high enough. There is a lot of inertia in this sector as the life span of a heater is about 15-20 years. Moreover, investment decisions depend mainly on the life cycle of the building, but also on its occupants. Finally, the rejection of the revision of the CO2 law by the people in June 2021 will have a major impact that may delay this renovation even further. For the localities, the development of a distance heating system depends largely on the presence on their territory of situational resources, locally available renewable resources such as unexploited waste heat (industry, water treatment, waste incineration plant etc.), wood, geothermal potential or biogas. The development of these infrastructures is often a major undertaking that takes many years to complete.

The gas switch is not a solution in itself, but may be desirable in certain cases

According to one of our respondents, the switch from oil to gas has already taken place in Switzerland when natural gas entered the heating market in the 1970s and took over a market share that was occupied by oil. A reduction in CO2 emissions through the switch was therefore already achieved at that time. However, in his opinion, this substitution is no longer sufficient. Moreover, all respondents agree that the CO2 savings achieved by switching from oil to gas in the heating sector are not sufficient as a strategy to achieve carbon neutrality in Switzerland by 2050. On the other hand, in cases where the use of renewable energy is not possible or would entail disproportionate costs, switching from oil to gas is still considered opportune by the respondents. In addition, for some, if the boiler is already fuelled by natural gas and switching to renewable energy is not

feasible, switching from a traditional boiler to more efficient systems such as combined heat and power plants or gas heat pumps may also be a welcome strategy.
In the field, some respondents observed that some homeowners with limited financial means opt for a building envelope upgrade, but keep their natural gas heating. As a result, respondents agree that the traditional use of natural gas (individual boilers) for heating buildings is tending to decline, but the rate at which this happens is unlikely to be as rapid as previously thought.

Solution: Natural gas-fired combined heat and power systems to accelerate the deployment of district heating

One area where the use of natural gas for heat production has increased in recent years is in district heating. Indeed, at present the majority of district heating systems powered by renewable energy are also powered by natural gas. The latter generally fulfils the role of covering the peaks during very cold periods. The proportion of renewables to gas in the supply of district heating systems is generally 60-80%. In the words of one of our respondents: "it is a question of finding an economic balance for the project, because if the costs are too high it will be more difficult to find customers who will agree to connect to it".

As mentioned above, the exploitation of situational resources such as geothermal is a process that can take several years to be successful. Here, the use of natural gas-fired combined heat and power systems would allow this heat network to be developed more quickly. It would provide heat for district heating, but also electricity in winter which could be consumed by heat pumps connected to the district heating network. These CHPs would play an intermediary role until the situational resources could be exploited. However, the CHPs would still be available to ensure security of supply in the event of a blackout. They could even continue to operate in the long term while being powered by renewable gases.

At present, there is no support from the cantons or the Confederation for the deployment of such district heating.

3.3.3 Evolution of the gas infrastructure: preparing for the reception of renewable gases and a decrease in natural gas consumption

Blending, repurposing or dismantling?

In general, respondents believe that gas infrastructure will have an important role to play in this energy transition. They are rather optimistic about their value and the fact that they can serve a purpose in the future. In the words of one respondent: "it is a discrete infrastructure that allows energy transfer to be done quite easily, at costs that are proportionally very low and with a popular acceptance that is very high". The current difficulty for gas network operators is how to transform this infrastructure to make it compatible with the energy transition.

Indeed, natural gas network operators are currently faced with some big questions. What should be done with our natural gas network, which is currently designed to transport mainly methane molecules? Should it be left intact so that it can transport natural gas, biomethane and synthetic methane with a small amount of hydrogen (blending)? Should it be converted to carry only hydrogen (repurposing)? Should new networks be built specifically for hydrogen? Or, on the contrary, with the demand for natural gas decreasing over time, should we start dismantling the existing network?

Hydrogen uncertainties

For many experts, the development of renewable gases is still uncertain. That is why "it is important to keep all doors open". To prepare for the possibility of network conversion, some network operators are already using 100% hydrogen-compatible materials when sections are to be renovated. In order to ensure the compatibility of the network with hydrogen, an inventory of all materials in the current network is being carried out. A priori, the Swiss network would support a proportion of hydrogen in the order of 10%-20%. However, safety issues arise as soon as hydrogen is injected into the grid. In general, the grid is more usable with methane than with hydrogen because the hydrogen molecule is extremely small and therefore more prone to leakage. In addition, hydrogen is highly flammable. For one of the respondents, the risks associated with the use of hydrogen "is not something that gives us nightmares because the "town gas" that was used before the arrival of natural gas was composed of 50% hydrogen. So we already have experience in this field". For another, on the contrary, accidents seem more difficult to avoid. Regarding blending, the greatest difficulty lies in the fact that the composition must be homogeneous at all times, in other words, a proportion of methane and hydrogen that does not vary over time.

Two impulses for the evolution of the network

For the most part, the evolution of the network will follow two impulses. First, a local impulse with specific projects with dedicated pipes between producers and consumers. Finally, the second impulse will come from abroad. In fact, in the words of one of our respondents, "Most of the changes that will affect gas infrastructures will be imposed on us by the European Union". This is a view shared by many of our experts. Indeed, the European Union has developed a hydrogen strategy and intends to develop a whole dedicated network. As Switzerland is integrated into the European network, it will not be able to say "we don't want hydrogen at the border". For many, Switzerland also needs a hydrogen and syngas strategy to anticipate these developments and send strong signals to the market.

Dismantling: a political response

At present, the expansion of the natural gas network has already been limited in some cantons by the publication of a sectoral strategy. In some cities, such as Zurich, there is even talk of network dismantling. For many, dismantling in the short or medium term "is not an operational response, but a political response". Indeed, some feel that the authorities, who often own the networks, would be tempted to talk about dismantling in order to send strong political signals. In general, our respondents agree that the issue of network dismantling is less relevant for supra-regional transport networks in the medium to long term. The infrastructure must be maintained, but must be ready for renewable gases. At the level of the distribution network, however, the subject is debated. For most, this infrastructure is there, it has cost a lot of money, so it should be used rather than dismantled. For one respondent: "Before removing it, I would like to make sure that it will not be needed in the future. You have to preserve all the opportunities. I don't want to dismantle my network or make technology choices that would be limiting at this stage”. For another: "We are no longer talking only in terms of the gas network, but in terms of energy companies. We want to keep our options open to see what will happen in 10-20 years' time and offer adapted energy solutions. A bit like a painter's palette”. So in the short to medium term, many agree that decommissioning would be precipitous. On the other hand, they all agree on the need for territorial planning with the municipalities, with an identification of the areas where the gas supply will have to be reduced in the long term and an identification of the priority axes to be maintained in the long term. They also agree that it is becoming highly strategic to develop an asset management strategy to manage these issues. Many believe that at the local level, greater synergy between the electricity grid, the gas grid or hydrogen grid and the district heating networks will be needed to ensure optimal convergence of these networks. A priori, the respondents believe that the evolution of the network will not be imposed by the Confederation. It is the companies who will best plan its evolution according to the objectives set by the territories they serve.

Methane leaks: principle of territoriality and no concrete strategy

With regard to methane leaks from the Swiss gas infrastructure, measures have been taken by the industry to limit them as much as possible. For instance, leaks are detected and when sections need to be vented, the gas is no longer simply allowed to escape. First, the pressure was reduced to a minimum before venting. Now the vented gas is recovered to the maximum and reinjected with compressors. Generally speaking, the respondents believe that methane leaks on Swiss territory do not represent a real problem. With regard to leaks abroad, particularly during extraction, the respondents acknowledge the problem and the disparities in leakage levels depending on the source of the gas. However, few concrete measures were discussed. Indeed, in accordance with the principle of territoriality, only methane leaks on Swiss territory are considered in the country's official greenhouse gas emission inventories. Generally speaking, methane leakage (on Swiss territory and abroad) has not been considered as a separate subject in cantonal or federal energy strategies. This is mainly because natural gas consumption is set to decrease in the long term, and it was deemed unnecessary to deal with this issue in greater depth.

4. Conclusion

This study adopted a qualitative and holistic approach in order to explore all the aspect of the question of the role of natural gas and its infrastructure in the Swiss energy transition.

Firstly, we realized a systematic literature review which enables us to identify three different roles, their expected benefits and concerns. The first role identified is the use of natural gas to replace other fossil fuels such as coal or oil. This switch allows for a rapid reduction in greenhouse gas emissions as well as an improvement in air quality. The second role identified is the use of natural gas and its infrastructure to compensate for the intermittent nature of renewable energy. This ensures flexibility and adequacy of the energy system. However, the expected benefits of these two roles are tempered by concerns such as methane leakage related to the use of natural gas, the delay it could cause in the deployment of renewable energies, the carbon lock-in it could cause and finally the security of supply of natural gas. The last role identified in the scientific literature is the fact that natural gas and its infrastructure help promote the production, transportation and storage of renewable gases. However, the potential for development of these renewable gases may seem limited and there are many unknowns in adapting the gas infrastructure to accommodate them.

Secondly, we transposed the roles identified in the literature to the Swiss context by looking at the official positions of the Confederation and the gas industry on this issue. We found that the industry's vision is not so far removed from that of the Federal Office of Energy but that, in contrast to the Swiss Federal Office of Energy, the gas industry believes that its infrastructure is essential to the country's security of supply and that it would allow seasonal storage.

Finally, in order to enrich these two visions, we conducted semi-structured interviews with fifteen experts in the field of energy in Switzerland. We were able to identify the biggest challenges related to the Swiss energy transition and the extent to which natural gas and its infrastructure could address them. We also identified the main challenges regarding the evolution of the gas infrastructure within this context. The results of our analysis show that electricity supply in winter is considered by our experts as one of the biggest challenges of the energy transition in Switzerland. To address this challenge, Switzerland might exploit more of its hydroelectric potential or extend the operation of its nuclear power plants. Besides that, respondents identify three ways in which natural gas and its infrastructure might help address this challenge. The first is the use of natural gas-fired combined heat and power plants as transitional solution. The second is a gas storage in rock cavities to improve security of supply. Finally, biomethane, syngas and hydrogen as long-term solution. The other challenge of the energy transition in Switzerland identified by our experts is the slow decarbonization of the buildings sector. In answer to that, the respondents agreed that the gas switch is not a solution in itself, but may be desirable in certain cases. They also identified another solution: natural gas-fired combined heat and power systems to accelerate the deployment of district heating.

This study made us realize how complex the question of the role of natural gas and its infrastructure in the energy transition is. In the context of the Swiss energy transition, many issues remain to be clarified. For instance, a national strategy for the development of infrastructure and deployment of renewable gases, in particular hydrogen, is desired by most of our experts. In addition, a strategy regarding the question of methane leaks needs to be developed. In conclusion, natural gas and its infrastructure in the energy transition is definitely a subject that needs to be addressed in full transparency in order to clarify all its grey areas. Further research in this area could be carried out in order to investigate more deeply the solutions identified in this paper. Indeed, the impact of their implementation in terms of feasibility and reduction of GHG emissions should be addressed.

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Paper II : Combined Heat and Power plants fuelled with natural gas as a power generation solution for the energy transition – impact on the hourly carbon footprint of the electricity consumed in Switzerland

Simon, E., Cimmino, F. M., & Genoud, S. (2021, juin). Combined Heat and Power (CHP) plants fuelled by natural gas as a power generation solution for the energy transition—Impact on the hourly carbon footprint of the electricity consumed in Switzerland. 1st iaee online conference 2021.

Highlights

- Assessment of the hourly GHG emission factors for the consumed electricity in Switzerland
- Analysis of historical data hourly natural gas consumption for region-level aggregation
- Development of a model of hourly gas consumption for heating purposes
- Assessment of the impact of CHP expansion on the hourly emission factors for the consumed electricity in Switzerland

Key words

electricity production, electricity imports, hourly GHG emission factor, CHP, natural gas

Abstract

Having started the phasing-out of nuclear process, Switzerland will have to face the challenge of replacing nearly 30% of its domestic power generation in the medium run. Currently, imports from the European Union are used when indigenous production is unable to meet demand. However, growing import dependency in winter represents not only a potential threat to the security of supply but also electricity import with a heavy GHG content. The development of decentralized power generation through natural gas-fired combined heat and power (CHP) plants could be a short-medium run solution allowing to produce electricity on the Swiss territory during winter. In this work, we evaluate how the replacement of a part of the inflows from neighbouring countries by decentralized CHP plants fuelled by natural gas impacts the hourly carbon footprint of the electricity consumed in Switzerland. We developed a four-step methodology to answer this question. Firstly, we assess, for the years 2016 to 2019, the GHG content of the electricity consumed in Switzerland in accordance with the consumption principle and applying the attributional Life Cycle Analysis (LCA) approach. Secondly, based on natural gas delivery data, we modelled hourly gas consumption for heating purposes by means of the heating degree-hour method. Then, based on the previous part, we simulated hourly electricity production with natural gas CHP plants. Finally, we assessed the hourly GHG emission from electricity consumption with the new solution. The results show that, actually, imports impact strongly and negatively the GHG footprint of the electricity consumed in Switzerland. The results of the last part show that the development of decentralized power generation through natural gas-fired CHP plants can lower the GHG footprint of the electricity consumed in Switzerland. Indeed, in nearly all the scenarios, the natural-gas CHP solution is a less-GHG-emitting alternative to imports.

