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Achieving −55% GHG emissions in 2030 in Wallonia, Belgium: Insights from the TIMES-Wal energy system model

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ABSTRACT

The Walloon Region has undertaken the ambitious engagement to reduce its greenhouse gases (GHG) emissions up to −55% in 2030. In this context, a regional model of the energy system is a useful tool to give insights to policy makers. We address the lack of an existing integrated tool by developing a technology-rich, bottom-up model for the region. The goal of this paper is twofold: we present the model and its functioning and then we analyse a cost-optimal way to reach the −55% regional target. Firstly, we describe the methodology, discussing how we build the sectors of our model and how the optimisation works. Secondly, we run the model with a constraint on GHG emissions to assess the impact of the mitigation target. We show that the total system cost of such an ambitious mitigation scenario is only ~0.5% higher than the cost of an unconstrained reference scenario and that emissions reduction must start as soon as possible to stay on the cost-effective trajectory. Concerning technologies, windmills, photovoltaic (PV) panels and building renovations are cost-optimal solutions even with high discount rates.

1. Introduction

In order to project future GHG emissions and to support climate policy, many climate-economy models have been developed in the past decades, following different modelling approaches (see for example Nikas et al. (2019) for a classification). In particular, energy system optimisation models are used to help determining optimal (least-cost) climate policies in many countries. Such models are detailed at the sectoral and technological levels and hence provide valuable insights to decision makers. Energy models are usually built on an aggregated level, at a national or multi-national level. However, it is highly valuable to detail a regional energy model in order to consider local specificities and to inform policy makers, in particular in cases such as Wallonia[1] which is legally competent in many policy fields related to energy transition and climate change (e.g. renewable energy sources, energy standards for buildings, rational use of energy). So far, no detailed model of the Walloon energy system was available. The TIMES-Wal model aims at filling this gap.

The TIMES model generator was developed by the International Energy Agency-Energy Technology Systems Analysis Program (IEA-ETSAP) (Goldstein et al., 2016; Loulou et al., 2005a, 2005b). TIMES belongs to the "bottom-up" energy system models, which are partial equilibrium models based on a detailed set of technologies with associated costs and technical parameters. Such models focus on the energy system, as opposed to "top-down" models, which are general equilibrium models covering the whole economy. TIMES is an integrated model: one change in a sector can impact any other sector. The optimisation is based on the maximisation of consumers and producers' surpluses under perfect foresight.

TIMES-Wal was developed for the Walloon Region. Indeed, public authorities need tools to aid decision-making. Such tools need to cover the entire energy system and have to be flexible, detailed as well as adapted to regional specificities. We built our TIMES-Wal model in close collaboration between public (the Public Service of Wallonia) and private actors (ICEDD and E4SMA). An important contribution of the modelling exercise is the detail with which the different sectors are

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[1] Belgium is made of 3 regions: the Flemish Region, Brussels-Capital Region and Wallonia which is the south part of the country.

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modelled. We use highly detailed data coming from regional studies, which are sometimes only partially public. In particular, the residential sector modelling is based on a comprehensive typology of buildings and specific net needs for space heating and hot water; the industrial sector is modelled with data on each specific sub-sector and accurate data on production processes; the transport sector includes an exhaustive representation of the road transport with the number of passengers and cars for instance; and the electricity generation sector is calibrated with historical data on individual plants. Moreover, we include innovative and highly detailed elements in the model and in the analysis such as 3 different types of wood fuels, or a constraint on air pollutant emissions (SOx, NOx, PM2.5, COV and NH_3).

Wallonia, being part of Belgium, has to respect the rules of the European Union (EU) climate & energy framework. However, the Region decided to go beyond the compulsory EU climate objectives, undertaking the highly ambitious objective to reduce GHG emissions by 55% in 2030 (compared to 1990). Moreover, Wallonia has to respond to various energy related challenges such as the planned shutdown of nuclear plants and an old and energy inefficient residential building stock.

In the first part of this paper, we present the TIMES-Wal model which allows for the first time to carry out an integrated assessment of the Walloon energy system. In the second part, we present the results of the model optimisation taking into account the binding objective of −55% in 2030 as well as a carbon budget constraint. We analyse the results, compare them to European and regional studies, and draw policy implications. We also perform a sensitivity analysis on the discount rate, on the ETS (Emissions Trading System) price and on the cumulative emissions budget.

The paper is organised as follows. Section 2 gives a general picture of Wallonia. Section 3 contains a brief literature review. Section 4 presents our regional model. It introduces the general framework of TIMES-Wal and describes the structure of each sector as well as the data used. Section 5 analyses a scenario to meet the −55% GHG target in 2030. We describe the central hypothesis and illustrate the main results, i.e. what are the costs, the primary energy consumptions, the cost-optimal technologies, and the optimal timing of emissions reduction. Section 6 concludes and discusses the constrained path results, highlighting key insights for policy makers.

2. About Wallonia

TIMES-Wal takes into account the socio-demographic context of the region. In 2014 (our reference year for the model), Wallonia had 3,576,325 inhabitants (BFP, 2020). The average annual economic growth was 1.3% over the period 2003–2017 (Iweps, 2019).

As to the energy system, the Walloon energy balances record its evolution (ICEDD ASBL on behalf of SPW Energie, 2017):

- The primary energy consumption of Wallonia amounts to 617 PJ in 2014. Nuclear fuels (31%), petroleum products (33%) and natural gas (23%) are the main sources of energy used in Wallonia. Tihange nuclear power plants represent 65% of Walloon net electricity production, while electricity from renewable sources represents 12.5% in 2014.
- Concerning energy consumption, significant changes have occurred in Wallonia in the three last decades. Its final consumption amounts to 447 PJ in 2014 with a drop of 15% compared to the level of 1990. While the industry represented more than half of the total Walloon energy consumption in 1990, it only represents 35% in 2014. This drop is also visible on Fig. 1 which shows the evolution of sectoral GHG emissions in Wallonia (1990–2014).[2] The commercial and transport sectors energy consumption has been growing strongly since 1990 (they represent 10% and 30% respectively of the total final consumption in 2014). The residential sector accounts for 25% of the final consumption.
- Wallonia's energy independence, although growing (due to the progression of renewable energy and the decrease of total final consumption), remains limited to less than 10% in 2014. In fact, Wallonia has few local energy resources and must therefore import most of the energy consumed.

Based on these characteristics, the Walloon decarbonisation strategy has to respond to various challenges, including:

- an old building stock which is a major energy consumer,
- the development of renewable energies in a small and densely populated landlocked territory,
- the planned nuclear phase-out,
- the high energy dependence of Wallonia,
- a transport sector whose consumption is growing and is highly dependent on fossil fuels.

From those facts, we believe that Wallonia case is interesting in many regards for other regions and countries facing similar challenges. More generally, the insights we will get on how to meet an ambitious GHG reduction target in the near term are highly valuable to other parts of the world. This is particularly the case for other European countries and regions in the context of the increased EU's ambition of reducing GHG emissions by −55% by 2030 (European Commission, 2020).

3. Literature review

Many countries have their own national TIMES model (e.g. Ireland (Glynn et al., 2019), Canada (Vaillancourt et al., 2014), Denmark (Balyk et al., 2019), Italy (Cosmi et al., 2009), Norway (Lind et al., 2013), Pakistan (Ur Rehman et al., 2019)). National models are also often multi-regional. For Wallonia, it makes sense from a political point of view to have a standalone regional model to get a detailed integrated assessment tool in order to inform policies (since many climate and energy related policies are taken at the regional level). Note that Belgium has also a TIMES model (Meinke-Hubeny et al., 2017), but at the moment it does not feature Wallonia as a standalone region and therefore it does not fit well to regional analysis. There are also more global TIMES models (e.g. ETSAP-TIAM modelling 15 regions of the world (Labriet et al., 2008) and JRC-EU-TIMES, a European model (Simoes et al., 2013)).[3] IPCC (Intergovernmental Panel on Climate Change) reports also use TIMES models (TIMES-VTT is used in AR5 WG3 for instance (Krey et al., 2014)).

Thus, the main research gap we fill is the absence of an integrated energy system model specific to Wallonia. We moved from an average national model to a detailed regional representation with a specific structure, sectors, data, potentials, and assumptions. We gathered many scattered data at the regional level, coming from many different consultation processes (references are provided in section 4). Moreover, the model and analysis we have developed for Wallonia could be used as a case study for other regions or more generally for energy system of

[2] In section 5 of the paper, the emissions of the industry and electricity generation sector are slightly different in 2014 than what is shown in Fig. 1. This is mainly due to the categorisation of one large CHP plant in the industrial sector in our model (and not in the electricity generation sector as in the emissions inventories).

[3] More references on TIMES models can be found on https://iea-etsap.org/index.php/applications.

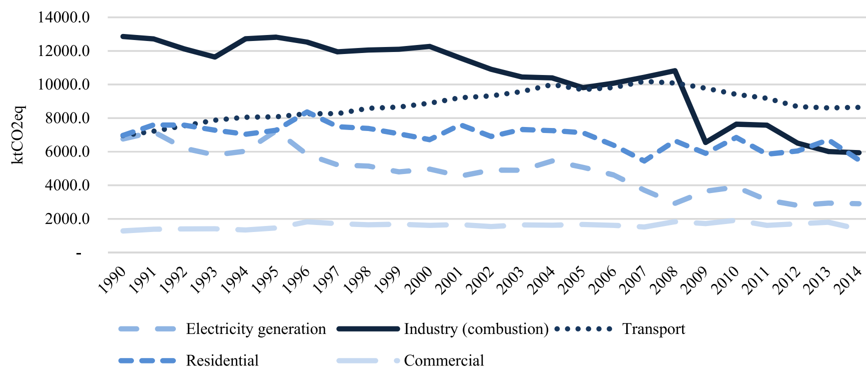

Fig. 1. Evolution of GHG emissions in Wallonia between 1990 and 2014 for the main sectors (in ktCO2eq). Note: the regional environmental agency "AWAC" provided us with the most recent data available. Only the combustion emissions are plotted for the industry.

similar size.[4]

Although quite standard in its structure (and, hence, similar to the abovementioned TIMES models), our TIMES-Wal model includes innovative and highly detailed elements: e.g. specific industrial sectors which are important energy consumers in Wallonia (sugar, milk powder and processed potatoes productions); three different types of wood fuels (pellets, logs, chips) with specific coefficients for air pollutants; a representation of the specific regional potential to produce biogas; a highly detailed building stock and renovations measures (which are specific to the type of building).