Abbreviations

CHP	combined heat and power
NG	natural gas
LCA	life cycle analysis
GHG	greenhouse gas
EF	emission factor

Nomenclature

Symbols

E	Electricity (MWh/h)
M	LCA GHG emissions (CO2-eq-Kg)
EF	Emission factor (g CO2-eq- /kWh)
Gen	Generation
Imp	Importation
Exp	Exportation
Cons	Consumption
CHP	CHP production (MWh/h)
$\hat{Y}Heat$	estimated hourly natural gas consumption for heating purposes (MWh/h)
Y	natural gas consumption (MWh/h)
$\beta_1,\dots,\beta_5$	regression coefficients
HDH	heating degree hour
Hour	categorical variable accounting for the hour of the day
Weekday	categorical variable accounting for the day of the week
Bankholiday	dummy variable accounting the Swiss holidays
ε	random error term
θ	temperature

Subscripts

l	neighbouring country identifier (GE, FR, IT, AT)
i	production type identifier (biomass, lignite…)
t	hour identifier (1…8760)
CH	Switzerland
in	internal
ex	external
th	threshold

Superscripts

New	result of the CHP simulation

1. Introduction

Switzerland has committed to a transition to a low-carbon energy system through the Energy Strategy 2050. One of the pillars of the strategy is phasing-out of nuclear power (OFEN, 2013). It means that the country will have to face the challenge of replacing nearly 30% of its domestic power generation (31.7% in 2017) (OFEN, 2018). In the long run, it should be compensated by the development of renewable energies and reduction in consumption, the two other pillars of the strategy. Currently, imports from the European Union are used when indigenous production is unable to meet demand. Indeed, for the last years, the use of electricity inflows from neighbouring countries has been growing, particularly in winter. The Federal Electricity Commission (ElCom) has warned about this winter dependency. Indeed, it estimated that this winter dependency could potentially become a threat to the security of supply if it keeps growing due to the decommissioning of the nuclear power plants. This is the reason the ElCom recommends "that a substantial part of this missing winter production continues to be produced in Switzerland" (ElCom, 2018, p. 15). The commission also wanted to raise awareness concerning the fact that the majority of the imports during this period are of fossil origin (ElCom, 2018). These imports probably have an important impact on the carbon footprint of the electricity consumed in Switzerland as around 20% of the European Union's electricity production came from coal (21.5% in 2017) (IEA, 2019).

The use of small distributed combined heat and power (CHP) units fuelled with natural gas can potentially represent a temporary solution until the development of renewable energies and the reduction in consumption fully compensate the missing electricity production. Indeed, CHP, is a highly efficient energy conversion process which produces electricity near the site of use and capture the waste heat for space and water heating. From a thermodynamic point of view, this approach allows a more efficient use of natural gas compared to its direct combustion for heating purposes. Furthermore, this decentralized system is also more efficient than other conventional power plants where the waste heat is not recovered. Finally, this distributed energy-efficient option also allows to reduce reliance on grid electricity. This efficient technology has been considered as a serious cog in the wheel of the energy transition for a growing number of countries. Indeed, Japan, Germany, the UK, the Netherlands, and the U.S.A. are active in the introduction of CHP as a power generation solution in the energy transition process (J. E. Brown et al., 2007a; Kobayashi et al., 2005a). However, there are still obstacles for an appropriate market implementation (Howard et al., 2014; Kuhn et al., 2008; M. Liu et al., 2014). In Switzerland, there is only 496 MW of installed CHP capacity, accounting for around 2.5% of total national power generation (in 2018) (Kaufmann, 2019). There is plenty of room for the development of this technology in Switzerland.

As a result, the purpose of this work is to evaluate the environmental impact of a short-medium run solution allowing to produce electricity on the Swiss territory during winter : the development of decentralized power generation through natural gas-fired combined heat and power plants. More precisely, this work aims to answer the two following research questions :

1) What is the impact of the electricity inflows from neighbouring countries on the hourly carbon footprint of the electricity consumed in Switzerland ?
2) How the replacement of a part of the inflows from neighbouring countries by Combined Heat and Power (CHP) fuelled with natural gas impacts the hourly carbon footprint of the electricity consumed in Switzerland ?

We developed a four-step methodology to answer those two research questions. Firstly, we assessed, for the years 2016 to 2019, the GHG content of the electricity consumed in Switzerland in accordance with the consumption principle and applying the attributional Life Cycle Analysis (LCA) approach. Secondly, based on natural gas delivery data, we modelled hourly gas consumption for heating purposes by means of the heating degree-hour method. Then, based on the previous part, we simulated hourly electricity production with natural gas CHP plants. Finally, we assessed the hourly GHG emission from electricity consumption with the new solution. One of the major contributions of our paper is the hourly granularity approach adopted in order to be closer to the real constraints of the electricity market.

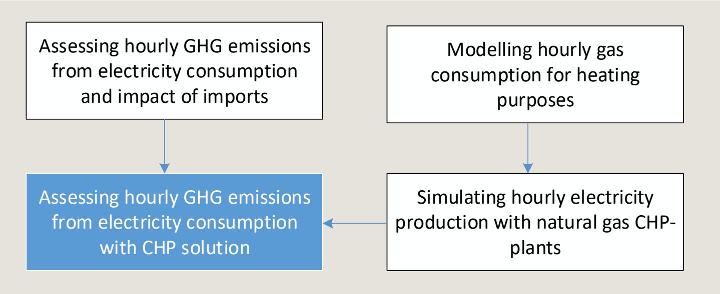

Figure 22: The four parts of the research process
Source: authors

The remainder of this paper is structured as follows: Section 2 has the literature review. Section 3 presents the data and methodology used to address the research questions. The results are then presented and discussed in section 4. Section 5 is dedicated to sensitivity analysis of the model. The paper concludes with section 6 with discussion and implication regarding the results.

2. Literature Review

Our paper addresses three different themes: CHP as a solution for the energy transition, the GHG content of the grid electricity consumed and natural gas heating demand modelling. This is the reason why we developed a literature review on the three of them. They are presented in the following sections.

2.1 Combined heat and power CHP as a solution for the energy transition

Combined heating and power systems, or sometimes called cogeneration, has been identified early as a highly efficient system which can lead to primary energy saving and emission reduction (IEA, 2008). Today, the body of literature analysing the potential role CHP can play in the energy transition toward a low-carbon energy system is extremely varied. This is due to the fact that different CHP systems (prime mover) exist such as turbines, engines and fuel cells, that they can work at different scales (from micro-scale to large-scale), that different operation strategies can be adopted (electric or thermal demand management) and that they can be deployed for different uses such as residential, industrial, commercial or for district heating. Liu et al. (2014) realized a survey of the state of the art around the world of this technology, highlighting all these different characteristics. The focus of this review has been on papers focusing on the analysis of CHP fuelled with natural gas deployed for residential or commercial use.

The most widely used measure to illustrate the environmental benefit of CHP implementation is primary energy saving (Bianchi et al., 2013) and GHG emissions saving. Sometimes, other measures are used such as exergy saving (Ehyaei et al., 2012; J.-J. Wang et al., 2011) and other air pollutant savings. For instance, Ehyaei et al. (2012) considered, in addition to exergy saving and CO2 emissions saving, nitric oxide saving, a gas responsible of the formation of smog and acid rain. Another aspect often explored in the literature is how the deployment of CHP facilitate or hinder the deployment of intermittent renewable. For instance, several papers have shown that CHP technology has a symbiotic relationship with solar photovoltaic technology and contribute to the stability of the electricity grid (Mostofi et al., 2011; Nosrat et al., 2014; Pearce, 2009).

To assess the GHG emissions saving from implementing CHP systems, the avoided burden approach has been frequently used. It means that the GHG emissions produce with the CHP system is compared with a reference system for heat and electricity generation. The reference system is often a traditional boiler and grid electricity (Dorer & Weber, 2009; Howard et al., 2014; Howard & Modi, 2017; Hueffed & Mago, 2010; Mago et al., 2011; Mago & Smith, 2012; Rosato et al., 2013). As a result, the GHG content of the grid electricity has a heavy impact on the magnitude of the environmental benefit of a CHP system. Indeed, an element which regularly emerges from the literature is that the GHG benefit of CHP lessened with cleaner electricity system (Howard & Modi, 2017; H. Liu et al., 2017; Mago et al., 2011). Some authors highlighted the fact that, indeed, it has potential to reduce carbon emissions in the near future. However, in a highly renewable electric future, the benefits become less obvious (Kelly et al., 2014).

The vast majority of the literature carried out these analyses at the building level. Authors intended to explore which operation strategies (J.-J. Wang et al., 2011), which scale (Wakui & Yokoyama, 2011), which technology (Rosato et al., 2013) offers the best performance in economic or environmental term (Bianchi et al., 2013; Dorer & Weber, 2009; Hueffed & Mago, 2010; Ren & Gao, 2010). Howard and Modi (2017) found out that, potential GHG reduction of the implementation of CHP systems fuelled with natural gas can range from less than 10% to 50% depending on the prime mover technology, the typology of the building, the operating strategy and the current GHG content of the grid electricity. Mago and Smith (2012) analysed different types of buildings in the same city in order to find out which type of building is more likely to save GHG emissions (Mago & Smith, 2012). Other authors analysed same hypothetical building in different cities to understand the impact of different climates on the results (Mago et al., 2011; Romero Rodríguez et al., 2016).

Starting from an analysis at the building level, some authors adopted a bottom-up approach to identify city or country CHP potential to reduce GHG emissions. This is the case for Howard et al. (2014) for New York City, H. Liu et al. (2017) for China and Kelly et al. (2014) for the UK. Another approach to identify CHP potential is a top-down approach, where global heating demand is used to derive potential CHP power and heating generation by applying average power to heat ration corresponding the current technology (IEA, 2008). This is the approach adopted by our paper.

In Switzerland, several authors have investigated the role CHP may play in the future Swiss energy system. Indeed, Rognon (2005) evaluated the efficiency potentials of heat pumps with CHP. A complete study has analysed how biogas-CHP swarms have the potential to balance intermittent renewable energy production (Buffat & Raubal, 2019; Panos & Kannan, 2016; Vögelin et al., 2016). The starting point of the analysis was that CHP units have to be fuelled only with biogenic resources. The result of the energy-economic modelling showed that CHP may have an important role in a very stringent climate policy environment.

To the best of our knowledge, there is no paper addressing the case of GHG emissions reduction potential of the deployment of CHP units fuelled with natural gas in Switzerland. One of the major contributions of our paper is addressing this question in an hourly approach. Indeed, the GHG content of the grid electricity is, in all the cases cited above, considered as constant over the year (Howard et al., 2014; Howard & Modi, 2017; Mago et al., 2011). Another contribution is that we adopted a top-down approach based on natural gas heating demand by using real hourly natural gas consumption.

Those two specific aspects are further discussed in the two following sections

2.2 GHG content of the electricity consumed

As pointed out in the previous paragraph, the GHG content of the grid electricity has a heavy impact on the magnitude of the environmental benefit of the deployment of CHP. However, determining GHG emission from electricity grid consumption is a challenging task (Soimakallio et al., 2011; Weber et al., 2010). Indeed, depending on the energy resource availability and the ever-changing demand, the generation mix varies continually and, as a result, it does not have the same GHG footprint over time. Moreover, because of the meshing of the network, it is not possible to trace back the electricity consumed to a specific power plant. This is the reason why there are plenty of different ways of associating GHG emission with electricity grid consumption. This is reflected in the great variety of studies attempting to achieve that result (Khan, 2019).

One of the most important features of carbon intensity of the electricity grid is its time-varying aspect. Indeed, the GHG content of electricity grid varies greatly over days and seasons. However, in his literature review on the GHG content of electricity generation, Khan (2019) identified that only 2% of studies considered this time-varying aspect. Fortunately, a growing body of literature is starting to focus on finer granularity (hourly, half-hourly) in order to be closer to the reality of the physical nature of electrons (Gordon & Fung, 2009; Khan, 2018; Khan et al., 2017; Kopsakangas-Savolainen et al., 2017; Messagie et al., 2014; Romano et al., 2019; Roux et al., 2016; Schram et al., 2019; Spork et al., 2015; St-Jacques et al., 2020; Vuarnoz & Jusselme, 2018).

Another aspect, as important as the temporal sensitivity of the GHG content of the electricity grid, is its spatial sensitivity such as the power exchanges with other countries. Two different approaches can be used: the production and the consumption principle (Munksgaard & Pedersen, 2001; G. P. Peters & Hertwich, 2008). The former is recommended by GHG quantification protocols such as the United Nations Framework Convention on Climate Change (UNFCCC) and is often used by national studies (Frischknecht et al., 2012). It takes into consideration production before exchange with other countries. It implies that countries are responsible for the GHG emissions of their electricity production. The latter, on the contrary, implies that countries are responsible for the GHG emissions of the electricity they consumed (local generation + import – export). Different degrees of details have been used to illustrate the GHG content of the power exchange between countries. For instance, Vuarnoz and Jusselme, (2018) considered the emission factor of the import of Switzerland as being the same as the European Network of Transmission System Operators for Electricity (ENTSO-E) mix supply emission factor. Some authors assessed the GHG emission factor of a country by taking into account imports and exports with its direct neighbours on top of the emissions generated in the local grids. They assumed that the imported electricity is entirely produced by the country of the origin of the import (Bai et al., 2014; Lindner et al., 2013; Romano et al., 2019). Other authors took into consideration exchanges between several interconnected grid (Ji et al., 2016).

Among the papers cited above, two different LCA approaches have been used: attributional and consequential. The former, also called average approach (Khan, 2019) can be described as "to describe the environmentally relevant physical flows of a past, current, or potential future product system" (Ekvall et al., 2005, p. 1). This approach calculates the average GHG content of the electricity mix. It has been used by authors willing to explore historical data or to compare different national mixes (Gordon & Fung, 2009; Ji et al., 2016; Khan, 2018; Khan et al., 2017; Lindner et al., 2013; Messagie et al., 2014; Roux et al., 2016; Schram et al., 2019; Spork et al., 2015; St-Jacques et al., 2020; Vuarnoz & Jusselme, 2018). Consequential, or sometimes called the marginal approach (Khan, 2019), can be described as a "Method for describing how environmentally relevant physical flows would have been, or will be, changed in response to possible decisions that would have been or will be made" (Soimakallio et al., 2011, p. 2). This approach takes into account the merit order of production (i.e. generators with low marginal cost are first brought on to meet demand) assuming that a change in electricity consumption will impact the generator with the higher marginal costs. This approach has been used by authors willing to assess the impact of a change in the electric system (Kopsakangas-Savolainen et al., 2017; Romano et al., 2019). The two different approaches have been discussed by Dotzaeuer (2010) and Soimakallio et al. (2011).

Concerning Switzerland, a few studies have analysed the GHG content of this country at the heart of Europe. Messmer and Frischknecht (2016) used three different approaches of carbon accounting. The generation mix, the supplier mix and the consumer mix. The first one is in accordance with the production principle presented earlier. The second one considers certified electricity through the system of Guarantee of origin. The last one, the consumer mix, is the carbon footprint for non-certified consumption. The paper considered neither exchanges with other countries nor time variability of the GHG content of electricity. On the contrary, Vuarnoz and Jusselme (2018) applied an hourly approach and considered exchanges with other countries. However, the emission factor of the import from neighbouring countries (Germany and Austria) have been considered as time-independent and as the same as the European Network of Transmission System Operators for Electricity (ENTSO-E) mix supply emission factor. Finally, Romano et al. (2019) also considered both spatial and temporal sensitivity. They applied the marginal technology approach and took into account exchanges with the country's direct neighbours.

There is a gap in the literature in the combination of both detailed consumption principle and finer time granularity. As a solution to the gap in literature, this paper used a method accounting for both aspects where the country of interest is Switzerland and adopts an attributional approach.

2.3 Natural Gas Heating Demand Modelling

As stated in the CHP literature review, our paper adopted a top-down approach, starting from a global heating demand, to identify CHP potential in Switzerland (IEA, 2008). To be precise, we derived natural gas consumption for heating purposes only starting from global natural gas consumption. The following section is dedicated to this specific aspect.

Natural gas consumption modelling has been the focus of many recent studies as pointed out by Tamba et al. (2018), Šebalj et al. (2017) and Soldo (2012) in their respective literature review on forecasting of natural gas consumption. They brought to light the great variety of methods being used such as time-series regression (Herbert, 1987; Herbert et al., 1987; Huntington, 2007; L.-M. Liu & Lin, 1991; Sailor & Muñoz, 1997; Timmer & Lamb, 2007; Vitullo et al., 2009), econometric models (Yu et al., 2014), artificial neural networks (R. H. Brown et al., 1994; Gorucu, 2004; Khotanzad & Elragal, 1999; Suykens et al., 1996; Szoplik, 2015), fuzzy logic (Khotanzad et al., 2000; Musilek et al., 2006; Tonković et al., 2009), genetic algorithms (N. Aras, 2008), a combination of different models (Potočnik, Govekar, et al., 2007; Potočnik et al., 2014; Soldo et al., 2014; Taşpınar et al., 2013). Šebalj et al (2017) identified that the most often used method was neural network or technique based on similar principles. According to Tamba et al. (2018), it is still not clear among researchers which models surpass the other. Indeed, clear criterion for the selection of relevant variables and features for the construction of forecasting models is clearly lacking.

However, the importance of outdoor temperature when modelling natural gas consumption has been recognized a long time ago. Indeed, many researchers concluded that the most acceptable models where the one taking temperature into account (Sabo et al., 2011). As a result, temperature is very often integrated as one of the most important variables in the model (Bianco et al., 2014; Gil & Deferrari, 2004; Herbert et al., 1987; Khotanzad et al., 2000; Khotanzad & Elragal, 1999; L.-M. Liu & Lin, 1991; Potočnik, Govekar, et al., 2007; Potočnik, Thaler, et al., 2007; Sabo et al., 2011; Soldo et al., 2014; Spoladore et al., 2016; Suykens et al., 1996; Szoplik, 2015; Timmer & Lamb, 2007) The heating degree-day approach is used to correct the temperature dependency when no heating is needed and the boilers are off. (N. Aras, 2008; Berger & Worlitschek, 2018; R. H. Brown et al., 1994; Durmayaz et al., 2000; F. Gümrah, 2001; Gorucu, 2004; Herbert, 1987, 1987; Herbert et al., 1987; Huntington, 2007; Sailor & Muñoz, 1997; Sarak & Satman, 2003; Timmer & Lamb, 2007; Vitullo et al., 2009; Yu et al., 2014). Another approach has been developed by Aras and Aras (2004) where they used an autoregressive time series models for two distinct periods within a year: heating and non-heating periods. Another aspect has been the use of stepwise regression in order to illustrate this feature (Soldo et al., 2014)[5].

As pointed out above, natural gas consumption has been mainly modelled for the purpose of forecasting. However, in our study we need to model the global natural gas consumption in order to derive, at an hourly time step, natural gas consumed for heating purposes. This aspect has not been the focus of many researchers. Brabec et al. (2015) and Brabec (2010) developed a statistical model for disaggregation and reaggregation of natural gas consumption data to different time intervals. Grandjean et al. (2012), realized an analysis of the different existing residential electric load curve models and pointed out different disaggregation aggregation methods. They highlighted two different approaches: the Top-down and the Bottom-up approaches (Fumo, 2014; Grandjean et al., 2012; Swan & Ugursal, 2009). The former uses macroscopic data (e.g. total residential sector energy consumption) to attribute energy consumption to a sector according to its characteristics while the second use microscopic data (e.g. individual energy consumption) and then extrapolate to a sector.

Among the studies cited above, only three have been working with hourly data (Potočnik et al., 2014; Soldo et al., 2014; Spoladore et al., 2016).

Concerning Switzerland, Buffat & Raubal (2019) realized a bottom-up approach GIS-based building energy demand model for residential buildings. Using the register of buildings and dwellings to identify building using natural gas for space heating, they developed a model able to estimate the monthly energy demand for space heating. Berger & Worlitschek (2018), in a top-down approach, used heating degree days and map of population density to create a tempo-spatial map of heating demand suitable for energy system modelling.

As stated earlier, the disaggregation of global natural gas consumption in order to derive, at an hourly time step, natural gas consumed for heating purposes is something which has not been covered in the literature. As a solution to the gap

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[5] The focus of this review has been on papers deploying the top-down approach to model natural gas consumption at city or country level using temperature or heating degree day as additional variables.

in literature, this paper used various methods such as an econometric model based on the heating degree-hour methods using real hourly data where the country of interest is Switzerland.

3. Data and Methodology

3.1 Data collection and pre-processing

3.1.1 Countries electricity generation and cross-border electrical physical flows

Country-specific hourly data (in MWh/h) on electricity generation per production type and countries cross-border electrical physical flows data (in MWh/h) have been obtained from the ENTSO-E Transparency platform (Hirth et al., 2018). This platform, operated by the European Network of Transmission System Operators for Electricity (ENTSO-E), is a freely accessible online data platform. Even though this platform is an incredible data source of the European power system, some shortcomings regarding data quality have been pointed out (Hirth et al., 2018a) .

This is the reason we conducted different stages of data pre-processing (see Figure 23). First, given the fact that countries operate in different power market, data are reported at different time unit. Germany and Austria data are reported every 15 minutes and the other countries every hour. As a result, we had to aggregate quarter-hourly data to produce an hourly dataset. After having analysed descriptively the dataset, we compared the yearly total of the hourly data with national publicly available statistics. For France, the match was nearly perfect (around 98%). For Austria, Germany and Italy, the data from the platform corresponded for more than 80% to national statistics. In contrast, for Switzerland, we were able to identify important differences, particularly concerning the hydropower base generation type. Even though these differences were fading out through time (from 55% in 2016 to 72% in 2019), we decided to scale up hourly data to match national statistics. Differences can partly be explained by the fact that only power plant with a generation capacity above 100 MW must be reported on the platform. Finally, outlier detection and missing value analysis were conducted to obtain final datasets.

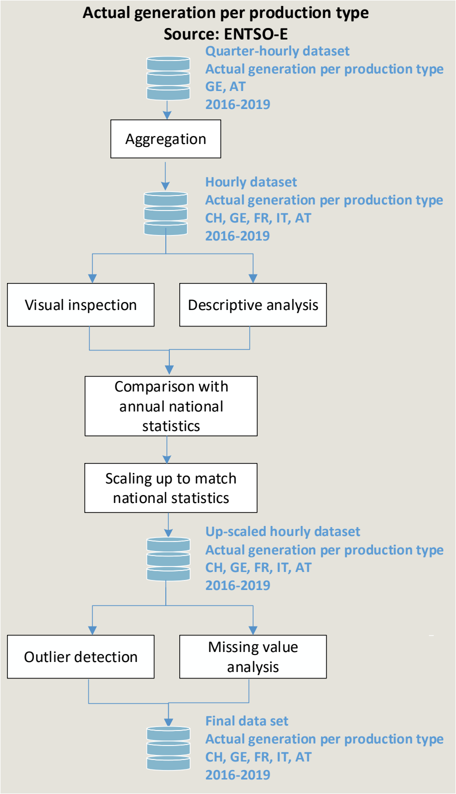

Figure 23 : Data processing process for country's electricity generation
Source: authors

3.1.2 GHG content of each generator type

Carbon intensity of each generator type (in kg of CO2-eq per kWh of the power produced) has been obtained from the 3.7.1 version of the Ecoinvent database on Life Cycle Inventory data (Wernet et al., 2016). After retrieving those data, we had to match them with the production type categories used in the ENTSO-E Transparency platform. The exact content of the categories used in the ENTSO-E platform is not clearly defined. Indeed, as reported by Hirth et al. (2018), this is due to the lack of accessible documentation and because there is room to interpretation of the few existing documentation. Even after mail exchanges with the platform, we had to make several assumptions regarding those categories.

3.1.3 Gas Consumption data

Hourly natural gas delivery data (in Nm3) and outside temperature (in °C) data have been made available thanks to the collaboration with the company which supplies and transports high-pressure natural gas to Western Switzerland. After discussion with experts and the company who provide us the data, we took the hypothesis that the hourly pattern of the Western part of Switzerland was similar to the whole country. This is the reason we decided to scale up Western Switzerland data to match national statistics. Then, we conducted the same stages of data processing than for the data from the ENTSO-E transparency platform.

3.2 Methodology

As stated earlier (see Figure 22), we developed a four-step methodology to answer the research questions. Each step is presented in detail in the following sections.

3.2.1 Assessing hourly GHG emission from electricity consumption and the impact of imports

The hourly carbon footprint (i.e. emission factor) of the electricity consumed in Switzerland in hour t ($EFCons_{CH,t}$) has been assessed according to the following equation:

$$EFCons_{CH,t} = \frac{MCons_{CH,t}}{ECons_{CH,t}} \tag{1}$$

The hourly electricity consumption in Switzerland ($ECons_{CH,t}$) in hour t and the related hourly GHG emissions ($MCons_{CH,t}$) in hour t have been assessed in accordance with the consumption principle (Vuarnoz & Jusselme, 2018; Bai et al., 2014; West et al., 2016). It means that the Swiss electricity generation mix has been considered as well as the country's electricity cross-border physical flows (imports and exports) with its neighbours (Germany, France, Austria and Italy) as illustrated in equations (2) and (3). Swiss hourly electricity generation ($EGen_{CH,t}$), importation ($EImp_{CH,t}$) and exportation ($EExp_{CH,t}$) data were taken from the ENTSO-E platform.

$$ECons_{CH,t} = EGen_{CH,t} + EImp_{CH,t} - EExp_{CH,t} \tag{2}$$

$$MCons_{CH,t} = MGen_{CH,t} + MImp_{CH,t} - MExp_{CH,t} \tag{3}$$

To assess the GHG emissions related to the electricity generation in Switzerland ($MGen_{CH,t}$) in hour t, the amount of hourly electricity generation by production type i ($EGen_{CH,it}$) in hour t has been multiplied by the emission factor of each production type i ($EF_{CH,i}$) as illustrated by equation (4). As stated earlier, the EF of a production type i in a given country l was taken from the ecoivent database version 3.7.1.

$$MGen_{CH,t} = \sum_{i=1}^{I} \left(EGen_{CH,it} * \ EF_{CH,i} \right) \tag{4}$$

Equation (5) expressed how the GHG emissions related to electricity imports from neighbouring countries to Switzerland in hour t ($MImp_{CH,t}$) has been assessed: by adding the amount of hourly physical electricity imports from each neighbouring countries l ($EImp_{lt}$) multiplied by an hourly emission factor of the electricity generated in each country ($EFGen_{lt}$).

$$MImp_{CH,t} = \sum_{l=1}^{L} (EImp_{lt} * EFGen_{lt}) \tag{5}$$

The latter has been assessed by the following equation:

$$EFGen_{lt} = \sum_{i=1}^{I} \left(\frac{EGen_{lit}}{\sum_{i=1}^{I}(EGen_{lit})} * EF_{li} \right) \tag{6}$$

As expressed in equation (5) and (6), the hourly GHG content of the electricity imports to Switzerland from neighbouring countries ($MImp_{CH,t}$) has been considered as being the same as the generation mix of the country of origin of the imports.

Finally, the hourly GHG content of the electricity exported from Switzerland to neighbouring countries ($MExp_{CH,t}$) has been assessed by the two following equations:

$$MExp_{CH,t} = \sum_{l=1}^{L} \left(Eexp_{lt} * \ EFExp_{CH,t} \right) \tag{7}$$

$$EFExp_{CH,t} = \frac{MGen_{CH,t} + MImp_{CH,t}}{EGen_{CH,t} + EImp_{CH,t}} \tag{8}$$

As illustrated in equation (7) and (8), the hourly GHG content of the electricity exported from Switzerland to neighbouring countries ($MExp_{CH,t}$) has been considered as being the same as the GHG content of the electricity generated in Switzerland and of the electricity imported from neighbouring countries.

3.2.2 Modelling hourly gas consumption for heating purposes

The second step of the methodology consisted of, based on raw hourly natural gas delivery data, deriving natural gas consumed for heating purpose only. We adopted a top-down econometric approach. Indeed, we used the two following equations to derive $\hat{Y}\mathrm{Heat}_t$, the estimated hourly natural gas consumption for heating purposes.

$$\hat{Y}Heat_{\mathrm{t}} = \beta_1 \, \mathrm{HDH_t} \tag{9}$$

$$Y_{\mathrm{t}} = \beta_0 + \beta_1 \, \mathrm{HDH_t} + \ \beta_2 \, \mathrm{Hour}_t \ + \beta_3 \, \mathrm{Weekday}_t \ + \beta_5 \, \mathrm{Bankholiday}_t + \ \varepsilon_{\mathrm{t}} \tag{10}$$

Where $\mathrm{Y_t}$ is natural gas consumption at the time t, $\beta_1,\ldots,\beta_5$ are regression coefficients which we want to estimate, $\mathrm{HDH_t}$ is the heating degree-hour value for hour t, Hour_t is a categorical variable accounting for the hour of the day i.e. $\mathrm{Hour}_t \in \{1,\ldots,23\}$, $\mathrm{Weekday}_t$ is a categorical variable accounting for the day of the week i.e. $\mathrm{Weekday}_t \in \{2,\ldots,7\}$, $\mathrm{Bankholiday}_t$ is a dummy variable accounting for the Swiss holidays i.e. $\mathrm{Bankholiday}_t \in \{0,1\}$ and ε_{t} is a random error . Assumptions for the errors are that they are independently identically distributed (i.i.d.) with distribution $\varepsilon \sim N(0, \sigma^2)$. Estimation of regression coefficients is done by ordinary least square (OLS).