Many TIMES models have already been used in order to analyse GHG targets, for instance, in California (McCollum et al., 2012; Yang et al., 2015) and in Ireland (Chiodi et al., 2013). Ireland has also recently done an analysis with a zero carbon objective beyond 2050 (Glynn et al., 2019). Our case analysis also considers a highly ambitious reduction target (−55%) but focuses on a much more near-term objective (2030).

Moreover, we do not only define a constraint on the GHG emissions (via a target and a carbon budget) but also on air pollutant emissions (SOx, NOx, PM2.5, COV and NH_3). It was important to consider a constraint on those emissions for three main reasons. Firstly, air pollution is an important issue in Belgium and in Wallonia as the region already faces air quality problems (e.g. European Environment Agency's report shows problematic level of NO2, especially exceeding limits in cities (European Environment Agency, 2020)). Secondly, biomass (a source of air pollutants) is seen as a possible solution for reaching ambitious GHG reduction targets. Thirdly, the Walloon Region aims at reducing those environmental pollutants (Etat fédéral et al., 2020).

Since the objective of reaching −55% GHG emissions in 2030 is a new target, there are only few studies (with similar scope, objective, and temporal horizon) available at this stage. However, the results of our −55% scenario will be compared to:

- The Walloon contribution to the National Energy Climate Plan 2030, setting a target of around −40% GHG emissions (SPW Energie, AWAC, 2019).
- The Impact Assessment accompanying the document stepping up Europe's 2030 climate ambition (European Commission, 2020), aiming at −55%.
- A report from the European Commission on an ambitious transition towards 2030 and 2050, comparing the results of scenarios coming from recent studies (Tsiropoulos et al., 2020).

Concerning the last study, the report compares 8 scenarios reaching between −51% and −56% GHG emissions reduction in 2030 (Tsiropoulos et al., 2020). Those scenarios use different modelling tools including two TIMES models. The authors conclude on similarities among the scenarios in 2030, notably: a decrease in fossil fuels use compared to 2017 (coal: −70%, oil: −25 to −50%, gas: remains at similar level or −25%). The authors also conclude on the main differences between the scenarios, notably: the growth of wind and solar power varies (growth factors from 1.5 to 4.5) as well as the use of biomass (from limited increase to +60%). We will compare those European results to ours in section 5.

4. Presentation of the model

The Integrated MARKAL-EFOM System (TIMES) is a model generator developed by the Energy Technology Systems Analysis Program, one of the longest Technology Collaborative Program of the International Energy Agency. A model generator as TIMES can customise models based on the choice of the reference energy system, input database and constraints defined by the user. There are four main inputs to a model: the energy services demands, the existing stock of technologies, the future technologies and the primary energy supply sources and potentials. In the TIMES framework, the "commodities" play a central role: they can be materials, emissions, energy carriers and services. They can be produced and consumed via many different processes (technologies). One key element of the TIMES modelling framework is the focus on a detailed set of technologies for each sector.

In TIMES, perfect foresight (i.e. all future events within the defined temporal horizon are known) and competitive markets are assumed. For the model to find an optimal solution, it must satisfy all energy services demands and constraints while maximising the net total surplus of consumers and producers (considering the whole temporal horizon). In our case, we did not assume any demand price elasticities, as in Vaillancourt et al. (2014) for instance. We believe it makes more sense to keep the demands exogenous and to take into account specific assumptions about the evolution of the demands coming from regional (or national) studies instead of theoretical elasticities. As a result of the absence of demands losses, the optimisation is equivalent to a cost minimisation under the defined constraints.

The model consists of linear equations. Basically, the TIMES linear program without elastic demands can be written as (Loulou et al., 2005a):

$$\text{Min } c \times X \tag{1}$$

$$\text{s.t.} \sum VAR_{ACT\,k,i(t)} \geq DM_i(t)\,, \quad i = 1, 2, \ldots I; t = 1, \ldots, T \tag{2}$$

$$\text{and } B \times X \geq b \tag{3}$$

[4] For instance, our analysis could offer valuable insights to European regions which are actively part of the national process for determining national energy policies (e.g., the Netherlands regions or Flanders in Belgium) or to regions of similar size which are landlocked (e.g., some regions of France, such as Grand Est or Bourgogne-Franche-Comté).

Equation (1) expresses the fact that the discounted costs (vector "c") have to be minimized. "X" are the variables (e.g. new capacity of processes, quantity of commodity (e.g. energy) consumed, produced or stored, imports, activity level of technologies, etc.). Equation (2) implies that the exogenous demands ("DM") must be satisfied by the activity variables of end-use technologies ("VAR_ACTk") ("i" is the demands related index and "t" is the time index). Equation (3) expresses the fact that all the other constraints defined in the model must be satisfied.[5]

4.1. General structure of TIMES-Wal

TIMES-Wal is a single region model. The interactions with other regions and countries are modelled through exogenous import and export processes.

Our reference year is 2014. Every year is divided into 24 representative timeslices. Those timeslices are obtained thanks to an optimisation method (Poncelet et al., 2016) which selects representative days in order to best reflect the variations in the load curve for electricity demand and intermittent energy sources. Each representative day is divided into multiple periods to consider different daytime and nighttime.

The model is calibrated in order to best reflect the energy consumption data provided in the regional energy balance (ICEDD ASBL on behalf of SPW Energie, 2017) and the emission inventories (AWAC, 2020).

The Walloon energy system is divided into 7 main sectors: residential, commercial, industrial, transport, agricultural, supply and the electricity generation sector. The different sectors are described in the following chapters. Note that TIMES-Wal contains 29695 data values, 626 commodities (fuels, materials, etc.) and 1941 processes. For this reason, we decided not to describe every single data used to model our energy system but rather the overall approach as done in Balyk et al. (2019) and Cosmi et al. (2009). An overview of the general structure of the TIMES-Wal model is available in Fig. 2. The following sections describe the sectors in more detail.

4.2. Residential

In the base year, our residential sector is divided into 20 different categories of existing buildings depending on the period of construction and on the number of facades (and distinguishing apartments from houses). For each category, the surfaces (m^2) of buildings are described and the net needs (PJ/m^2) for space heating and hot water are differentiated, taking into account that the needs of old 4 facades buildings are different than the needs of middle-aged 2 facades or new apartments for instance. Those highly detailed data on net needs come from regional data which are not yet published but the main study is public (3E et al., 2018).[6] The m^2 come from the national cadastre (Statbel, SPF Finances, 2019).[7]

For the future, we define the evolution of demand for new m^2 of buildings according to the expected growth in the number of households (BFP, 2020).[8] Those new buildings have also specific net needs based on the existing regional regulation for new buildings.

In addition to hot water and space heating, we have defined other energy services for the residential sector including lighting, cooking, refrigeration and freezing, cloth washing and drying, dish washing and other electricity services.

To satisfy all the demands (space heating, hot water, and other services), a set of technologies is described through the standard parameters: stock, efficiency, availability factor, lifetime, etc. As all the processes in TIMES, the new technologies are also defined by the commodit(y)(ies) that go(es) in the process (e.g. electricity, gas) and the commodit(y)(ies) coming out of the process (e.g. heat or hot water). The consumptions are calibrated in order to correspond to the quantities reported in the regional energy balance (ICEDD ASBL on behalf of SPW Energie, 2017) for the base year.

Moreover, we define 4 types of retrofitting options in which the model can choose to invest (walls, roof, windows, and ground renovation) based on 3E et al. (2018). The retrofitting options are also differentiated according to the 20 categories of buildings defined above.

Finally, the new technologies in which the model can invest are described. The data come mainly from 3E et al. (2018) and include values for the technical parameters as well as the investment and fixed costs.

4.3. Commercial

The commercial sector is divided into 7 subsectors: education, health, culture and sports, shops, private offices, public offices, datacentres. Different energy services are defined: heating, hot water, cooling, and other services including cooking, private and public lighting, refrigeration, and other electrical devices. The demands are only defined here in PJ and not in m^2 as in the residential sector due to the lack of detailed data on m^2 for the commercial sector. Apart from that, the structure of the sector is similar to the residential one: the base year technologies and new technologies are defined in the same way and come mostly from the same sources. Concerning new technologies, the level of detail of the 3E et al. (2018) study allows us to take into account that technologies powers are higher in the commercial sector and that the costs differ.

Retrofitting options are also included in the commercial sector. The data on costs and energy savings come from confidential data on actual renovations (SPW Energie, 2019) that detail the type of retrofitting option (walls, windows, roof and ground) and the commercial subsector concerned. The evolution of the demands is linked to GDP growth.[9]

4.4. Industry

The industrial sector is divided into 20 subsectors: milk, sugar, processed potatoes, other food industry, cement, lime, hollow glass, flat glass, bricks, ceramics, other non-metallic minerals, ammonia, other chemicals, wood industry, pulp and paper, iron and steel, non-ferrous metals, non-energy consumption (chemicals and others) and other industries. The base year is calibrated to replicate the production and the final energy consumption of the industry subsectors in 2014 as shown by the Walloon energy balance. The future evolution of demands is driven by a simple hypothesis: the industrial sector level of activity in Wallonia will stay the same in 2030 as it was before[10]. This hypothesis is dictated by the lack of prospective study on the Walloon industry in the medium to long-term and it is backed by the political willingness of inversing (or at least halting) the job losses in the industrial sector. With regards to the costs as well as the temporal availability of new technologies in the

[5] Please refer to the documentation (Loulou et al., 2005a, 2005b) for more details on the equations: there is a great number of different variables and equations that are taken into account but the above system gives a general view on the optimisation program.

[6] The net needs for heating are available in Appendix B, Table B 3.

[7] Data on the building stock (km^2) are available in Appendix B, Table B 2.

[8] The drivers (expected growth in the number of households) are available in Appendix B, Table B 1.