Heating degree hour $(\mathrm{HDH_t})$ has been assessed by adopting the definition of the heating degree day of the Swiss SIA standard 381/3 (SIA, 1982) to an hourly usage as represented in the following equation:

$$\boldsymbol{HDH}(\theta_{\mathrm{in}}, \theta_{\mathrm{th}}) = \mathrm{m_t} \sum_{t=1}^{T} (\theta_{\mathrm{in}} - \theta_{\mathrm{ex,t}}) \tag{11}$$

$$\mathrm{m_t} = 1\, hour\ \ if\ \theta_{\mathrm{ex,t}} \leq \theta_{\mathrm{th}}$$
$$\mathrm{m_t} = 0\, hour\ \ if\ \theta_{\mathrm{ex,t}} > \theta_{\mathrm{th}}$$

Where θ_{in} denotes the internal temperature, $\theta_{\mathrm{e,t}}$ the hourly mean external temperature, θ_{th} the threshold temperature for heating, t stands for the hour number in the year i.e. t ∈ {1,…,8760}. According to the Swiss SIA standard 381/3, $\theta_{\mathrm{in}} = 20°C$ and $\theta_{\mathrm{th}} = 12°C$ were assumed in this study.

To define equation (10) we first identified in the literature potential model and variables. Then, we developed an equation which we tested and transformed (inclusion/exclusion of variables) until we reached the validity of the model and ruled out any hypotheses of endogeneity, serial-correlation, heteroskedasticity and non-normality of the error term. The process is illustrated in Figure 24:

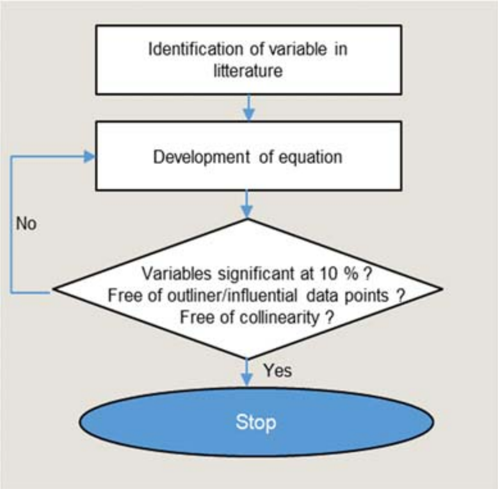

Figure 24 : Flow chart diagram illustrating the methodology to develop the equation
Source: authors inspired by (Aydinalp-Koksal & Ugursal, 2008))

In order to ensure the robustness of the model, we compared it with two others: an engineering approach which is the heating signature and a two-point regression model. Those two models are illustrated in Appendix 2.

3.2.3 Simulating hourly electricity production with natural gas CHP plants

The approach adopted here was that the hourly heat needs identified earlier had to be covered by the thermal output of the CHP plant. We considered the CHP plant as a linear model which is an energy converter with fixed electrical and thermal efficiencies. We did not consider load modulation. As stated in the literature review, we adopted a top-down approach, where global heating demand is used to derive potential CHP power and heating generation by applying average power to heat ratio corresponding the current technology (IEA, 2008).

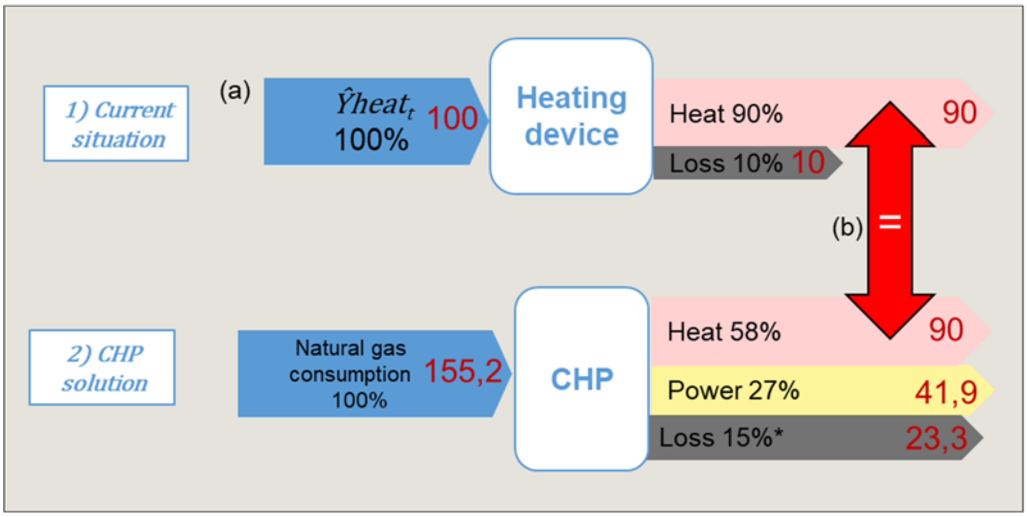

Figure 25: CHP plant model schem and its parameters
Source: authors

As Bianca Howard et al. (2014), only internal combustion engines and microturbines were considered for the current analysis because of their great range of sizes and because they can easily be fuelled with natural gas. We used CHP plant parametrization indicated in the EcoIvent 3.7.1 database for the electricity generated with CHP in Switzerland. In order to ensure the robustness of the model, we conducted multiple simulation with variation of those parameters.

3.2.4 Assessing hourly GHG emissions from electricity consumption with CHP solution

For the last part, we used a conditional attribution of the electricity produced with the simulated CHP solution. Indeed, the electricity produced replaced at first imports (without any generation type selected or country but the global mix). If the CHP electricity production was higher than the imports, the domestic generation was replaced.

The following equations illustrated how the new emission factor $(EFCons_{CH,t}^{New})$ is assessed when the electricity produced by the simulated CHP solution $(ECHP_{CH,t})$ is strictly smaller than the imports $(EImp_{CH,t})$ (see equation (12)). The other cases are presented in appendix 3.

$$ECHP_{CH,t} \leq EImp_{CH,t} \tag{12}$$

As in the first step of the methodology, the new hourly electricity consumption in Switzerland $ECons_{CH,t}^{New}$ in hour t and the related hourly GHG emissions $MCons_{CH,t}^{New}$ in hour t have been assessed in accordance with the consumption principle as illustrated in equations (14) and (15).

$$EFCons_{CH,t}^{New} = \frac{MCons_{CH,t}^{New}}{ECons_{CH,t}^{New}} \tag{13}$$

$$ECons_{CH,t}^{New} = ECHP_{CH,t} + EGen_{CH,t} + EImp_{CH,t}^{New} - EExp_{CH,t} \tag{14}$$

$$MCons_{CH,t}^{New} = MCHP_{CH,t} + MGen_{CH,t} + MImp_{CH,t}^{New} - MExp_{CH,t}^{New} \tag{15}$$

The difference is that, we have in addition electricity produced by the simulated CHP solution ($ECHP_{CH,t}$and the GHG related emissions ($MCHP_{CH,t}$). As stated earlier, the electricity production from the CHP solution is used to diminish the importation as illustrated in equation (16).

$$EImp_{CH,t}^{New} = EImp_{CH,t} - ECHP_{CH,t} \tag{16}$$

The GHG emissions related to the electricity produced by the simulated CHP solution ($MCHP_{CH,t}$) has been assessed by multiplying the hourly electricity production by an emission factor (EF_{CHP}) taken from the Ecoivent database version 3.1.

$$MCHP_{CH,t} = ECHP_{CH,t} * EF_{CHP} \tag{17}$$

As stated earlier, the approach adopted was that the electricity produced replaced imports without any generation type selected or country, but the global mix. This is illustrated in the two following equations:

$$MImp_{CH,t}^{New} = EImp_{CH,t}^{New} * EFImp_{CH,t} \tag{18}$$

$$EFImp_{CH,t} = \frac{MImp_{CH,t}}{EImp_{CH,t}} \tag{19}$$

As illustrated in question (20) et (21), the GHG content of the export has been assessed similarly as in the first part, with the exception of the fact that we have taken into consideration the electricity produced and the GHG emissions related of CHP solution.

$$MExp_{CH,t}^{New} = Eexp_{CH,t} * EFExp_{CH,t} \tag{20}$$

$$EFExp_{CH,t} = \frac{New_{MImp_{CH,t}} + MGen_{CH} + MCHP_{CH}}{New_{EImp_{CH,t}} + EGen_{CH} + ECHP_{CH}} \tag{21}$$

4. Results

4.1 GHG content of the electricity consumed in Switzerland and impact of imports

This section presents the results answering our first research question. The results for the year 2016 to 2019 show that, imports impact strongly and negatively the GHG footprint of the electricity consumed in Switzerland. More precisely, it is heavily impacted by imports from Germany and its coal-based power production. As illustrated in Figure 26, for the year 2016, imports from Germany account for 19% of the electricity consumed in Switzerland while they account for 74% of its GHG content. On the contrary, domestic electricity generation accounts for 67% of the electricity consumed while it accounts only for 19% of its GHG content. Indeed, in Switzerland, electricity is mainly generated by hydropower and nuclear power (respectively 64% and 35% in 2016), two low-carbon technologies.

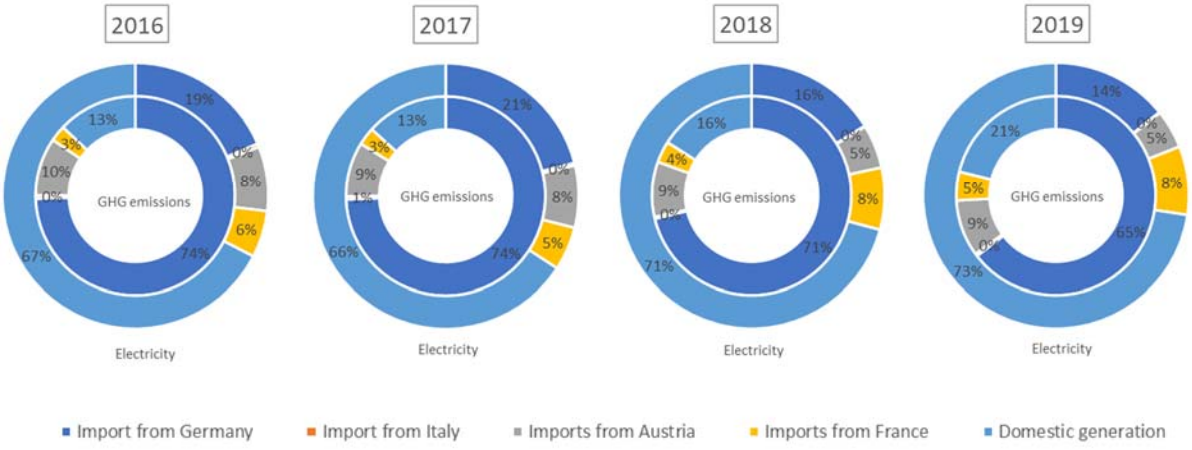

Figure 26: Source of the electricity consumed in Switzerland and its related GHG content
Source: authors

The impact of the imports from Germany on the carbon footprint of the electricity consumed in Switzerland is fading through time. Indeed, it accounts for 74% in 2017, 71% in 2018 and finally drops to reach 65% in 2019. This downward trend can be explained by the change in the generation mix in Germany. Indeed, as presented in Figure 27, we can see that share of new renewable energies increased from 29% in 2016 to 42% in 2019 and the share of coal and lignite decrease from 40% in 2016 to 29% in 2019. Imports from Italy, Austria and France have a relatively low importance on the carbon footprint of the electricity consumed (15 % for the three of them in 2016) even if they account for 14% of the electricity consumed in 2016.

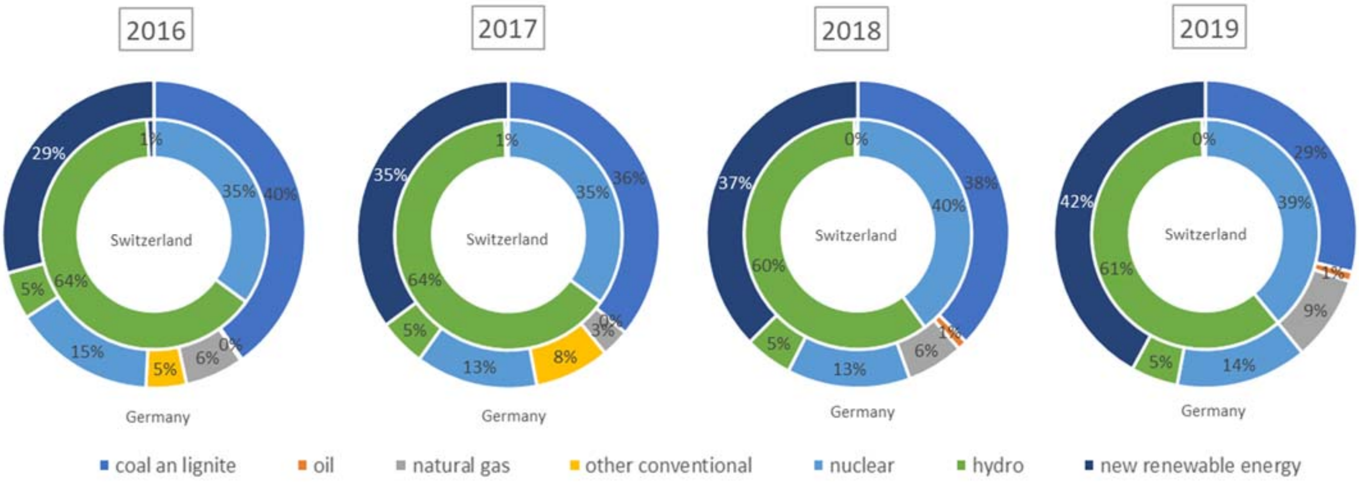

Figure 27: Switzerland and Germany Generation Mix
Source: authors

Figure 28 displays the huge range between which the hourly EF varies over time. Indeed, between 2016 and 2019 the maximum value in winter was up to 579.640 g CO2eq/kWh and the minimum value, in summer, was less than 5.126 g CO2eq/kWh. It means that the carbon footprint of electricity consumed in winter can be 113 times higher than in summer. The seasonal impact on the carbon footprint of the electricity consumed is very pronounced in Switzerland. It is interesting to note that the pattern is very similar to the seasonal pattern of the natural gas consumption (see Figure 29) which confirms the validity of the idea of the deployment of CHP fuelled with natural gas.

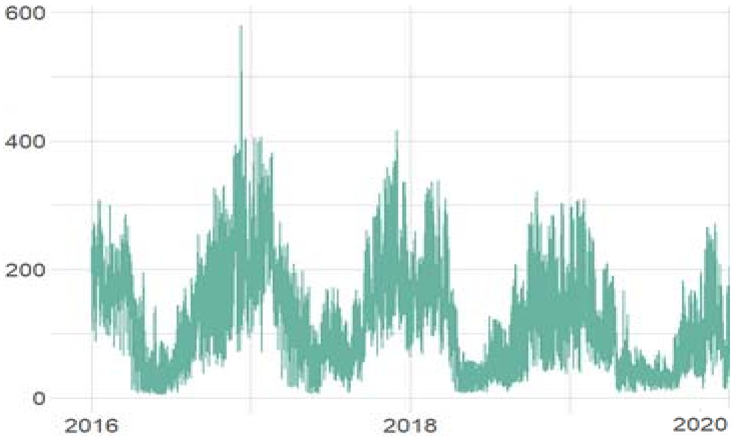

Figure 28: Hourly emission factor of the electricity consumed in Switzerland (in g CO2eq/kWh)
Source: authors

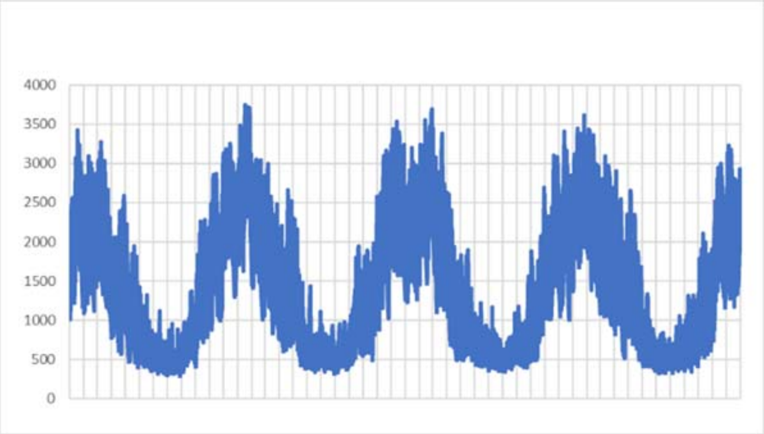

Figure 29: Hourly natural gas consumption in Western Switzerland (MWh/h)
Source: authors

4.2 GHG content of the electricity consumed in Switzerland with the CHP simulation

The results of the simulation part show that the development of decentralized power generation through natural gas-fired CHP plants can lower the GHG footprint of the electricity consumed in Switzerland (see Table 11). Indeed, for the year 2016 the EF is 6.83% lower for the CHP simulation (133.76 g CO2eq/kWh) than the actual situation (143.58 g CO2eq/kWh). As it was expected, the benefit of the simulation is also fading through time because of the growing part of new renewable electricity generation in Germany. Indeed, the benefit of the deployment of CHP fuelled with natural gas decreases gradually. Indeed, it even become a drawback in 2019, as the EF of the CHP simulation is 1.07% higher than the actual EF.

Year	$\mathbf{EFCons_{CH}}$ (g CO2eq/kWh)	$\mathbf{EFCons_{CH}^{New}}$ (g CO2eq/kWh)	Variation (%)
2016	143,58	133,76	-6.83
2017	150,83	140,84	-6.62
2018	118,18	114,36	-3.23
2019	94,36	95,37	1.07

Table 11 : Actual emission factor of the electricity consumed and results of the CHP simulation
Source: authors

The deployment of the CHP fuelled with natural gas would allow to reduce the impact of the imports from Germany on the carbon footprint of the electricity consumed in Switzerland (Figure 30). Indeed, from 74% (Figure 26), it would decrease to reach 52% for the year 2016. The electricity imports from Germany would decrease from 19% (Figure 26) to 12% in 2016.

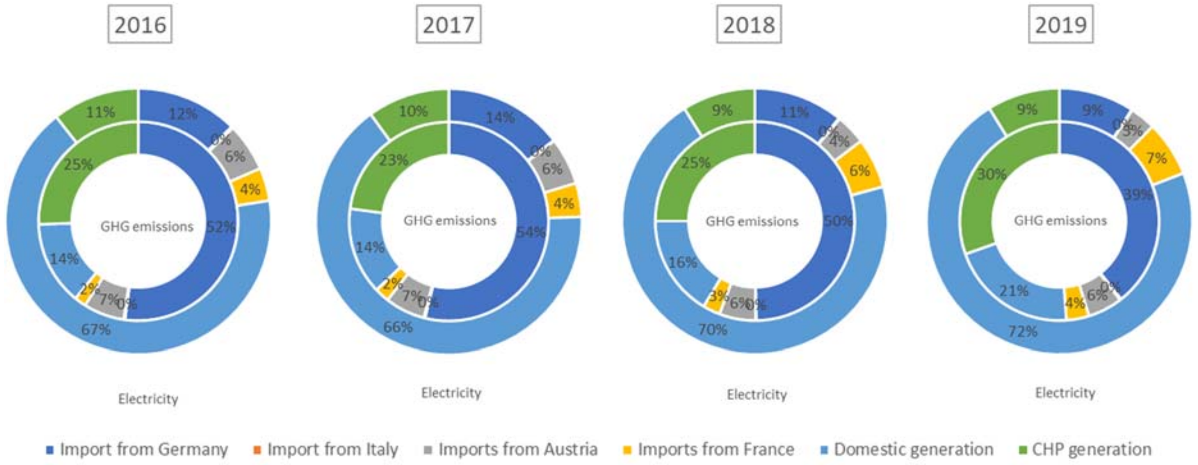

Figure 30: Source of the electricity consumed in Switzerland and its related GHG content after the CHP simulation
Source: authors

The Figure 31 shows how the deployment of CHP would actually help reduce the peaks of the carbon intensity of the electricity consumed in Switzerland in winter.

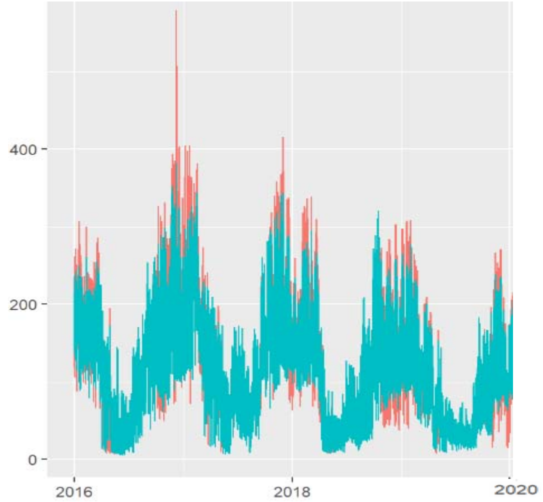

Figure 31: Actual hourly emission factor of the electricity consumed in Switzerland (in red) and hourly emission factor after the simulation (in blue) - (in g CO2eq/kWh)
Source: authors

5. Conclusion

This paper applied an hourly approach to evaluate, for the years 2016 to 2019, the hourly carbon footprint of the electricity consumed in Switzerland. We measured, the impact of the electricity imports from neighbouring countries and simulated how the deployment of CHP fuelled with natural gas would impact this carbon footprint. The geographical scope of this analysis was Switzerland with its direct neighbours (Germany, France, Italy and Austria). It demonstrates that, the Swiss growing dependency on electricity imports during winter has, indeed, a non-negligible impact on the environment. More precisely, it is heavily impacted by imports from Germany and its coal-based power production. Indeed, for the year 2016, imports from Germany accounted for 19% of the electricity consumed in Switzerland while they accounted for 74% of its GHG content. This impact on the carbon footprint of the electricity consumed has decreased through time (from 74% in 2016 to 65% in 2019) due to Germany increasing new renewable energies generation. However, this downward trend should be taken with caution as Germany intend to reach its total coal phase out only by 2038 (BMWi, 2019). In addition, Switzerland has only recently started its nuclear phasing-out process. Indeed, Mühleberg nuclear power plant was the first nuclear power plant to be permanently shut down the 20th of December 2019. Eventually, Switzerland will have to be able to replace 40% of its electricity production. It is probable that, until the development of renewable energies and the reduction in consumption fully compensate the missing electricity production, imports in winter will increase.

The natural gas-fired CHP solution examined in this study could represent a less-carbon intensive alternative. Indeed, it would allow to reduce the carbon footprint of the electricity consumed in Switzerland by up to 6.83%. In addition, being based on existing technology and infrastructure (gas grid), this solution could be deployed in a very short span. This aspect is of particular importance because CO2 emissions shall start to diminish before 2030 if we want to limit global warming to 1.5C° (IPCC, 2018). The necessity to act before 2030 is an aspect that has been neglected in the Energy Strategy 2050 whose objectives are more farsighted. Policy-makers should examine the fact that natural gas could play a temporary role in the energy transition. Another aspect highlighted in this study is the importance of taking into consideration spatial and temporal sensitivity of the carbon content of the electricity consumed. Indeed, as seen in the results, imports from neighbouring countries strongly impact the carbon footprint of the electricity consumed. Moreover, the range between which the carbon footprint varies through time is huge: it can be 113 times higher in winter than in summer. It is essential for policy-makers to take into consideration those two aspects when designing new energy policies. Further research in this area could be carried out in order to investigate the feasibility and the costs of deploying such a solution. In addition, the effect of the nuclear phase out on the hourly carbon footprint should be explored.

6. Acknowledgement

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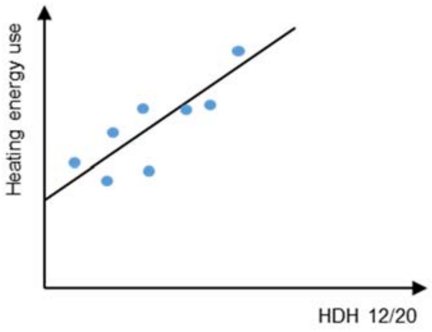
1. Appendix 1- ENTSO-E generation categories

Biomass,
Fossil Brown coal/Lignite
Fossil coal-derived gas
Fossil gas
Fossil Hard coal
Fossil oil
Fossil oil shale
Fossil peat
Geothermal
Hydro pumped storage
Hydro Run-of-River and poundage
Hydro water reservoir
Marine
Nuclear
Other
Other renewable
Solar
Waste
Wind offshore
Wind onshore

2. Appendix 2 – Additional natural gas consumption for heating purposes models

Heating Signature

$$Y_t = \beta_0 + \beta_1 \,\mathrm{HDH}_t + \varepsilon_t$$
$$\hat{Y}Heat_t = Y_t - \beta_0$$

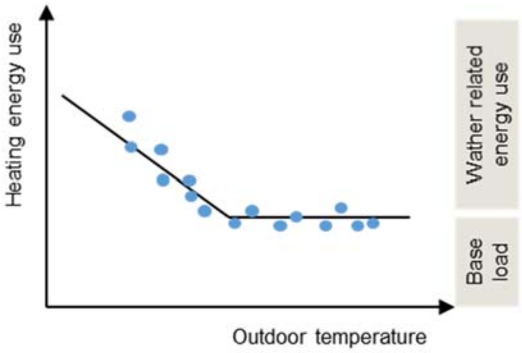


Symbols

Y_t	*natural gas consumption*
$\beta_0,\ldots,\beta_1$	*regression coefficients*
HDH_t	*heating degree hour*
ε_t	*error term*
$\hat{Y}heat_t$	*estimated natural gas consumption for heating purposes*

Piecewise linear relationships in segmented regression models

This method allows us to identify a the "real" breakpoint, the outside temperature after which natural gas consumption is not related to.