[9] GDP growth comes from regional projection (BFP et al., 2020) for the short term and from European projections (recommended parameters provided by the European Commission for the mandatory reporting of national GHG projections) for the medium and long term. The drivers of the demands (GDP growth) are available in Appendix B, Table B 1.

[10] We use historical data for industrial activity until 2018. Then, we define the industrial activity until 2030 as the average activity over the last years (2014–2018).

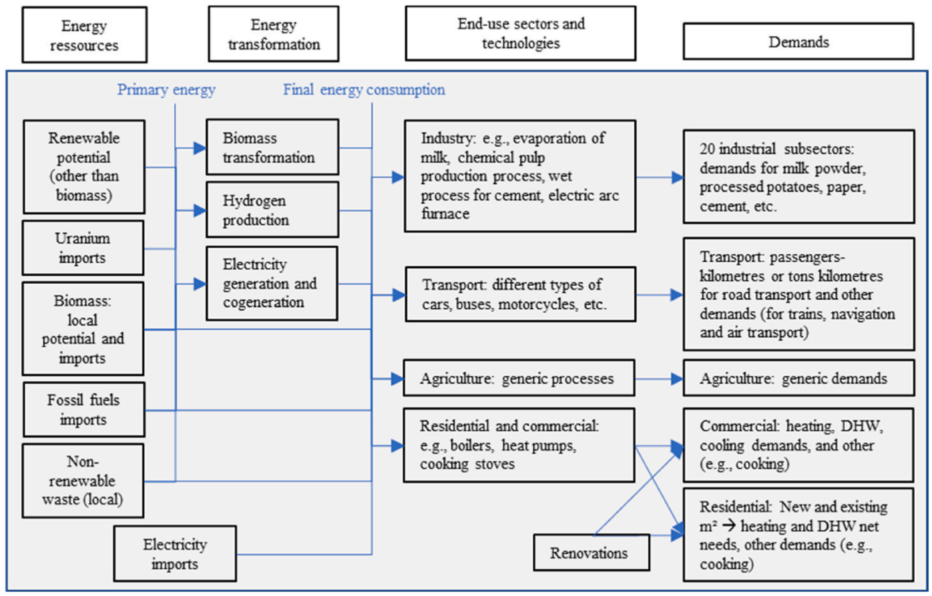

Fig. 2. An overview of the general structure of the TIMES-Wal model: a simplified energy system diagram.

different industrial subsectors, the data in the model is mainly coming from TIMES-BE. The data set has been completed/updated with other studies in specific cases (e.g. for sugar production processes).

4.5. Electricity generation

The electricity generation sector of the base year is described in detail regrouping all the main activities producers, that is those generating electricity (and heat) for sale to third parties through the grid. Three main types of producers are separately regrouped: the nuclear, the renewable and the thermal power plants.

Plants are described using the fuel used as input, their electrical power, the commissioning year (or the date of the last major revamping), their efficiency and maximum availability during the year as well as an utilisation-dependent efficiency factor. While the most important plants (in particular nuclear and gas power plants) are described at individual level (based on historical data), the smaller plants as well as renewable energy plants (windmills and hydropower stations) are regrouped by fuel and commissioning year. The data for the base year come from the regional energy balances.

Concerning new technologies, the model can make its choice on a varied list of new plants based on technical parameters and costs. These values were taken from a European study (Carlsson et al., 2014) and completed/updated with data from the Walloon regional administration in particular for biomass and renewable technologies (CAPGEMINI on behalf of SPW, 2015).[11]

4.6. Transport

Concerning road transport, the demands are described in terms of passengers-kilometres or in tons kilometres (for freight transportation). For other transport modes, the demand is simply described in terms of energy demand. As in typical TIMES models, individual modal travel demand is exogenously defined over the model time horizon and while technologies can compete within modes on the basis of technical parameters and cost, there is no competition between modes. As explained before, we prefer using regional studies to define exogenously the drivers than to use theoretical elasticities. Regarding road, rail and river transport, the demand drivers come from a federal study on transportation which analyses a “no policy changes” scenario (BFP, SPF Mobilité et Transports, 2019).[12]

The TIMES-Wal transport sector comprises a stock of technologies, in competition, that contribute to meet each exogenously defined modal travel demand. While for air transport, rail transport and navigation only one generic technology is described, for road transport the model includes a great number of different technologies for passengers (cars but also motorcycles and buses) and freight (lorries). For the base year, the full stock of road transport technologies is described in terms of vehicles, tons or passengers-kilometres and energy consumptions. This detailed structure is based on the data from the COPERT model (Ntziachristos et al., 2009) for road transport which is used by the regional environmental agency (AWAC) to compute road transport emissions.

Concerning the new technologies, detailed data are only described for road transport (both for passengers and freight). The model can select different types of cars, buses, motorcycles and lorries based on technical and economic parameters from the new technologies database which includes “traditional” gasoline and diesel (as well as natural gas and biofuels) motorisations but also different types of hybrid, electric and hydrogen motorisations. The data come from multiple sources: from the Belgian TIMES model, from the PRIMES energy model used in Belgium by the Federal Planning Bureau (BFP et al., 2017) and from a McKinsey study (McKinsey, 2010).

4.7. Other considerations

Agricultural and supply sector are also described in the model. The agricultural sector is accounted for in order to calibrate the base year energy consumptions thanks to a few generic processes. Given the low levels of consumption, we did not describe the sector in detail, as in Cosmi et al. (2009). Concerning the supply sector, we consider some “mining” processes (local production of energy sources: waste or wood for instance), import and export processes. The import prices of main energy commodities come from data obtained thanks to the Belgian Federal Planning Bureau which uses it for its energy outlook studies

[11] Data on windmills and PV panels are available in Appendix B, Table B 7.

[12] The drivers of the main demand (passengers-kilometres for cars) are available in Appendix B, Table B 1.

(BFP et al., 2017).[13] For future years, we added a detailed representation of biogas and hydrogen production (see Fig. 3 for an illustration of how biogas is produced and consumed in TIMES-Wal). As mentioned before, we also consider 3 different types of wood fuels: logs, pellets and chips. Fig. 4 illustrates how they are included in the model. Concerning the production, distribution and storage of hydrogen, the data from JRC-EU-TIMES (Bolat and Thiel, 2014a, 2014b; Ruiz and Nijs, 2019; Sgobbi et al., 2016) is used.

Concerning GHG emissions, we disaggregated the different GHG gases into CO2, CH4 and N2O, distinguishing emissions from ETS and non-ETS sectors. Note that TIMES-Wal does not include all the regional emissions. The model considers only the combustion emissions of the main regional sectors described in the model (which account for most of the combustion emissions). In order to consider another environmental dimension, we include emission factors for the main air pollutants: SOx, NOx, PM2.5, COV, NH_3.[14] The emissions coefficients were defined with the help of the regional environmental agency, and consistency with the regional inventories of air pollutants was verified.

5. A constrained path to 2030

The 2019–2024 political declaration of the Walloon government explicitly states that "The climatic urgency and the environmental degradations are such that the whole society is called upon to change its behaviour in depth. Wallonia acts in line with the necessary and desirable evolution towards a low carbon society. It aims for carbon neutrality by 2050 at the latest, with an intermediate step for 2030 that targets a reduction of greenhouse gas emissions by 55% compared to 1990". The political declaration also states that "All sectors must contribute jointly and fairly to the climate objectives for Wallonia"[15] (Government of Wallonia, 2019). In this context, studying the optimal contribution of each sector and each technology is useful to help policy makers define a more ambitious Air Energy Climate Plan.

5.1. Main hypothesis

In our constrained scenario, we do not only use the emissions reduction objective in 2030 (−55% compared to 1990 which corresponds to −29% compared to 2014) but we also constrain the model to respect a carbon budget. We define a constraint on the cumulative emissions of the 3 GHGs considered in the analysis (i.e. the sum of the emissions of all sectors until 2030). Carbon budgets in TIMES scenarios were already used in several studies (Glynn et al., 2019) (Huang et al., 2017). A carbon budget has more sense than just objectives in a climate perspective because it is the cumulative emissions over the whole period that define the temperature increase and the climate change impacts. Moreover, there is no interim political target prior to 2030 in Wallonia (except GHG budgets for the period until 2022). We defined the GHG budget by deriving the cumulative emissions that would arise from a linear path to the objectives and by increasing this linear budget by 2%.[16] In addition, a constraint of −80% emissions in 2050 is set in the −55% GHG scenario in order to take into account that emissions should continue to decrease after 2030 (and to avoid end-game strategies).

To reflect better the reality of our region, we take into consideration actual taxes and delivery costs on energy commodities as well as actual subsidies for renewable electricity and biogas production (until 2024). An increasing price for ETS emissions is also considered (according to the recommended parameters provided by the European Commission for the mandatory reporting of national GHG projections, see Appendix B, Table B 4).

To avoid an increase in emissions of atmospheric pollutants in the future, an additional constraint is set on SOx, NOx, PM2.5, COV and NH_3.[17] Indeed, the ambitious GHG target should not be reached at the expense of air quality.

Moreover, we do not consider investments in new coal power and nuclear plants due to the political choice to phase out nuclear and the fact that coal plants have already been phased out. We do not take into account CCS or CCU options because of the uncertainty underlying the technical implementation in Wallonia and the costs of the technologies as well as the fact that we analyse a very near term target whose imminence does not allow a large deployment of those options. In the residential and commercial sector, a maximum annual retrofit rate of 3% (of the total m^2 of the sector) is taken into account so that the full renovation potential can be reached in 2050 (in accordance with the regional renovation strategy), while taking into account technical limitations (the whole sector cannot be fully renovated in a few years).

Concerning renewable energy sources, the local potentials are bounded to reflect the findings of regional and federal studies. The potential for onshore windmills is set to 5.2 GW (ICEDD ASBL and APERe ASBL on behalf of Elia, 2009). The limit for new PV (photovoltaic) panels is 12 GW (Vito, Climact on behalf of FPS Health, Food Chain Safety and Environment, 2013). Biomass limits come mainly from 2 regional studies (CAPGEMINI on behalf of SPW, 2015) (ValBiom on behalf of SPW, 2019; 2016). Concerning electricity importations, we consider the limit used in the regional energy climate plan for 2030: 5.76 PJ (SPW Energie, AWAC, 2019).