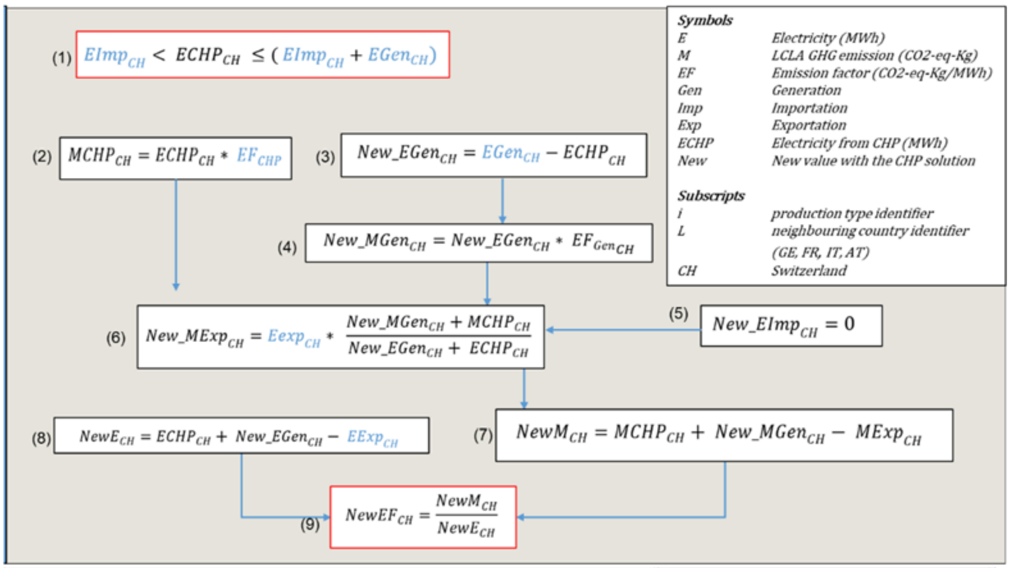
$$Y_t = \beta_0 + \beta_1 \,\mathrm{Temp}_t + \beta_2 \,(\mathrm{Temp}_t - \psi)_+ + \varepsilon_t$$
$$\hat{Y}Heat_t = \beta_0 + \beta_1 * \psi$$

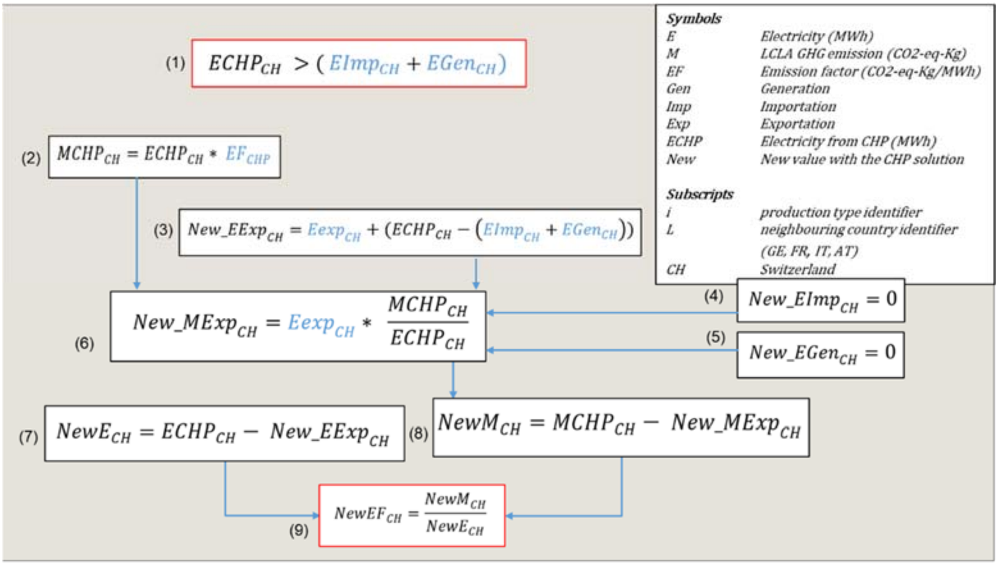
Symbols

Y_t	*natural gas consumption*
$\beta_0,\ldots,\beta_2$	*regression coefficients*
Temp_t	*outside temperature °C*
ψ	*breakpoint*
ε_t	*error term*
$\hat{Y}heat_t$	*estimated natural gas consumption for heating purposes*

We performed a breakpoint analysis with the R Package "segmented" (Muggeo, 2003, 2008). It calculates multiple linear regressions for data with dependent variables that can be expressed by two or more straight lines with different slopes linked at a breakpoint and calculates these breakpoints.

3. Appendix 3 – Conditional attribution of the simulated CHP electricity produced





Paper III : Sector coupling of power and gas with combined heat and power plants: An investment to foster the Swiss energy system decarbonization ?

Simon, E., Cimmino, F. M., & Genoud, S. (Eds.). (2021b). Sector coupling of power and gas with combined heat and power plants: An investment to foster the Swiss energy system decarbonization ? In Proceedings of the 10th FSR Annual Conference—Infrastructure Investment Challenges: Reconciling Competition, Decarbonisation and Digitalisation. 10-11 June 2021.

Abstract

Switzerland is currently phasing out from nuclear energy. This represents a real challenge for the country as it represents nearly 30% of its domestic power generation. This phasing-out might further increase the Swiss power import dependency, especially in winter. This winter dependency might become a threat to the security of supply, magnified with the electrification of the Swiss energy system with heat pumps and battery electric vehicles. In this paper, we explore how Combined Heat and Power (CHP) plants fuelled with natural gas or biogas might represent a short-term solution to produce power in winter on the Swiss territory. We analysed effect of the deployment of this solution on the hourly carbon footprint of the electricity consumed in Switzerland. We used a four-step methodology developed in our previous work but extended the geographical scope of the analysis to Switzerland with its direct neighbours (France, Italy, etc.) and their neighbours (Spain, Danemark, etc.). We run the analysis from the years 2016 to 2020 which allows us to analyse the effect the decommissioning of the Mühleberg nuclear in December 2019. The results show that the deployment of this solution could lower the GHG footprint of the electricity consumed in Switzerland up to 7.51%. However this effect is fading through time and even increase the electricity footprint for the year 2020. This is mainly due to the fact that the power generation mix of Germany is constantly getting cleaner. We also examined the barriers to the deployment of small CHP units for domestic usage in Switzerland. The results show that the technology is facing many obstacles. As long as there is no clear definition of a strategy regarding CHP technology at federal and cantonal level, a real market penetration seems compromised.

Key words: combined heat and power, sector coupling, hourly GHG emission factor, natural gas, regulatory and policy barriers

1. Introduction

The Fukushima nuclear disaster in 2011 combined with the release of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in 2014 highlighted the need to build a secure energy system capable of meeting energy demand while taking into account the absolute necessity of preserving the environment in order to mitigate global warming and natural resource depletion. A growing number of countries have therefore committed to a transition to a low-carbon energy system. This is the case in Switzerland, which has developed the Energy Strategy 2050. This strategy is based on three pillars: reducing energy

consumption and increasing energy efficiency, promoting renewable energies and phasing-out of nuclear power. The latter represents a real challenge for the country as it represents nearly 35% of its domestic power generation capacity (OFEN, 2020d). In addition, it means removing a low-carbon source of power in the medium-long run. Therefore, phasing-out of nuclear power represents an additional challenge to meet the country's policy objectives on climate change mitigation.
In the long term, the missing nuclear capacity should be fully compensated by the development of renewable energies and decrease in consumption. In the short-medium term, it might increase the already growing power import dependency, especially in winter. This winter dependency might become a threat to the security of supply, as pointed out by the Federal Electricity Commission (ElCom, 2020). This is why, the commission asked for the development of production capacities during the winter semester on the Swiss territory. The electrification of the Swiss energy system with heat pumps and battery electric vehicle might further increase those winter imports and increase the threat to the security of supply (Rüdisüli et al., 2019).

In this paper, we demonstrate how sector coupling of natural gas infrastructure and power infrastructure might play a welcome role in addressing this challenge. The main idea is to use small distributed combined heat and power (CHP) units fuelled with natural gas or biogas to produce power in winter on the Swiss territory. This simple, short-term solution might represent an investment opportunity for both sectors but also a reduction in GHGs, an improvement in the energy balance and a greater resilience of the electricity network.

Combined Heat and Power system (CHP) is a technology which produces electricity and captures the waste heat for different processes such as space and water heating. It is a highly efficient system which can lead to primary energy saving (Bianchi et al., 2013) and GHG emission reduction (IEA, 2008). Indeed, this combined system is more efficient than separate conventional technologies such as centralized power plant where the heat is not recovered and an on-site boiler. Another advantage is that by producing electricity locally, it reduces reliance on the electricity grid. Finally, it produces power in winter, and can, as a result offset the low power capacity of solar and hydropower during this season. This symbiotic relationship contribute to the stability of the electricity grid (Mostofi et al., 2011; Nosrat et al., 2014; Pearce, 2009)

Our study aims at exploring the impact of the deployment of such solution in terms of decarbonization. More precisely, it aims at answering the following research questions:

- What effect the deployment of small CHP units fuelled with natural gas would have on the hourly carbon footprint of the electricity consumed in Switzerland ?

- How this result would potentially change after the decommissioning of the Mühleberg nuclear power plant?

- What are the economic, regulatory and policy barriers hindering penetration of CHP in Switzerland?

Section 2 presents the literature review, the methodology and the results of the effect of the deployment of small CHP units on the Swiss hourly carbon footprint. Section 3 presents the literature review and the results of the identified barriers to CHP development in Switzerland. Finally, the paper concludes with section 4 with conclusions and potential policy implication.

2. Effect of the deployment of small CHP units on the Swiss hourly carbon footprint of the electricity consumed

2.1 Literature review

A great number of studies have explored the potential role CHP can play in reducing GHG emission and help cities or countries meet their objectives on climate change mitigation.

Most of the authors adopted a bottom-up approach and carried out analyses at the building level and then extrapolated it to the country or city level. This is the case for Howard et al. (2014) for New York City, H. Liu et al. (2017) for China and Kelly et al. (2014) for the UK. Another less common approach is the top-down approach, where global country/city heating demand is used to derive potential CHP power and heating generation by applying average power to heat ratio corresponding to the current technology (IEA, 2008). This is the method adopted in this study.

In the studies cited above, CHP systems are compared with a reference system for heat and electricity generation such as traditional boiler and electricity from the grid (Dorer & Weber, 2009; Howard et al., 2014; Howard & Modi, 2017; Hueffed & Mago, 2010, 2010; Mago et al., 2011; Mago & Smith, 2012; Rosato et al., 2013).

The GHG content of the electricity from the grid is often pointed out as a critical element when evaluating the benefit of CHP solution compared to another (Howard & Modi, 2017; H. Liu et al., 2017; Mago et al., 2011). In all those studies, the GHG content of the electricity from the grid has been considered as constant over time and only the domestic power generation mix has been considered. However, the latter changes continuously depending on the ever-changing demand and the energy resource availability. Moreover, electricity exchanges between countries may also affect the GHG content of the electricity consumed.

We addressed this gap in the literature in our previous work where we used an hourly approach and took into account Swiss power physical exchanges (imports and exports) with its neighbours. (Simon et al., 2021). In the present paper, we took the analysis further by extending the geographical scope of the analysis to direct neighbours (France, Italy, etc.) and their neighbours (Spain, Denmark, Poland, etc.).

2.2 Methodology

To answer the first research question, we used the four-step methodology developed in our previous work (Simon et al., 2021) (see Figure 32) .
Firstly, we assessed, for the years 2016 to 2019, the GHG content of the electricity consumed in Switzerland applying the attributional Life Cycle Analysis (LCA) approach. We adopted a fine granularity (hourly) and took into account physical exchanges (imports and exports) with other countries. We extend the geographical scope of this analysis to Switzerland with its direct neighbours (France, Italy, etc.) and their neighbours (Spain, Danemark, etc.). It has been realized by a combination of data from the Ecoinvent database version 3.7.1 (Wernet et al., 2016) and data from the ENTSO-E transparency platform (Hirth et al., 2018b).
Secondly, based on natural gas delivery data, we modelled hourly gas consumption for heating purposes. We adopted a top-down econometric approach using heating degree hours according to the Swiss SIA standard 381/3 (SIA, 1982). Data have been made available by the company which supplies and transport high-pressure natural gas to Western Switzerland.
Thirdly, based on the previous part, we simulated hourly electricity production with natural gas CHP plants. The hourly heating demand identified earlier had to be covered by the thermal output of the CHP plant. We considered the CHP plant as a linear model, or in other words, an energy converter with fixed electrical and thermal efficiencies.

Finally, we assessed the hourly GHG emission of the electricity consumed in Switzerland with the CHP solution. We used a conditional attribution of the electricity produced with the simulated CHP solution.
To answer the second question, we used the same methodology than previously explained but on the year 2020. Indeed, since 20 December 2019, Mühleberg nuclear power plant has been permanently shut down. This allowed us to see the impact in terms of GHG emissions.

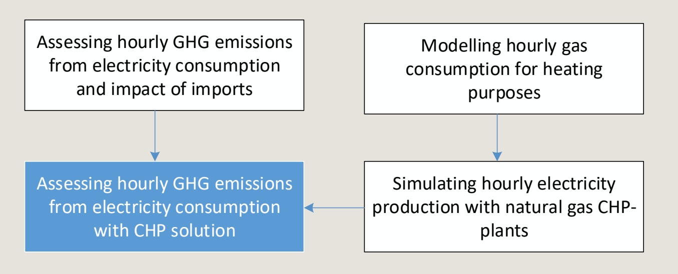


Figure 32 : The four parts of the research process
Source: Simon et al. (2021)

2.3 Results

The results show that the deployment of CHP plants fuelled with natural gas can lower the GHG footprint of the electricity consumed in Switzerland up to 7.51% (see Table 12). Indeed, for the year 2016 the emission factor is 7.51% lower after the CHP simulation going from 149.30 g CO2eq/kWh to 138.09g CO2eq/kWh. However, the benefit of the simulation is fading through time and become even a disadvantage in 2020. Indeed, in 2020 the emissions factor increases by 8.67% after the simulation going from 80.58 g CO2eq/kWh to 87.56 g CO2eq/kWh.

Year	**Emission Factor** Actual (gCO2eq/kWh)	**Emission Factor** After CHP simulation (gCO2eq/kWh)	**Variation** (%)
2016	149.30	138.09	-7.51 %
2017	155.46	144.49	-7.06%
2018	121.24	116.63	-3.81%
2019	96.85	97.12	0.28%
2020	80.58	87.56	8.67%

Table 12 : Actual emission factor of the electricity consumed and results of the CHP simulation (first and second ring countries)
Source: authors

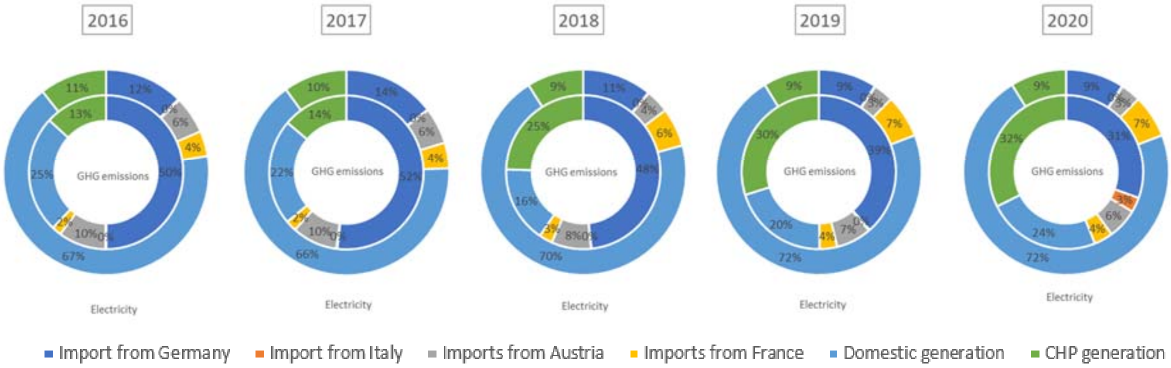


Figure 33: Source of the electricity consumed in Switzerland and its related GHG content after the CHP simulation
Source: authors

This tendency is because of the growing part of new renewable electricity generation in Germany. Indeed, the impact of the imports from Germany on the carbon footprint of the electricity consumed in Switzerland, as shows in Figure 33, went from 50% in 2016 to 31% in 2020. The proportion of the imports from Germany of the electricity consumed in Switzerland went from 12% in 2016 to 9% in 2020.

This tendency is also because of a growing part of new renewable electricity generation in Switzerland. This can be observed in grey in Figure 34 which shows the hourly domestic generation mix of Switzerland from the years 2016 to 2020. In this figure, we can also observe the decrease in the nuclear generation due to the decommissioning of the Mühleberg power plant in December 2019. It produced 13.4 % of Switzerland 's nuclear electricity from 2016 to 2019 (OFEN, 2020d).

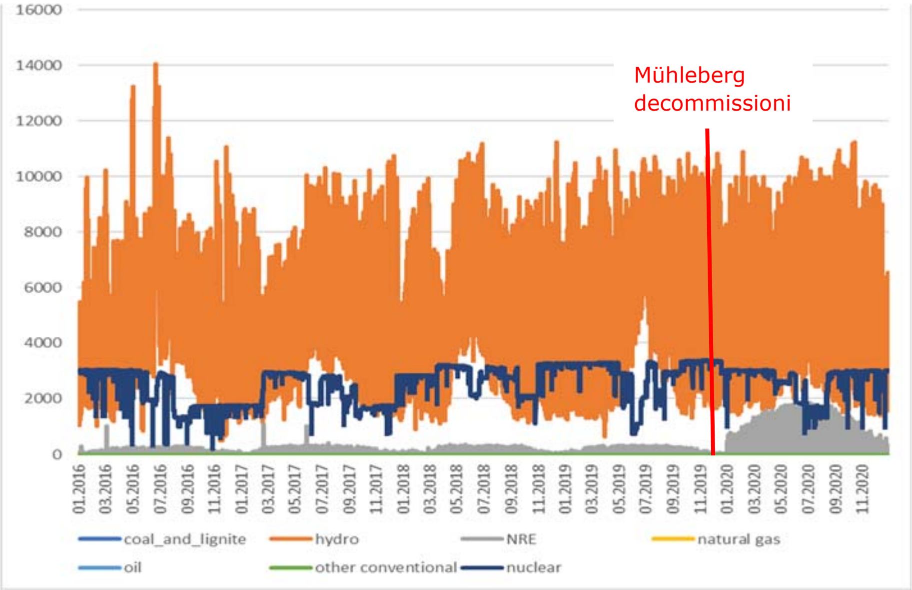


Figure 34: Hourly domestic generation mix of Switzerland
Source: authors

This decrease in 2020 can be observed in dark blue in Figure 34. It is hard to clearly identify the effect of the Mühleberg decommissioning because it has been accompanied by a large increase in new renewable energy generation. We cannot know if this increase is related or independent from the decommissioning. Further studies should be carried out in order to analyse this phenomenon.

Table 13 shows the results of the simulation when only Switzerland's direct neighbours (France, Italy, Germany and Austria) are taken into account. It is interesting to note that the actual emission factors (before CHP simulation) are lower when we take into account only direct neighbours than when we integrate second ring countries (Spain, Denmark, Poland, etc.) in the analysis. This is mainly due to Germany's imports from Poland which are heavily carbonized.

Year	**Emission Factor** Actual (CO2eq/kWh)	**Emission Factor** After CHP simulation (CO2eq/kWh)	**Variation** (%)
2016	143.58	133.76	-6.83 %
2017	150.83	140.84	-6.62%
2018	118.18	114.36	-3.23%
2019	94.36	95.37	1.07%
2020	79.15	86.49	9.27%

Table 13 : Actual emission factor of the electricity consumed and results of the CHP simulation (direct neighbour countries only)
Source: authors

Table 14 displays the results of the simulation when we consider that the CHP are fuelled both with natural gas and biogas. When CHP are fuelled with a proportion of 30% of biogas and 70% of natural gas, the benefit of the deployment of CHP goes up to 12.69% in 2016. The proportion of 30% corresponds to a commitment made by the Swiss gas association to reach 30% of renewable gas in the gas segment of the heating market by 2030 (A. S. de l'Industrie G. ASIG, 2018).

Year	**EF** After sim. 10% biogas (CO2eq/kWh)	**Var.** (%)	**EF** After sim. 30% biogas (CO2eq/kWh)	**Var.** (%)
2016	135.51	-9.42%	130.35	-12.69%
2017	142.04	-8.63%	137.14	-11.78%
2018	114.50	-5.56%	110.26	-9.06 %
2019	94.98	-1.94%	90.69	-6.37 %
2020	85.45	6.06%	81.25	0.83 %

Table 14: Emission Factor after simulation with different proportions of biogas
Source: authors

In conclusion, the deployment of this solution could lower the GHG footprint of the electricity consumed in Switzerland. However, this observation does not hold with an increase in new renewable generation in Switzerland and Germany. It is important to consider not only the electricity exchange with direct neighbour countries (France, Italy, Germany and Austria) but also with second ring countries (Spain, Denmark, Poland, etc.). The effect of the decommissioning of the Mühleberg nuclear power plant on the GHG footprint of the electricity consumed in Switzerland is hard to isolate. Further studies should be carried out in this direction.

3. Identified barriers to CHP development in Switzerland

3.1 Literature review

In the Netherlands, the UK, Germany, Japan and the USA, CHP systems are considered as part of the energy transition strategy (J. E. Brown et al., 2007b; Kobayashi et al., 2005b). These countries have put in place favourable conditions for the deployment of this technology. However, in those countries and elsewhere there are still barriers for an appropriate market penetration.

The financial barriers are one of the biggest obstacles. Indeed, the high capital investment is an important barrier both in the UK (Howard et al., 2014) and in the USA (M. Liu et al., 2014). Another critical financial aspect is the difference between the price of electricity and the price of gas. For instance, in the UK, the high volatility of those prices makes the return on investment uncertain. Those aspects, combined with an unstable carbon price are slowing down the place of the CHP deployment in the UK (M. Liu et al., 2014).

The interconnection to the local utility is an important barrier to CHP market implementation in the USA (Howard et al., 2014; M. Liu et al., 2014). Indeed, the process to evaluate the impacts of a CHP on the existing grid is often long and complicated, adding extra cost to the project.

In their market studies, Kuhn et al. (2008, p. 8) identified the fact that few systems were available as an explanation why there was so few progress in market penetration in the UK.
They also pointed out that decision maker such as architects or civil engineering are not familiar with the system. Finally, the lack of installation and service network is also a barrier identified both in the UK and the Netherlands.

Small CHP units for domestic usage have a huge technical potential in Switzerland but are facing many obstacles such as technical problems in operation, high cost of installations and lack of operator skills. There, CHP systems are confronted to too many obstacles to penetrate the market by themselves in the coming year. On the other hands, CHP related to municipal waste incineration and water treatment are facing fewer barriers and as a result their potential is already almost fully exploited (Rieder et al., 2009).

3.2 Methodology

Barriers for the deployment of CHP in Switzerland were identified by conducting documentary research enriched with exchanges with experts.

3.3 Results

Legal barriers : improvement of the framework conditions but not enough

Generally speaking, the existence of strict and different legislations at national, cantonal and communal levels results in complex framework conditions in Switzerland.
However, at the federal level, we can notice an improvement of the conditions for CHP system plants with the new **Federal Energy Act** (2016). Those improvements are the following:

- network operators are obliged to accept and remunerate all the electricity fed-in from small CHP plants (≤3MWel or≤5000MWhel annually). The minimal remuneration is based on the current spot price on the electricity market (day ahead);
- CHP plants operators have the right to consume the electricity they produce on site (right to self-consumption). A grouping of several owners in order to maximize the self-consumption is also possible under certain conditions;
- the tax on CO2 levied on fossil fuels that are proven to be used to generate electricity (CHP) is refunded up to 60% upon request (only for plants which do not participate in emissions trading scheme and have a rated thermal input of between 0.5 and 20 MW).

The first and second points have improved the profitability of the installation. However, the measure concerning the tax on CO2 applies only for plants with a thermal output between 0.5 and 20 MW. Small plants (below 0.5 MW) are excluded while small CHP units for domestic usage have a huge technical potential. For installations that meet the size criteria, the CO2 tax is only partially refunded.

In Switzerland, it is the cantons that define the regulations that apply to buildings. In order to ensure a decent uniformization of the different cantonal legislation, they developed the Model Energy Regulations of the Cantons (MoPEC in French) to serve as a guide for the development of cantonal laws (2018).

The MoPEC provides eleven standard solutions for heating replacement. Owners can freely choose the solution that best suits their situation from those eleven standard solutions. CHP is one of these standard solutions as long as the installation achieves an electrical efficiency of at least 25% and covers at least 60% of the heat requirements for heating and hot water production. Being part of the eleven standard solutions, shows that the high efficiency of the CHP technology is recognized and tolerate. However, this measure is not subsidized when it is fuelled with fossil fuel and the usage of biogas certificates is not recognized as a renewable energy.

In conclusion, improvements have been made but there are still obstacles for the implementation of CHP in Switzerland. The strategy regarding CHP technology at federal or cantonal level is not clearly defined. Indeed, the Commission on Environment, Land Use and Energy of the parliament have charged the Federal Council to develop a strategy for the regulation of CHP. The objective is to contribute to the security of winter electricity supply as long as they do not compete with renewable energy (*Postulat 20.3000 - Stratégie d'avenir pour le couplage chaleur-force*, 2020).

Financial barriers : small CHP plant fuelled with natural gas are barely profitable

As seen in the literature review, financial barriers are one of the biggest obstacles also in Switzerland. The high capital investment combined with the CO2 tax makes small CHP pants fuelled with natural gas barely profitable. In addition, some type of installation such as engines have high maintenance costs. However, the possibility of self-consumption introduced with the new Federal Energy Act has improved the profitability of the installations.

For CHP fuelled with renewable energy such as biomass and waste, the profitability is better thanks to the subsidies.

Historical barriers: Swiss utilities never fully adopted this technology

Swiss utilities never have fully adopted this technology. It is mainly historical. Indeed, at the origin of the electrification of the country, there were the hydroelectric dams. After, the country has moved toward nuclear power generation and never toward thermal power generation. Utilities have never had to integrate this technology into their production portfolio. The first CHP were accompanied with strong resistance from electric utilities. Today this technology is fully accepted by the market players. However, it is not promoted either by utilities or by architects or civil engineer. It is a niche technology that is more complicated to set up, which gives them more work.

Technical barriers: wide range of type of installations and size makes harder to communicate and train operators

The range of type of CHP installations is extremely wide. This is due to the fact that different CHP systems (prime mover) exist such as turbines, engines and fuel cells. But also because they can work at different scales (from micro-scale to large-scale). In addition, different operation strategies can be adopted (electric or thermal demand management). Furthermore they can be deployed for different uses such as residential, industrial, commercial, for district heating or in combination with heat pumps. Finally, CHP can be fuelled with different energy carriers such as natural gas, biogas or hydrogen.

This wide variety makes it difficult to raise awareness of the technology and to define a clear strategy. Indeed, there is no consensus among experts as to the type of installations that are optimal to achieve the objectives of the 2050 energy strategy. This wide variety also makes hard to properly train technicians to ensure the maintenance and the repair of the devices.

Confronted with this great variety, there are very few devices available on the market

Conclusion

The barriers to CHP development in Switzerland have not changed much since the study from Rieder et al. in 2009. Improvement of the framework conditions have been made with the introduction of the new Federal Energy Act in 2016. However, those improvements do not seem to make much difference in the deployment of this technology.

As long as there is no clear definition of a strategy regarding CHP technology at federal and cantonal level, a real market penetration seems compromised. Indeed market players would necessitate clear measure such as a general exemption from the CO2 tax for all CHP or CO2 tax of the heavily carbonized electricity imports in order to enter the market.

4. Conclusions and Policy Implication

In this paper, we explored how Combined Heat and Power (CHP) plants fuelled with natural gas or biogas might represent a short-term solution to produce power in winter on the Swiss territory. More precisely, we analysed the effect of the deployment of this solution on the hourly carbon footprint of the electricity consumed in Switzerland. We used a four-step methodology developed in our previous work but extended the geographical scope of the analysis to Switzerland with its direct neighbours (France, Italy, etc.) and their neighbours (Spain, Danemark, etc.). We run the analysis from the years 2016 to 2020 which allows us to analyse the effect the decommissioning of the Mühleberg nuclear in December 2019. The results show that the deployment of this solution could lower the GHG footprint of the electricity consumed in Switzerland up to 7.51%. However this effect is fading through time and even increase the electricity footprint for the year 2020 by 8.67%. This is mainly due to the fact that the power generation mix of Germany is constantly getting cleaner. The results improved significantly when the CHP are fuelled with a proportion of biogas going from an improvement of 12.69% in 2016 to a small increase of 0.83% in 2020.

The effect of the decommissioning of the Mühleberg nuclear power plant on the GHG footprint of the electricity consumed in Switzerland is hard to isolate because it has been accompanied by a large increase in new renewable energy generation.

We also examined the barriers to the deployment of small CHP units for domestic usage in Switzerland. The results show that the technology is facing many obstacles. As long as there is no clear definition of a strategy regarding CHP technology at federal and cantonal level, a real market penetration seems compromised.

However, Switzerland needs to find a solution to the power import dependency in winter which will be magnified with the electrification of the Swiss energy system with heat pumps and battery electric vehicles. Our paper showed that this simple, short-term solution might represent a solution.

Further research in this area could be carried out in order to investigate more deeply the effect of the phase-out of nuclear power in Switzerland. In addition, further investigations should be done in order to compare alternative solutions to produce power in winter.