Concerning the general discount rate, we use the Ramsey's social discount rate formula and find a discount rate of 1.8%. For the pure time preference rate and the elasticity of marginal utility of consumption, we use the median values of a recent experts survey (Drupp et al., 2018).[18] We only adapt the growth rate in order to reflect the regional context.[19] Considering the range of discount rates used in energy models, 1.8% is among the lowest values but we believe a low general discount rate is preferable to get the view of a planner. We do not consider hurdle rates in our model.

There is a long-lasting debate between experts on the value of the discount rate. Moreover, it was previously stated that the impact of the discount factors on TIMES results was important (García-Gusano et al., 2016). Given those facts, a sensitivity analysis is performed to highlight the impact of the discount rate on the main results.

5.2. Results

To analyse the consequences of the ambitious mitigation target, we compare 2 main scenarios: a reference scenario (Scenario REF) and a mitigation scenario (Scenario −55%). Both scenarios have the same

[13] See Appendix B (Table B 5) for the main fossil fuels prices projections.

[14] Emissions factors for the residential sector are shown in Appendix B, Table B 6.

[15] Translated from French (Government of Wallonia, 2019).

[16] Concerning the 2%, it is an assumption to allow some flexibility and to not constraint the path to be at least linear. Moreover, we perform a sensitivity analysis on that GHG emissions budget to show its impact on the emissions trajectory. Our GHG budget includes the 3 GHGs we consider in our analysis -CO2, CH4 and N2O- (The Walloon Government also considers those 3 GHGs when fixing the five-year GHG budgets for the Region).

[17] The constraint on atmospheric pollutants is defined for each pollutant (SOx, NOx, PM2.5, COV and NH_3). It bounds the sum of emissions from all the sectors apart from the transport sector (limiting total emissions of each pollutant at their 2014 level). Indeed, with the current modelling approach of atmospheric pollutants, it was not possible to accurately consider the various emissions of all the different technologies in the transport sector.

[18] Ramsey social discount rate formula is $r = p + n*g$. r, the discount rate; p, the pure time preference rate; g, the growth rate. We take $p = 0.5\%$, $g = 1.3\%$ and $n = 1$.

[19] We consider a growth rate of 1.3%. It was the average growth over the period 2003–2017 (Iweps, 2019). It also fits the European and regional previsions.

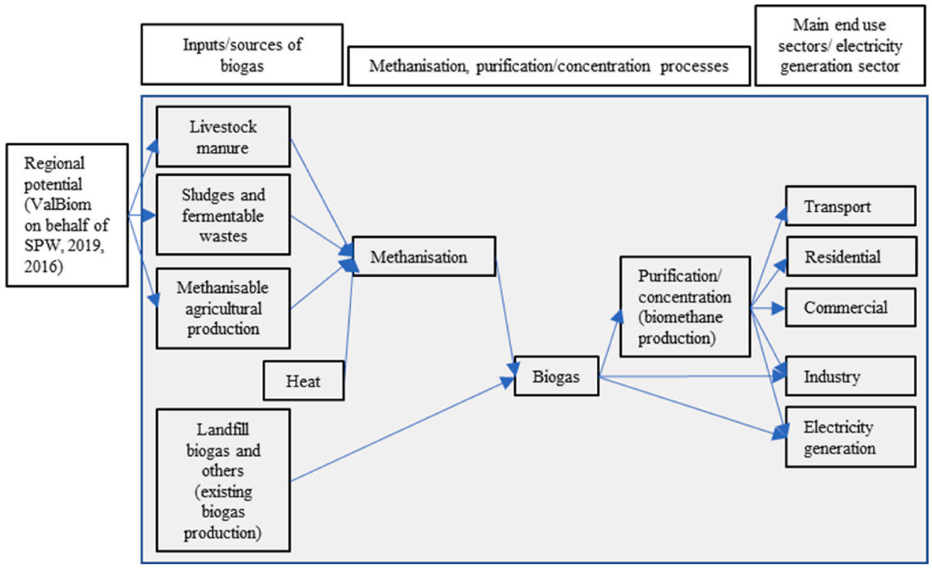

Fig. 3. Inclusion of a specific biogas production module in TIMES-Wal.

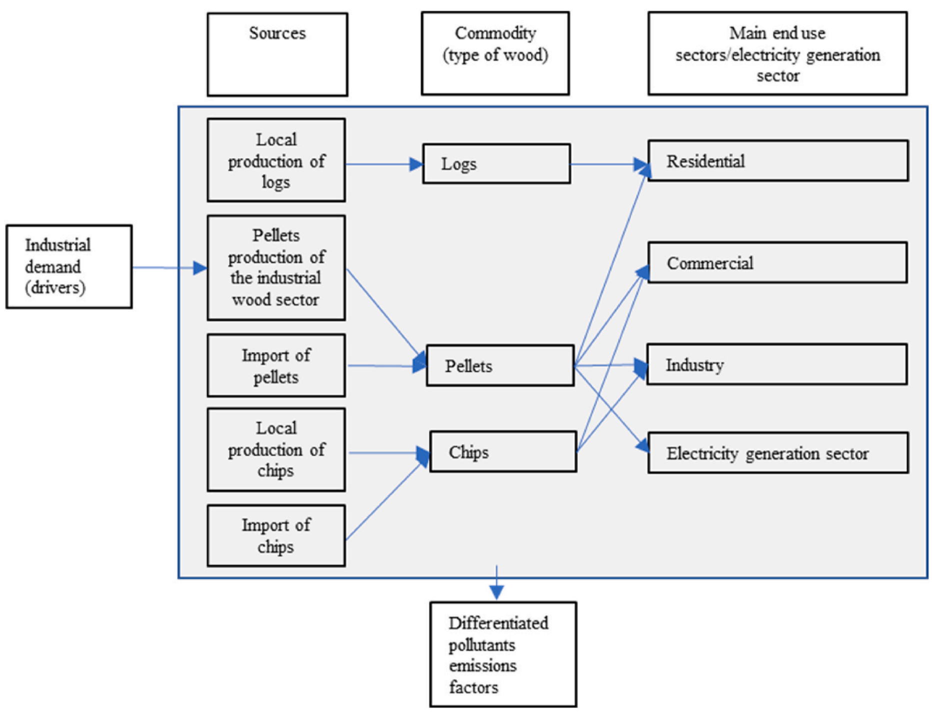

Fig. 4. Inclusion of 3 types of wood fuels (logs, pellets, chips) in TIMES-Wal.

central hypothesis. They only differ for 2 elements: the constraint on the GHG emissions in 2030 and the GHG budget, which are only included in the mitigation scenario. We first look at the primary results concerning emissions trajectories and the energy mix. Second, we detail the main outcomes by sector. Finally, we compare the costs of our scenarios. The results of a sensitivity analysis on the discount rate are detailed in Appendix A. Moreover, a brief analysis on air pollutant emissions is available in Appendix C.

5.2.1. Overall energy system outlook and emissions

In the unconstrained case (Sc. REF), emissions first decrease until 2025 and increase slightly afterwards notably because of the shutdown of nuclear plants (which are partly replaced by gas turbines) (Fig. 5). In the constrained scenario (Sc.-55%), the emissions reduction is almost linear. This is partly because we added an emissions budget and partly because there are some cost-effective options that the model chooses well before 2030 (renewable sources for electricity production and retrofitting options for instance).

Without any GHG emissions budget, TIMES-Wal tends to put slightly less effort in the beginning and more effort on the last years of the temporal horizon. Indeed, when doing a sensitivity analysis on the emissions budget, we see that a higher budget (or no budget at all) leads to a slightly more concave path (Fig. 5). Emissions are still decreasing all along the path due to the cost-effective options chosen by the model in any case (even in the reference scenario).

Thus, we show here that, even without constraining the model to take into account a GHG emissions budget, emissions are decreasing all along the path, almost linearly, to reach the 2030 target. This result is

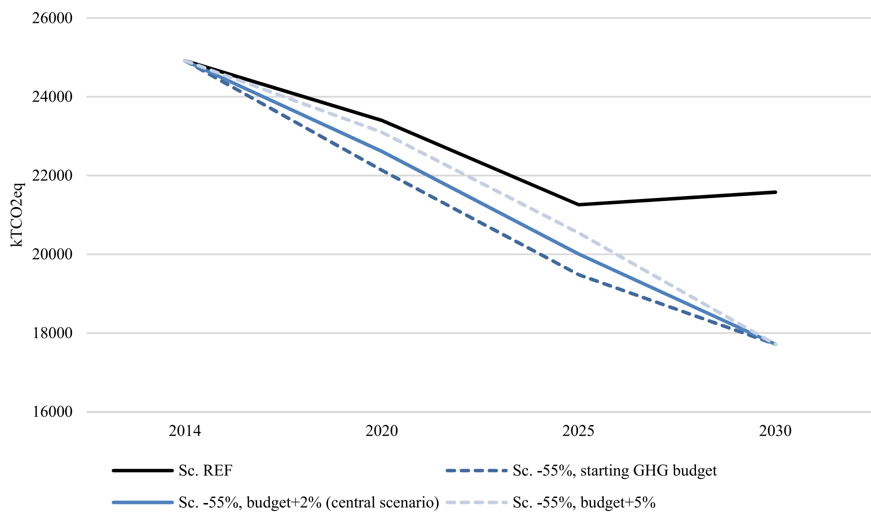

Fig. 5. Total GHG emissions (ktCO2eq) in Wallonia in our central scenarios and sensitivity analysis on the GHG emissions budget. Note: "Sc. REF" is the unconstrained, reference scenario and "Sc. −55%" are the mitigation scenarios that include constraints on GHG emissions. The starting GHG emissions budget corresponds to the cumulative emissions that would arise from a linear trajectory to −55%. The curves show the emission trajectories to the −55% target for several budget values. Note that when the budget is increased by 5%, the whole budget is not used anymore (it is thus equivalent to infinite budget or no budget constraint). The historical divergence until 2020 is due to the fact that our reference year is 2014. However, we did some alignments to consider historical changes (such as considering historical data on GDP growth until 2020 or industrial productions until 2018).

also influenced by the fact that renovations are bounded by a maximum annual rate and by the shutdown of nuclear plants, which calls for investments from 2023[20]. To conclude, starting acting now is necessary to reduce our cumulative emissions but it is also cost-effective, even if we do not take into account a budget constraint.

Moreover, when disabling the GHG budget constraint and doing a sensitivity analysis on the discount rate,[21] we see that the path remains also quite similar. Important efforts are taken from the start even with a discount rate of 10%. However, higher discount rates lead to significatively more concave paths and more cumulative emissions. The detailed results concerning the sensitivity analysis to the discount rate are presented in Appendix A (Fig. A 1, Fig. A 2).

As the next graphic illustrates (Fig. 6), the main reductions in 2030 in Sc.-55% compared to the base year are achieved in the residential sector (−57% GHG emissions). The industrial (−31%) and commercial sectors are also contributing significantly (−31% and −15% respectively). Retrofitting the buildings plays an important role in those trends as well as fuels substitution in the industry. Transportation continues to be the main emitting sector even though its emissions decrease (−18%). Finally, the electricity generation sector decreases by 9%. Note that in the reference scenario emissions in the building sector (commercial and residential) are decreasing by more than 20%.[22]

Those differentiated efforts provide policy insights for the definition of the effort sharing between sectors in the context of the Walloon climate decree.[23] Moreover, we compare the reduction by sector to what was planned in the Walloon contribution to the National Energy Climate Plan 2030 (see Table 1). This comparison can provide policymakers with insights regarding an update of the sectoral efforts in order to achieve a more ambitious goal (with an economic optimisation criterium): e.g. much greater efforts should be undertaken in the residential, industrial and in the electricity generation sectors. Table 1 also compares our results to the Impact Assessment of the European Commission (European Commission, 2020), showing one tremendous difference in the efforts of the electricity generation sector. The fact that our scenario is "less ambitious" in this sector is due to the local challenge of phasing out nuclear power plants.

Specific outcomes by sector are discussed afterwards. The second panel of Fig. 6 shows the primary energy sources and gives a general idea on the main switches in the Walloon energy system.

In both scenarios, renewable energy sources (excluding biomass) are skyrocketing: +479% in the constrained scenario and +465% in the reference one, compared to 2014. As we will see in detail in the next section, this growth comes mainly from huge investments in windmills. As to biomass, while its use is decreasing in Sc. REF, it is becoming an important source of energy in the mitigation scenario (+65% compared to 2014).[24] The use of natural gas is growing in the reference scenario (+27% compared to the base year) while it remains at a stable level in the constrained scenario (+3%). Oil and solid fossil fuels are decreasing significantly. Oil is notably decreasing by 44% in Sc. REF and by 52% in Sc −55%, compared to the base year. Before jumping to sectoral conclusions to explain those main trends, we can already conclude here on the importance of renewable and biomass in meeting the GHG target in a cost-optimal way. Also, we see that fossil fuels use should decline except for natural gas use which is stable. Those results are similar to the findings of the European Commission study (Tsiropoulos et al., 2020) concerning the main evolutions of the primary energy mix in 2030 (the use of oil and coal declines sharply while gas consumption remains quite stable). Concerning biomass use, the European study found that results vary a lot between the different scenarios and models they compared (from limited growth up to 60% compared to 2017); in our scenario for Wallonia, we see that our biomass growth is at the highest end of this range.

[20] A first nuclear reactor (out of three) is stopped in 2023, the others are shutdown in 2025.

[21] In this case, the sensitivity analysis is performed with discount rates ranging from 0.01% to 10% (with 2%, 4%, 6% and 8% as intermediate steps).

[22] The fact that, in the commercial sector, GHG emissions are slightly higher in the mitigation scenario than in the reference scenario in 2030 is explained by investments in sector-specific cogenerations in the Sc. −55%. So, the sector produces part of his electricity (which is produced by the electricity generation sector in the Sc. REF).

[23] One of the objectives of the climate decree is to establish targets to reduce GHG emissions in the short, medium and long term, in particular by defining five-year sectoral GHG budgets.

[24] This is partly due to an increase in wood consumption. More specifically, chips consumption drops in Sc. REF (−72%) but rises in Sc.-55% (+128%) in 2030, compared to the reference year (11.88 PJ in 2014). Pellets consumption remains stable in Sc. REF but increases significantly in Sc. −55% from 3.76 PJ to 10.39 PJ (+177%). Logs consumption is decreasing in both cases (−58% in Sc. REF and −61% in Sc.-55%), compared to 2014 (5.67 PJ). The increase of biomass consumption in Sc.-55% is also due to a rise in biogas production and consumption, from 2.04 PJ in 2014 to 11.74 PJ in 2030 (it increases also in Sc. REF, reaching 8.32 PJ in 2030). Note that all the biogas goes to industrial end-users in 2030.

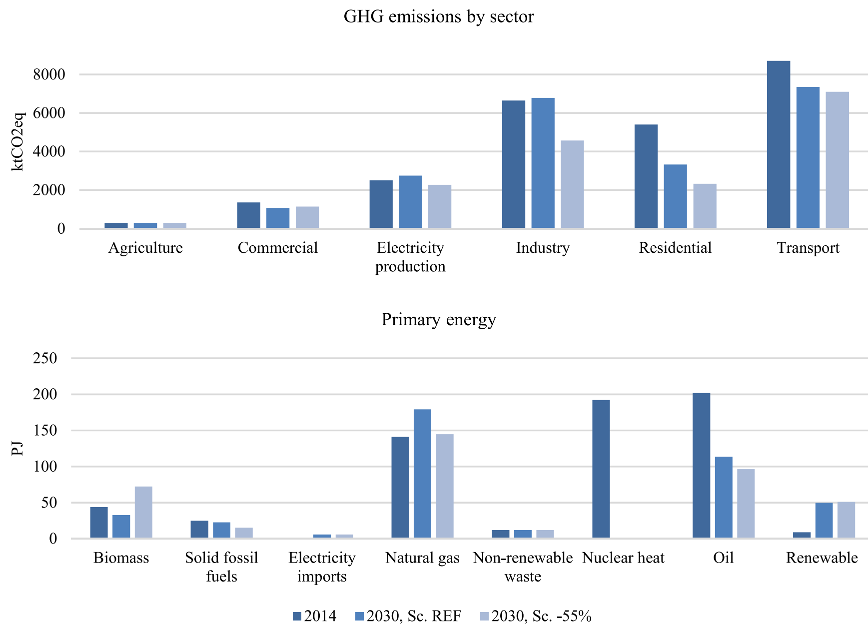

Fig. 6. GHG emissions by sector (ktCO2eq) and primary energy (PJ). Note: first bars represent the emissions (in the first panel) and energy consumption (in the second panel) in the base year. Second bars and third bars show them in 2030 for the reference scenario and the mitigation scenario, respectively.

Table 1
Emissions evolution by sector from 2014/2015 to 2030 under different scenarios.

Emissions evolution by sector from 2014/2015 to 2030	(1) Walloon contribution to the National Energy Climate Plan 2030 (SPW Energie, AWAC, 2019)	(2) Impact Assessment of the European Commission (European Commission, 2020)	(3) TIMES-Wal, Sc.-55%
Residential	−32%	−61% to −64%	−57%
Commercial	−37%	−53% to −60%	−15%
Industry	+7%	−21% to −23%	−15%
Transport	−19%	−16% to −18%	−18%
Electricity generation	+86%	−69% to −71%	−20%

Note: the scenario (1) "with additional measures" from the Walloon contribution to the National Energy Climate Plan SPW Energie, AWAC (2019) is updated by the regional Administration with the latest data; the scenarios (2) are from the Impact Assessment of the European Commission (scenarios "REG"; "MIX"; "CPRICE") (European Commission, 2020); the scenario (3) is the one presented in this paper, i.e., the results of the −55% scenario with the TIMES-Wal model. Emissions evolution is expressed in percentage change from 2015 to 2030 for the (2) European scenarios and in percentage change from 2014 to 2030 for the regional (1) and (3) scenarios. Since our TIMES-Wal model did not include process emissions from industry, we added them exogenously to compute the percentage change presented in this table, so that it can be compared to the other studies which include process emissions from industry (we consider 5153 ktCO2eq for all years in our scenario). To be able to compare (1) and (3), the emissions of one large CHP plant (used in the chemical sector) are subtracted in the industry and added in the electricity sector in the results of the TIMES-Wal Sc.-55% (to do the same categorisation of this particular CHP plant as in the regional inventories).

5.2.2. Sectoral results

The shutdown of the nuclear plants leads the model to invest in many new technologies. Fig. 7 (first panel) shows how the energy sources for public production of electricity change.

In both scenarios, the model chooses to invest massively in renewables. The model almost reaches the maximum potential of windmills in both scenarios (90% of the total potential). The remaining potential is only related to small windmills (100 kW) which are not as attractive as the larger ones. The contribution of PV panels is also rising substantially in both cases, reaching 24% of the total potential in Sc.REF and 28% in Sc.-55%. As to the regional objectives regarding the electricity production of PV panels and Windmills (11.88 PJ and 16.56 PJ in 2030 respectively (SPW Energie, AWAC, 2019), our mitigation scenario almost reaches the political objective for PV panels (10.70 PJ) but greatly exceeds the one for windmills (36.85 PJ).[25]

This result (for Windmills and PV panels) is not affected by the inclusion of subsidies in the model or by the ETS price. The model would still invest as much as in our central scenarios. The only difference is that PV panels capacity is 1% lower in the mitigation scenario and 16% lower in the reference scenario if there is no ETS price. Moreover, the discount rate and the carbon budget do not affect investments in Windmills in the Sc.-55%. There is only a marginal effect of the discount rate on the capacity of PV panels in 2030 (see Appendix A, Fig. A 3 for more details).

The factor of increase of variables renewables is higher than the ones reported in the recent European Commission report (Tsiropoulos et al., 2020) even though the increase of PV is in the range found in the European study. This comes obviously from the massive investments in windmills which are notably occurring because of the need to cope with the phase-out of nuclear power.