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Chapter IV : Conclusion

4.1 Research question, objectives and the three empirical papers

The main objective of this thesis was to explore the role that natural gas and its infrastructure can play in Switzerland's transition to a low-carbon energy system? In order to answer this research question, the thesis had the following research objectives:

1. Identify the roles presented in the scientific literature for natural gas and its infrastructure in the context of the decarbonization of the energy system

2. Present the official positions of the Confederation and the Swiss gas industry regarding the future of natural gas and its infrastructure

3. Identify the biggest challenges in the Swiss energy transition and how natural gas and its infrastructure could help addressing them

4. Assess how the deployment of combined heat and power plants fuelled with natural gas as a winter power generation solution can help the Swiss energy transition in terms of GHG emissions reduction.

5. Identify the barriers to the deployment of combined heat and power plants in Switzerland

These objectives have been addressed in three different empirical papers.

In paper I, a qualitative and holistic approach was adopted in order to address the objectives 1, 2 and 3. We firstly realized a systematic literature review in order to identify the potential roles that natural gas and its infrastructure could take. Then, we transposed the roles identified in the literature to the Swiss context by looking at the official positions of the Confederation and the gas industry on this issue. Finally, in order to enrich these two visions, we conducted semi-structured interviews with 15 experts in the field of energy in Switzerland.

In paper II, a quantitative approach through simulation was adopted in order to address objective 4. We developed a four-step methodology to evaluate how the replacement of a part of the power inflows from neighbouring countries by decentralized CHP plants fuelled with natural gas impacts the hourly carbon footprint of the electricity consumed in Switzerland.

In paper III, both quantitative and qualitative approaches were adopted in order to address objectives 4 and 5. We used a four-step methodology developed in paper II but extended the geographical scope of the analysis to Switzerland with its direct neighbours (France, Italy, etc.) and their neighbours (Spain, Danemark, etc.). We run the analysis from the years 2016 to 2020 which allowed us to analyse the effect of the decommissioning of the Mühleberg nuclear plant in December

2019. Finally, we realized semi-structured interviews with experts to identify the barriers to the deployment of combined heat and power plants in Switzerland.

4.2 Summary of findings

In paper I, we identified in the scientific literature three roles for natural gas and its infrastructure in the energy transition. The first role identified is the use of natural gas to replace other fossil fuels such as coal or oil. The second role identified is the use of natural gas and its infrastructure to compensate for the intermittent nature of renewable energy. The last one is the fact that natural gas and its infrastructure help promote the production, transportation and storage of renewable gases. Each of these roles presents benefits for the energy transition. However these benefits might be tempered by concerns regarding methane leakage, delay in the deployment of renewable energies, carbon lock-in, the security of supply of natural gas or the limited potential of renewable gases.

The results of the analysis of the interviews show that electricity supply in winter is considered by our experts as one of the biggest challenges of the energy transition in Switzerland. Respondents identify three ways in which natural gas and its infrastructure might help address this challenge. The first is the use of natural gas-fired combined heat and power plants as transitional solution. The second is a gas storage in rock cavities to improve security of supply. Finally, biomethane, syngas and hydrogen as long-term solution. The other challenge of the energy transition in Switzerland identified by our experts is the slow decarbonization of the buildings sector. In answer to that, the respondents agreed that the gas switch is not a solution in itself, but may be desirable in certain cases. They also identified another solution: natural gas-fired combined heat and power systems to accelerate the deployment of district heating.

Paper II demonstrates that the Swiss growing dependency on electricity imports during winter has, indeed, a non-negligible impact on the environment. More precisely, it is heavily impacted by imports from Germany and its coal-based power production. Indeed, for the year 2016, imports from Germany accounted for 19% of the electricity consumed in Switzerland while they accounted for 74% of its GHG content. This impact on the carbon footprint of the electricity consumed has decreased through time (from 74% in 2016 to 65% in 2019) due to Germany increasing new renewable energies generation. The natural gas-fired CHP solution examined in this study would allow to reduce the carbon footprint of the electricity consumed in Switzerland by up to 6.83%.

In **Paper III**, the results show that the deployment CHP plants fuelled with natural gas could lower the GHG footprint of the electricity consumed in Switzerland up to 7.51%. However this effect is fading through time and even increase the electricity footprint for the year 2020 by 8.67%. This is mainly due to the fact that the power generation mix of Germany is constantly getting cleaner. The results improved significantly when the CHP are fuelled with a proportion of biogas going from an improvement of 12.69% in 2016 to a small increase of 0.83% in 2020. The effect of the decommissioning of the Mühleberg nuclear power plant on the GHG footprint of the electricity consumed in Switzerland is hard to isolate because it has been accompanied by a large increase in new renewable energy generation. Finally, CHP is facing many obstacles. As long as there is no clear definition of a strategy regarding CHP technology at federal and cantonal level, a real market penetration seems compromised.

In conclusion, natural gas and its infrastructure can help the energy transition in Switzerland. Indeed, it offers concrete answers to certain challenges. However, the evolution of its network is subject to significant uncertainties. Heat-power couplings fuelled by natural gas or renewable gases have the potential to support the energy transition in Switzerland. However, this technology is subject to too many barriers to fully fulfil this role.

4.3 Contributions, limitations, and suggestions for further research

4.3.1 Contributions

At the theoretical level
The contribution of **paper I** is the adoption of a holistic and qualitative approach to deal with the subject of natural gas in the energy transition which is quite uncommon. Moreover, it was possible to gain access to experts who are generally not easily accessible thanks to the contacts of the author of this thesis.

Paper II : One of the major contributions of the paper is addressing this question in an hourly approach. We also took into account real physical exchanges between countries. Another contribution is that we adopted a top-down approach based on natural gas heating demand by using real hourly natural gas consumption.

The main contribution of **paper III** is the analysis of the recent decommissioning of the Mühleberg nuclear plant and the identification of barriers slowing the penetration of combined heat and power plants in Switzerland.

At the empirical level
The findings of this thesis have practical implications mainly on policy level. Indeed, policy-makers could use our results in order to elaborate a hydrogen strategy as well as a CHP strategy. More generally, this thesis contributes to the heated debate of the role of natural gas and its infrastructure in the energy transition.

Overall, this thesis has also demonstrated the validity of a pragmatic approach to provide practical solutions for the private sector while maintaining scientific rigour and high quality.

4.3.2 Limitations

One of the limitations of this thesis is the fact that it is a case study of Switzerland. The results are therefore limited to this country and cannot be transposed to other energy contexts.

Another limitation concerns the use of a qualitative approach in **paper I**. Consequently, the results are not generalizable and are limited to the Swiss context. In addition, the paper includes the perspectives of energy experts. Responses may be biased based on the participants' knowledge and their individual perspectives. As a result, their answer may not be representative. Indeed, a different sample could have led to slightly different results.

The last identified limitation concerns **paper II and III**. These studies only analyse the impact of the deployment of combined heat and power plants in terms of GHG emission reduction. The effects that it can have on the energy system such as an improvement of the power grid resilience or on the contrary an overuse of the natural gas grid capacity have not been treated. The economical and technical feasibility of deploying such a solution have not been explored either.

4.3.3 Further research

The role identified to address the challenges related to the Swiss energy transition in **paper I** should be examined in terms of technical and economical feasibility. In addition, this paper should be re-evaluated based on recent events (see section 5.1)

Regarding **papers II and III**, as stated above, the effects CHP can have on the energy system such as an improvement of the power grid resilience or on the contrary an overuse of the natural gas grid capacity should be examined. In addition, further research could be carried out in order to investigate more deeply the effect of the phase-out of nuclear power in Switzerland.

4.4 The thesis in light of recent events

It is important to note that the elaboration of the three articles took place from 2019 to summer 2021. Indeed, since then two events have completely changed the context and implications of this thesis.

The first event is the fact that in October 2021, Federal Councillor Guy Parmelin announced to the population that Switzerland could have an electricity shortage by 2025. Indeed, electricity could be available in too small quantities for weeks or months. The planned phase-out of nuclear power will further increase Switzerland's dependence on electricity imports in winter. As neighbouring countries are also facing a decarbonization of their energy system, they may not have enough export capacity in winter. Switzerland's withdrawal from the Institutional Framework Agreement with the European Union has further weakened the situation. The Federal Councillor therefore invites companies to prepare themselves for this situation. This was the first time that the government recognized this risk. Prior to this announcement, dependence on electricity imports in winter was not considered a supply risk. The baseline scenario of the Energy Outlook 2050+, even predicted an increase in such imports after the shutdown of nuclear power plants. The electricity commission published a first report pointing out this dependence and questioning the ability of our neighbouring countries to supply us with electricity in winter (rts, 2021). As mentioned above, one of the strengths of this thesis is the fact that it identifies this dependence on electricity imports in winter as the main challenge of the energy transition in Switzerland. Indeed, before the Federal Council officially recognized this threat, it was already well felt by energy experts in Switzerland.

The second event is, of course, the invasion of Ukraine by Russia. As the world's largest exporter of oil and gas, this war and the sanctions against Russia have disrupted the global energy system. These repercussions are also being felt in Switzerland, which is also threatened with a gas shortage by winter. Before this, the supply of natural gas seemed secure and such an eventuality hardly seemed possible. This threat, unlike the threat of electricity shortage, was less identified by the respondents to this thesis. Indeed, they considered the risk of a natural gas shortage to be much less important than that of an electricity shortage.

The war in Ukraine further increases the risk of electricity shortage, as countries like Germany, from which we import our electricity, use natural gas for power generation. In addition, there have been breakdowns in nuclear power plants in France. The accumulation of these events means that Switzerland is now preparing for a shortage of electricity and natural gas this winter. This is an unprecedented situation in the country's history. And of course, these changes considerably the contributions of this thesis. For instance, the use of combined heat and power plant fuelled with natural gas to produce both power and heat is a feasible solution only if it is accompanied by natural gas saving measures in other areas.

As a result, further study should be carried out in order to explore the role of natural gas and its infrastructure in the context of potential power and gas shortage.

4.5 General conclusion and prospects for the future

A pragmatic solution

Natural gas and its infrastructure can definitely help the energy transition in Switzerland. Indeed, it offers concrete pragmatic quick answers to certain challenges such as the shortage of electricity supply in winter and the slow decarbonization of the buildings sector. The solutions provided by natural gas and its infrastructures are pragmatic solutions. Ideally, of course, we should do without them and move directly to a carbon-neutral energy system based solely on renewable energies. But there is a gap between the objectives of carbon neutrality to be achieved by 2050 and the reality of the deployment of these solutions in the short or medium term. Indeed, the actors of the energy transition at the local level are often confronted with barriers to the deployment of renewable energies on their territory. Whether it is due to limited situational resources (renewable primary energy sources on their territory such as wind, sun, heat, unused waste heat, etc.), because it is large-scale projects that will take several years to come to fruition or projects that come up against the reluctance of the population. The use of natural gas and its infrastructure makes sense in this search for pragmatic solutions.

A solution with advantages and disadvantages

But its role definitely needs to be discussed openly between the different stakeholders such as energy scientists, federal, cantonal and municipal representatives and the gas industry to be anticipated and planned. This reflection must take into account both the advantages of this energy and its infrastructures and its disadvantages, such as methane leaks, the threat in the security of supply of natural gas, the delay in the deployment of renewable energy and the limited potential of renewable gases. Indeed, all solutions envisaging the use of natural gas and its infrastructures must take into account the risk of methane leaks, not only on its territory but also abroad. This also applies to the production of biomethane and synthetic gas. Concerns about the security of supply of natural gas also require upstream planning to ensure the most judicious use of this energy. Indeed, natural gas consumption must be reduced and used in specific contexts to limit this risk in particular. Furthermore, any investments made in gas infrastructures must be made with the aim of promoting the deployment of renewable energies and must not in any case be responsible for a delay in the deployment of these. Finally, the uncertainties about the potential of renewable gases in Switzerland, which some people believe to be limited, should not in any way dampen discussions about the usefulness of the gas infrastructure. At present, every renewable energy source that strengthens the country's energy sovereignty must be developed and considered as part of the solution to decarbonize the Swiss energy system.

A solution that needs to be treated seriously

This dialogue between scientists, federal, cantonal and municipal representatives must take place as soon as possible. It is indeed a more than legitimate subject that must be an integral part of the country's strategy. Indeed, many subjects such as the implementation of mechanisms to limit methane leaks on our territory or abroad have not been sufficiently addressed because natural gas and its infrastructures have been considered as a "non subject", a solution of the past. It is therefore essential to be aware of the fact that natural gas is an energy that will obviously tend to disappear from our energy mix in the long term but will probably still be used a lot in the short or medium term. It is therefore important to address with the utmost seriousness these forgotten issues such as methane leaks, a strategy concerning the use of CCS to produce blue hydrogen and the evolution of transport and distribution networks. All these issues must be addressed with the utmost rigour and not be a political response but a technical response to the need for energy transition in Switzerland.

Another example of those forgotten subject is the solutions explored in this thesis: the use of combined heat-and-power plants fuelled with natural gas or renewable gases. This pragmatic solution could definitely help the Swiss energy transition. However, this subject has never been discussed in depth and has not been considered as a concrete solution. Indeed, at present, this technology is subject to too many barriers to fully fulfil this role. As long as there is no clear definition of a strategy regarding CHP technology at federal and cantonal level, a real market penetration seems compromised.

After the thesis : a memorandum as a basis for a strategy and fossil energy considered as a “common”

This doctoral thesis will not stop here. In the near future, a memorandum for the gas industry as well as for political decision makers at the communal, cantonal and federal level will be drafted based on the results of this thesis. The aim is to provide the basic principles for the development of a strategy for the use of natural gas and its infrastructure for the energy transition in Switzerland. The aim of this document will also be to open a dialogue between the different stakeholders. The elaboration of this memorandum is also in line with the pragmatic and applied approach taken throughout this thesis. The author's aim is to come up with practical and applicable solutions.

Another dimension that the author wishes to give to this thesis in the near future is to address the issue of the use of natural gas and its infrastructure in the energy transition to a carbon-neutral future from the perspective of the collective management of common resources proposed by Ostrom et al., (1999) with their eights principles for managing a common.

4.6 References

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