In the constrained case, total final electricity consumption (excluding auto-consumption of the electricity generation sector) is 79.9 PJ in 2030 (80.7 PJ in Sc. REF) which means electricity used regionally decreases slightly by 3% (2% in Sc. REF), compared to 2014. Moreover, the electricity exportations (12.17 PJ in 2014) totally disappear in 2030. On the other hand, electricity importations are used up to the limit we defined.

[25] The objective for windmills is already reached in 2025 in our scenarios (their electricity production is already of 36.10 PJ in Sc.-55% and 36.27 PJ in Sc. REF). PV panels are installed later than windmills: in 2025, the electricity production of PV panels is "only" 3.52 PJ in both scenarios. Therefore, investments in Windmills should be the priority in this sector even though the timing of investments should also depend on many non-economic constraints, which are not represented here.

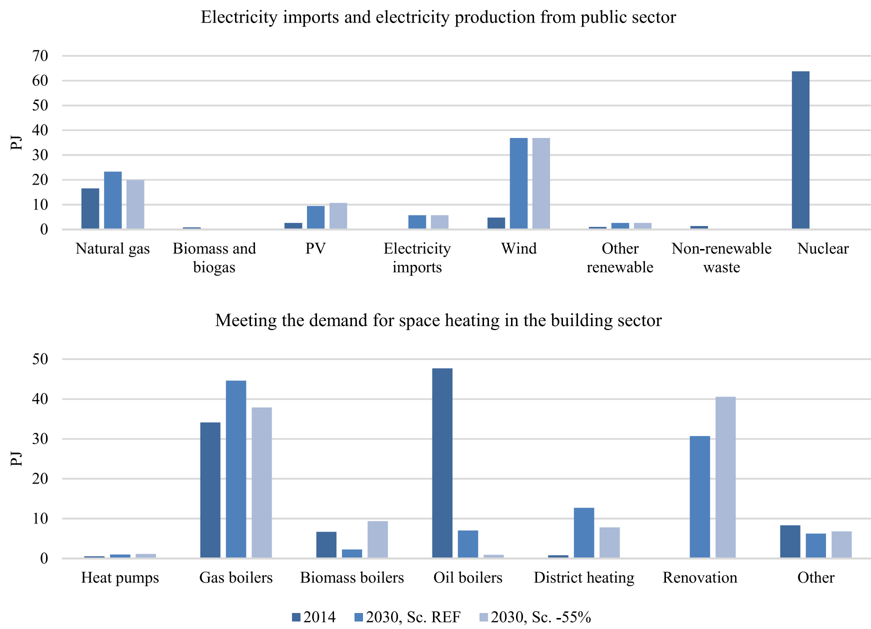

Fig. 7. Electricity production by energy source from public sector (PJ) and the technologies for space heating in the building sector. Note: the first panel excludes industrial and commercial electricity production. The second panel shows how the building sector (residential and commercial) demand for space heating (in PJ) is met in 2030. "Renovation" shows the total energy savings in 2030 coming from investments in retrofitting options since 2014. "Other" includes mainly resistances. In 2030, it also includes LPG boilers (mainly in Sc. REF) and cogeneration (mainly in Sc. 55% for the commercial sector). First bars show the electricity sources (in the first panel) and the technologies for space heating (in the second panel) in 2014. Second bars and third bars show them in 2030 for the reference scenario and the mitigation scenario, respectively.

Thus, concerning the electricity production sector, we believe the main insight is that in both cases, windmills and PV panels are cost-effective choices. Massive investments should be facilitated in the coming years to allow such a potential to be used. This is obviously the most economical way to cope with the shutdown of the nuclear plants and the GHG emissions objective. However, it should also be mentioned here that nuclear plants in Wallonia are so important that those investments in renewable sources are not sufficient. Importations from neighbouring regions should be considered as well as investing in new gas plants capacity.

Concerning the industrial sector, the results (and the modelling) of the various subsectors would need to be discussed in a full-length paper. Let us just mention here that a fuel switch is occurring to reduce GHG emissions in the mitigation scenario. The main changes are a drop in natural gas use and a raise in biogas and wood fuels use.

In the transport sector, there is one main result: hybrid diesel cars are becoming the main technology in both scenarios. While there is still an important share of standard diesel cars in the reference scenario, this technology almost disappears in the mitigation scenario.

In the residential sector and commercial sectors, there are a lot of renovations taking place and new boilers installed (see second panel of Fig. 7). Every type of renovation is present in the results of both scenarios: we see window, wall, roof as well as ground renovation. The constrained scenario goes further than the reference case: total energy savings from renovation are 32% higher. In 2030, total demand for heating in the building sector (residential and commercial) would be 104.5 PJ without renovation; with the investments in retrofitting (in Sc. −55%), it boils down to 64 PJ.[26] We wish to highlight here that the amount of total renovations is limited by our hypothesis on maximum annual retrofit rate (3%). For some renovation options, the model would renovate even more if this limit was withdrawn. Note that our TIMES-Wal model goes further than what is planned so far in the renovation strategy of the Walloon Region for the residential sector. The amount of retrofitting is greatly influenced by the discount rate even though there is still a lot of renovation even with high discount rates (a detailed description of the impact is available in Appendix A, Fig. A 4).

Concerning technologies of the building sectors for space heating, the main outcomes of both scenarios are the investments in new and more efficient gas boilers and the use of district heating while the quantity of oil boilers is declining tremendously. In Sc.-55%, oil boilers almost disappear in 2030. In this same scenario, to reduce GHG emissions further, the cost-optimal solution includes also less gas, more biomass, and more heat pumps than in the reference scenario. Nevertheless, gas boilers remain the main technology while heat pumps only satisfy around 1% of the total demand in 2030. Heat produced by heat pumps in our scenarios is significantly lower than the objective set in the regional plan for 2030 (the plan's goal is 6.75 PJ (SPW Energie, AWAC, 2019) while our scenarios reach 1.14 PJ in Sc.-55% and 0.98 PJ in Sc. REF). However, we wish to highlight that heat pumps become the main technology in our constrained scenario in 2050. Let us also mention here that for lighting purpose, LED lights are replacing all old devices as soon as possible. Their higher efficiency makes them profitable. Overall, the cost-optimal solution for the building sector includes massive investments in retrofitting the old stock as well as installing more efficient technologies.

5.2.3. Costs

Overall, the total discounted cost of the energy system in Sc.-55% is only 0.46% higher than in the reference scenario. The cost gap is dependent on the discount rate. If we take into account a higher discount rate, the cost difference between the scenarios becomes slightly higher (see Table A 1 of Appendix A for more details).

The total cost increase comes mainly from higher investment costs. Renewable alternatives, retrofitting options as well as more efficient cars for instance have a higher upfront cost but allow to consume less energy afterwards, reducing the flow costs.

Besides, the shadow price of emissions is 87 euros/t in 2030. We obtain a highly convex curve with a shadow price around 10 euros/t in 2020 and 2025. However, this carbon price is quite sensitive to the discount rate (see Fig. A 5 of Appendix A for marginal abatement cost curves considering several discount rates).

[26] In 2025, the total demand for heating is already reduced to 75.4 PJ thanks to renovations (note that the total demand would be 102.8 PJ without renovation in 2025).

6. Conclusion and policy implications

In this paper, we offered insights on the future transition of Wallonia towards −55% GHG emissions in 2030. The results of the TIMES-Wal model are also valuable to other regions in the world, especially in the EU, in the context of the updated climate ambition as well as to regions or countries facing similar challenges, such as a planned nuclear phase-out, an old building stock or the development of renewable energies in a small landlocked territory.

We showed that even though the cost of a scenario reaching such an ambitious objective in the near term is only about 0.5% higher than in the reference case, massive investments should be made in the coming years in order to reach the target in a cost-optimal way.

In our scenarios, the energy mix considerably evolves. Renewable sources and biomass become significant sources of primary energy while fossil fuels use declines, except for natural gas. These results are similar to the conclusions of a recent comparison of scenarios made by the European Commission (Tsiropoulos et al., 2020). The fact that natural gas use remains stable is partly due to the planned shutdown of the regional nuclear plants.

Regarding energy dependence, this transition is actually a chance to improve the regional dependence rate (with more renewable energy sources and greater use of local biomass as well as less importation of fossil fuels and uranium). Concerning the effort sharing between sectors, additional emissions reductions should take place in the electricity generation, industrial and residential sectors compared to what is currently planned in Wallonia.

As to the challenges of the planned nuclear phase-out and the development of renewable energies in a small landlocked territory, we saw that Wallonia should invest as soon and as much as possible in windmills and in PV panels. The fact that both technologies are cost-optimal (even in the unconstrained case) is a strong signal for investments in the Walloon region and in other regions or countries facing a similar challenge. Reaching the number of windmills and PV panels shown in the results will be a challenge in itself. In fact, our TIMES-Wal model almost reaches the full regional potential of windmills in 2030 in both the reference and the constrained scenario, exceeding greatly the political objective, which should be raised. As to the regional objective regarding PV panels, our mitigation scenario almost reaches it.

In order to respond to the challenge of an old building stock, which is a major energy consumer, renovations should be the first focus. Renovations are a cost-optimal choice in both scenarios. This is a strong conclusion for the building sector and his actors (citizens, companies, and policy makers) in Wallonia and abroad. Moreover, our results showed that the renovation rate in the residential sector should go beyond what is currently planned in the renovation strategy of the Walloon Region. In addition, more efficient heating technologies should be used even though heat pumps are only installed massively after 2030 to meet the 2050 objective.

More generally, our technologically detailed model does not go for a lot of "disruptive" or breakthrough technologies to reach the target in 2030. These only become necessary afterwards, to reach a low carbon society in 2050. We would like to highlight that the cost-optimal solutions for 2030 are well-known technologies. Certainly 2030 is very near, but we do not need to invest in uncertain alternatives to reach an ambitious mitigation target in the near term.

Moreover, we showed that efforts and investments must start as soon as possible in order to stay on the cost-effective path. Indeed, emissions are being reduced even in the reference case at the beginning of the model temporal horizon and emissions are decreasing almost linearly in the constrained case.

Besides, when doing a sensitivity analysis on the discount rate and on the GHG emissions budget, we showed that even with a high discount rate/budget, emissions reductions are still important from day one even though the emissions path becomes more concave. Moreover, the choice of the discount rate does not change the main technological conclusions (concerning windmills, PV panels, retrofitting options) even though the amounts of PV panels and especially of retrofitting options are sensitive to it.

Some limitations of this analysis are related to the structure of the TIMES-Wal model, e.g. the absence of analysis of non-combustion emissions, of the materials use, of the whole economy. The TIMES-Wal model is under continuous improvement. For instance, the base year will be updated as well as the data for the new technologies as new information is collected. We have also planned to improve the temporal resolution. Future research concerning Wallonia or other regions could also better assess the role of sufficiency or behavioural measures in the transition to achieve an ambitious short-term climate objective and could for instance include endogenous shift between modes in the transport sector. Another area of improvement is the modelling of interdependencies with other Belgian regions and with neighbouring countries.

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CRediT authorship contribution statement

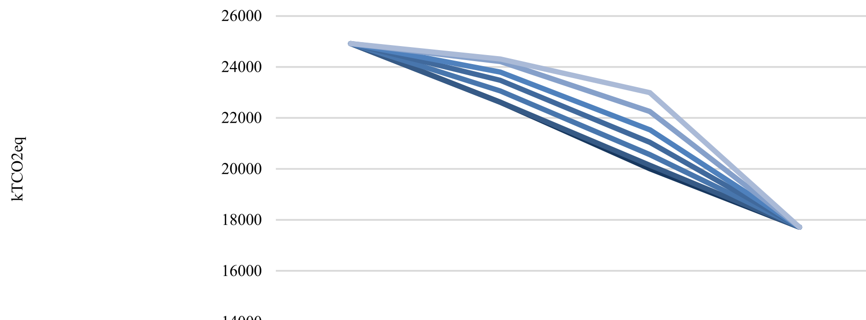
Léo Coppens: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Maurizio Gargiulo:** Methodology, Writing – review & editing. **Marco Orsini:** Methodology, Resources, Writing – review & editing. **Nathalie Arnould:** Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Sensitivity analysis on the discount rate

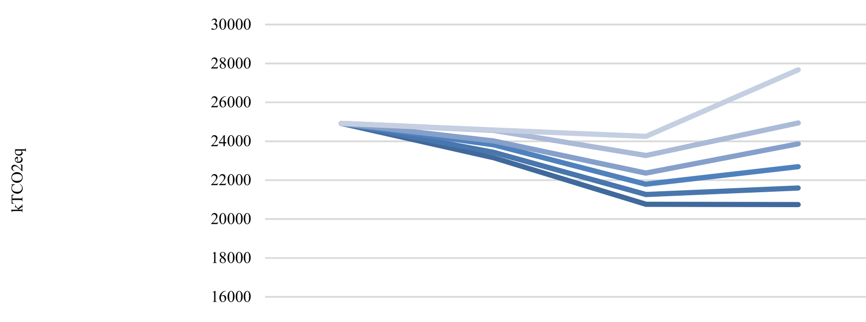
In this Appendix, the results of the sensitivity analysis to the discount rate are shown. We describe and illustrate the consequences of the choice of the discount rate on the emissions trajectory, on the main technological results (PV panels, windmills, renovation), on the costs and on the shadow price of emissions.



	2014	2020	2025	2030
Sc. -55%, with GHG budget	24916	22615	20008	17715
Sc. -55%, no budget, discount rate=0%	24916	22617	20145	17715
Sc. -55%, no budget, discount rate=2%	24916	23057	20562	17715
Sc. -55%, no budget, discount rate=4%	24916	23478	21041	17715
Sc. -55%, no budget, discount rate=6%	24916	23800	21539	17715
Sc. -55%, no budget, discount rate=8%	24916	24215	22255	17715
Sc. -55%, no budget, discount rate=10%	24916	24312	22993	17715

Fig. A 1. Sensitivity analysis on the discount rate: emissions trajectories for the mitigation scenario. Note: the scenario "with GHG budget" is our central scenario of this paper. "No budget" means there is no constraint imposing a GHG budget (i.e. it is the same as infinite budget). On the graphic, from bottom to top, there are first the central scenario, then the "no budget" scenarios with increasing discount rates..

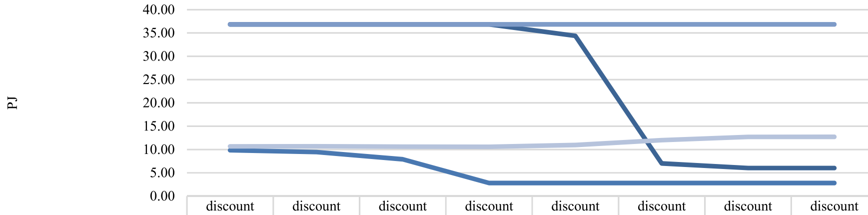
The first graphic shows trajectories for the mitigation scenario, comparing our central case (which includes a constraint on cumulative emissions and a discount rate of 1.8%) with scenarios which have infinite GHG emissions budget and consider different discount rates (Fig. A 1). As we could expect, the path becomes more concave: the higher the discount rate, the higher the cumulative emissions. However, as previously said, important efforts are taken from the start even with a discount rate of 10%.



	2014	2020	2025	2030
Sc. REF, discount rate=0%	24916	23156	20763	20745
Sc. REF, discount rate=2%	24916	23428	21263	21602
Sc. REF, discount rate=4%	24916	23815	21792	22692
Sc. REF, discount rate=6%	24916	24021	22365	23869
Sc. REF, discount rate=8%	24916	24557	23268	24942
Sc. REF, discount rate=10%	24916	24577	24250	27671

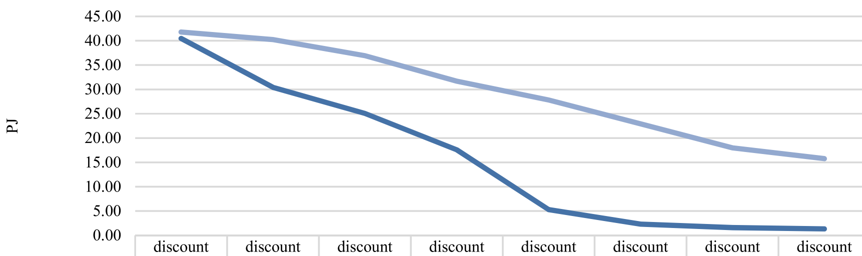
Fig. A 2. Sensitivity analysis on the discount rate: emissions trajectories for the reference scenario. Note: on the graphic, from bottom to top, the curves correspond to the reference scenario with increasing discount rates.

As to the Sc. REF, the path remains quite similar with high discount rates (Fig. A 2). Emissions are still decreasing in the beginning and then increasing after 2025 and the shutdown of the nuclear plants (except if the discount rate is 0%, then emissions do not increase between 2025 and 2030). Even though the curve shape remains similar, the endpoint can vary significantly: with a discount rate of 8% or more, total emissions in 2030 become higher than in 2014.



	discount rate=0%	discount rate=2%	discount rate=4%	discount rate=6%	discount rate=8%	discount rate=10%	discount rate=12%	discount rate=14%
Sc. REF, Windmills	36.85	36.85	36.85	36.85	34.38	7.01	6.02	6.02
Sc. REF, PV panels	9.84	9.44	7.89	2.81	2.81	2.81	2.81	2.81
Sc. -55%, Windmills	36.85	36.85	36.85	36.85	36.85	36.85	36.85	36.85
Sc. -55%, PV panels	10.68	10.70	10.62	10.58	10.96	12.02	12.68	12.72

Fig. A 3. Electricity production from Windmills and PV Panels in 2030 depending on the discount rate.



	discount rate=0%	discount rate=2%	discount rate=4%	discount rate=6%	discount rate=8%	discount rate=10%	discount rate=12%	discount rate=14%
Sc. REF	40.46	30.42	25.07	17.58	5.30	2.30	1.59	1.33
Sc. -55%	41.78	40.21	36.93	31.68	27.82	22.91	17.97	15.76

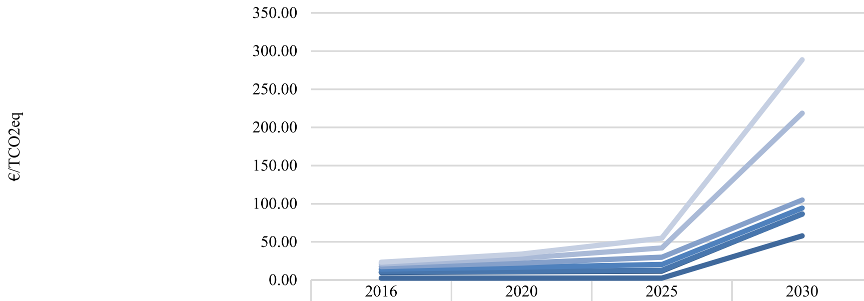
Sc. REF   Sc. -55%

Fig. A 4. Total energy savings from renovation in 2030 depending on the discount rate.

In the paper, we concluded that the main technological choices do not change with high discount rates. Fig. A 3 and Fig. A 4 show more in details the consequences of the discount rate on renewable electricity production (PV panels and windmills) and on renovation, respectively. As to the mitigation scenario, the electricity production from windmills is insensitive to the discount rate and the amount of PV Panels only change marginally. However, the total energy savings from renovation are dropping considerably for each additional percent even though there is still an important amount of energy savings even with the highest discount rates. As to the reference scenario, quantities of PV panels and Windmills start dropping when a certain discount rate is reached (from 8 to 10% for the windmills and from 4 to 6% for the PV Panels). Investments in renovation are dropping even faster in the reference scenario than in the Sc. −55%.

Table A 1
Total increase in energy system costs, considering different discount rates.

Scenario, discount rate	Total increase in energy system costs compared to Sc. REF
Sc. −55%, central scenario, discount rate = 1.8%	0.46%
Sc. −55%, discount rate = 0%	0.27%
Sc. −55%, discount rate = 2%	0.46%
Sc. −55%, discount rate = 4%	0.63%
Sc. −55%, discount rate = 6%	0.66%
Sc. −55%, discount rate = 8%	0.78%
Sc. −55%, discount rate = 10%	0.86%



	2016	2020	2025	2030
Sc. -55%, central scenario, discount rate=1.8%	9.98	10.72	11.72	86.68
Sc. -55%, discount rate=0%	2.62	2.62	2.62	57.97
Sc. -55%, discount rate=2%	10.67	11.55	12.75	86.33
Sc. -55%, discount rate=4%	14.37	16.80	20.44	94.29
Sc. -55%, discount rate=6%	17.75	22.36	29.92	104.95
Sc. -55%, discount rate=8%	21.13	28.63	42.07	218.64
Sc. -55%, discount rate=10%	23.44	34.11	54.93	288.69

Fig. A 5. Sensitivity analysis on the discount rate: the shadow price of emissions..

Finally, the impact of the discount rate on the total cost and on the shadow price of emissions is presented in Table A 1 and Fig. A 5. The total cost gap between the Sc. REF and the Sc. −55% is slightly growing with the discount rate but remains below 1% even with a discount rate of 10%. However, the shadow price of emissions in 2030 becomes quite high when considering such a discount rate. Indeed, from 86.68 €/t in our central scenario, it grows to 288.69 €/t when a discount rate of 10% is considered.

Appendix B. supplementary data and assumptions

In this Appendix, some data and assumptions which are essential to the analysis are presented.

The first table shows the main drivers of the demands: households (used in residential sector), GDP (used in commercial sector), and passengers-kilometres of cars (transport sector).

Table B 1
Main drivers assumptions (households, GDP, passengers-kilometres for cars). Note: GDP growth comes from regional projection (BFP et al., 2020) for the short term and from European projections (recommended parameters provided by the European Commission for the mandatory reporting of national GHG projections) for the medium and long term. The expected growth in the number of households comes from a Belgian study (BFP, 2020). Regarding cars, the demand drivers come from a federal study on transportation (BFP, SPF Mobilité et Transports, 2019).

Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Households	1	1.004	1.008	1.014	1.019	1.026	1.032	1.036	1.042	1.048	1.054	1.06	1.065	1.071	1.076	1.081	1.086
GDP	1	1.013	1.027	1.044	1.059	1.074	0.963	1.041	1.074	1.086	1.099	1.11	1.119	1.128	1.137	1.146	1.157
Cars (passengers-kilometres)	1	1.008	1.016	1.024	1.032	1.040	1.048	1.056	1.064	1.073	1.081	1.090	1.092	1.095	1.097	1.100	1.103

The second and third tables provide data on the residential sector concerning the way we modelled our building stock and the net needs for heating.

Table B 2
Building stock (km^2) in Wallonia by type of building. Note: we distinguish the buildings based on the period of construction and on the number of facades (and distinguishing apartments from houses). These data are computed based on a federal study (Statbel, SPF Finances, 2019).

Building stock (km^2)	<1945	1946–1970	1971–1981	1982–1995	1995–2014
2 facades	39	5	1	1	1
3 facades	16	6	3	1	2
4 facades	16	7	12	8	13
Apartments	5	4	2	1	4

Table B 3
Net needs for heating (PJ/km^2) in Wallonia by type of building. Note: we distinguish the buildings based on the period of construction and on the number of facades (and distinguishing apartments from houses). These data are computed based on regional data (3E et al., 2018).

Net needs for heating (PJ/km^2)	<1945	1946–1970	1971–1981	1982–1995	1995–2014
2 facades	0.39	0.59	0.55	0.26	0.37
3 facades	0.77	0.94	0.46	0.55	0.38
4 facades	0.61	0.75	0.41	0.49	0.34
Apartments	0.51	0.42	0.32	0.35	0.41

Table B 4 shows our assumptions on the ETS price. The consequences of the ETS price on the electricity generation sector are discussed briefly in Section 5.2.2 of the paper.

Table B 4
ETS price assumptions. Note: we use the recommended parameters provided by the European Commission for the mandatory reporting of national GHG projections.

Year	ETS price (€'16/tCO2)
2020	25
2025	28
2030	30

The import prices of the main fossil fuels used in our analysis are indicated in Table B 5.

Table B 5
Main fossil fuels prices projections (imports). Note: the import prices of main energy commodities come from data obtained thanks to the Belgian Federal Planning Bureau which uses it for its energy outlook studies (BFP et al., 2017)

Year	Oil (€'13/GJ)	Gas (€'13/GJ)	Coal (€'13/GJ)
2020	9.3	6.1	2.6
2025	11.9	7.3	3.3
2030	14.6	8.7	3.9

In order to give an example on how air pollutant emissions are included in the model, Table B 6 shows emissions factors for the main pollutants in the residential sector. Emissions from logs and pellets are differentiated.

Table B 6
Emission factors for the main air pollutants (SOx, NOx, PM2.5, COV, NH_3) in the residential sector. Note: the emissions coefficients were defined with the help of the regional environmental agency.

kt of pollutants by PJ of fuels	Coal (residential)	LPG (residential)	Oil (residential)	Gas (residential)	Logs (residential)	Pellets (residential)
SOx	0.6	0.0003	0.047	0.0003	0.011	0.011
NOx	0.1	0.042	0.0435	0.02826	0.05	0.08
PM2	0.45	0.0002	0.0015	0.0002	0.74	0.06
COV	0.6	0.0018	0.00017	0.0018	0.6	0.01
NH_3	0.0003	0.0006	0.0001	0.0006	0.07	0.012

A model such as TIMES is also driven by the data and assumptions on the costs of the new technologies (as well as their other parameters, such as the availability of the technologies). Table B 7 indicates the costs and availability of different windmills and PV panels technologies, which are central to our analysis.

Table B 7
Data on solar PV panels and windmills: investment, fixed costs, and operating hours per year. Data are from the Walloon regional administration (CAPGEMINI on behalf of SPW, 2015).

Technology	Operating hours per year	Investment costs in 2015 (€'14/kW)	Investment costs in 2020 (€'14/kW)	Investment costs in 2030 (€'14/kW)	Annual fixed costs (€'14/kW/year)
Windmill Onshore Small 100 kW Motorway	1130	3000	2736	2600	55
Windmill Onshore Large	2190	1610	1562	1443	47
Solar PV Residential Homes 3 kW (1–10kw)	855	2444	1869	1301	13
Solar PV Buildings 100 kW (10–500 KW)	912	1716	1256	983	17
Solar PV Large Roofs 1 MW (1–5 MW)	912	1510	1230	852	17

(continued on next page)

Table B 7 (*continued*)

Technology	Operating hours per year	Investment costs in 2015 (€'14/kW)	Investment costs in 2020 (€'14/kW)	Investment costs in 2030 (€'14/kW)	Annual fixed costs (€'14/kW/year)
Solar PV Greenfield 10 MW (1–30 MW)	912	1422	1163	800	16

Appendix C. Brief analysis on air pollutant emissions

In our central cases, we define a constraint on air pollutant emissions. It was important to consider a constraint on those emissions for three main reasons, as explained in section 3. We include emission factors for the main air pollutants: SOx, NOx, PM2.5, COV, NH_3. For instance, emissions factors for the residential sector are shown in Appendix B, Table B 6. The emissions coefficients were defined with the help of the regional environmental agency, and consistency with the regional inventories of air pollutants was verified. However, we do not aim at providing a highly detailed and accurate analysis of future air pollutant emissions, which is out of the scope of this article and of our model definition. Instead, we aim at taking into account the fact that air pollutant emissions must not rise in the future and at providing an indication on how they evolve in our scenarios.

The constraint on atmospheric pollutants is defined for each pollutant (SOx, NOx, PM2.5, COV and NH_3). As mentioned in section 5.1, it bounds the sum of emissions from all the sectors apart from the transport sector (limiting total emissions of each pollutant at their 2014 level). With the current modelling approach of atmospheric pollutants, it was not possible to accurately consider the various emissions of all the different technologies in the transport sector.

Fig. C 1 shows the evolution of atmospheric pollutants emissions included in the constraint between 2014 and 2030 in our two main scenarios (Sc. REF and −55%). Firstly, we see that the industrial and the residential emissions are far more significant than the emissions of any other sector, both in the base year and in 2030. Secondly, in the residential sector, the emissions of all the 5 atmospheric pollutants are decreasing significantly between 2014 and 2030 in both scenarios. This can be linked to the renovations and the more efficient technologies used in this sector. Thirdly, the total of each atmospheric pollutant (summing all the emissions of each pollutant across all the sectors) is decreasing in both scenarios except for the NOx in Sc. REF and for NH_3 in Sc. −55%. In both scenarios, this last result is due to larger emissions in the industrial sector.

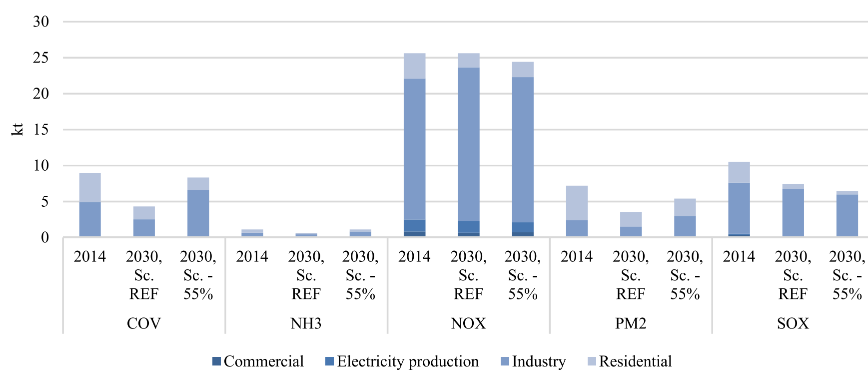


Fig. C 1. Evolution of atmospheric pollutants emissions included in the constraint. Note: the emissions are shown from 2014 to 2030 in our two main scenarios (Sc. REF and −55%). The emissions from all the main sectors apart from the transport sector are represented. The graphic shows first the evolution of the COV emissions between 2014 and 2030 (for our 2 central scenarios), then the evolution for the NH_3, NOx, PM2.5 and SOx emissions.

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