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Impact analysis of carbon pricing strategies on the decarbonisation of the Italian electricity market

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A mia nonna

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Contents

Abstract

We analyse the impacts of a carbon tax regime on the Italian economy and the evolution of the Italian electricity system toward carbon neutrality by 2050.

In order to frame the problem, first we address the climate change issue and its link to the production of energy (i.e. the electricity industry). We review how Italy decided to tackle this issue and how it compares with Europe's objectives. In so doing, we report the various carbon pricing instruments available to the policy makers with quotes on what previous experiences have taught us.

After this overview, we introduce the different energy models frameworks adopted in support of the scope of the research. We present the results of two case studies. On the firsthand, we illustrate how even imposing a 50% carbon tax regime will only partially alleviate the problem and make capital owners worse off. Secondly, we show that no less than 10 GW per year of additional photovoltaic panels should be deployed and how around €18 bln per annum need to be invested overall in greener technologies to fully decarbonise the Italian electricity system by 2050.

In the conclusions, we stress on: (i) the importance of the combination between batteries and photovoltaic technology, (ii) the irrelevance that carbon pricing assumes on the long term, (iii) the higher cost of becoming independent from electricity imports and (iv) the potential cost saving curtailment holds against batteries.

Chapter 1

Introduction

1.1 The underlining climate change issue

Greenhouse gases (abbreviated GHG) are gases that absorb and emit radiant energy within the thermal infrared range. They are part of Earth's atmosphere and thus, let sunlight pass but trap the heat it brings. This heat is, in turn, reradiate towards Earth's surface causing the *greenhouse gas effect*. The most notorious greenhouse gases are CO_2, CH_4, N_2O, HFCs, PFCs and SF_6. Although GHG emissions are often expressed as CO_{2eq}, it is not unusual to use CO_2 as a proxy being of more simple measurement and monitoring. In addition CO_2 is by far the most prevalent gas emitted of all the greenhouse gases.

Atmospheric concentrations of GHG point out the balance between the sources (emissions up until the late 1700s was largely due to natural systems such as animals or volcanoes) and sinks (removal of the gas i.e through converting it in a different chemical compound). Fortunately, this is not the case. The presence of CO_2[1] and, moreover, the greenhouse gas effect makes it possible of having an average temperature of Earth's surface of 15°C rather than -18°C. This has permitted Earth to be a comfortable place to live with concentrations ranging between 172 and 300 ppm[2] for the past one million years. However, humans activities have recently, around the start of the Industrial Revolution (*circa 1750*), started to emit greenhouse gases contributing to an increase of their concentration in the atmosphere. In particular, it has been observed that the concentration of CO_2 has risen from a 280 ppm pre-Industrial Revolution level to 417[3] ppm, as of 2020. This number indicates that in the last 300 years it has been registered a 49% increase of CO_2 concentration in our atmosphere.

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[1] From now on it shall be extensively used as a proxy of greenhouse gases for the motives previously explained.

[2] The number of a given gas molecules in a million molecules of air, after water vapour has been removed.

[3] Measurement by the National Oceanic and Atmospheric Administration (NOAA).

Earth's surface is getting more warmer than it should be. This phenomenon is commonly known as *global warming* and is now well established that anthropogenic greenhouse gases, especially carbon dioxide, emissions have been the dominant cause.

In its Fourth Assessment Report (AR4), the Intergovernmental Panel on Climate Change (IPCC 2007) stated that the warming of the climate system is "unequivocal" and that "most of the observed increase in global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic gas concentrations". Seven years later when the IPCC released it's Fifth Assessment Report (AR5), the Working Group III assessed and collected multiple long-term mitigation pathways that yielded different global surface temperature increases based on the amount of CO_2 concentration in 2100. For example, if the level of CO_2 were to arrive at 450 ppm there would be a 66-100% probability that the temperature change is kept under 2°C relative to the pre-Industrial period (baseline). Achieving such concentration quota entails a heavy cut of annual GHG emissions of at least 50% by 2050. Despite this endeavour, the issue of rising average temperature still looms and the 2°C has been set as a general threshold. The complications of going beyond this number are severe and damaging. Temperatures will hit new extremes and heatwave will become more frequent. Water availability will become more scarce due in part to an increase of droughts all over the world. Ocean levels will rise of at least 0.2 m with exactly a 2°C increase and this is true for 70% of Earth's coastlines. The Arctic Ocean will be summer ice-free once every decade and the likelihood of marine ecosystems having irreversible losses is alarming. All of these impacts will reflect in some measure on humans in terms of health, livelihoods, food security, water supply and economic growth. To sum it up, climate change is appalling and has been deemed more than once one of the greatest challenges facing the world.

1.2 The role of energy in society development

Energy has been a key human thematic since the Industrial Revolution. At the beginning of the last century, the political talks mainly focused on which energy source should drive the prosperity of the country. In the US, Winston Churchill incentivised the use of oil for naval ships against the common consensus on coal because it reduced ship refuelling time (Wirth and others 2003). In the German lands, fuel oil was chosen to fuel the newly invented Diesel engine rather than coal. Example like the formers show that strategic political choices in this field have always looked at energy as a mean to increase the wealth and quality of life of the people in any given nation. However, the energy discussion cannot be entertained without taking into account the implications of other external variables. Starting from 1850, the world population experienced an exponential growth. Fig. 1.1, shows how much it took for the world population to add one more billion people. The most interesting aspect is that it took all of humanity to reach one billion in 1803 but only 124 years to double after that.

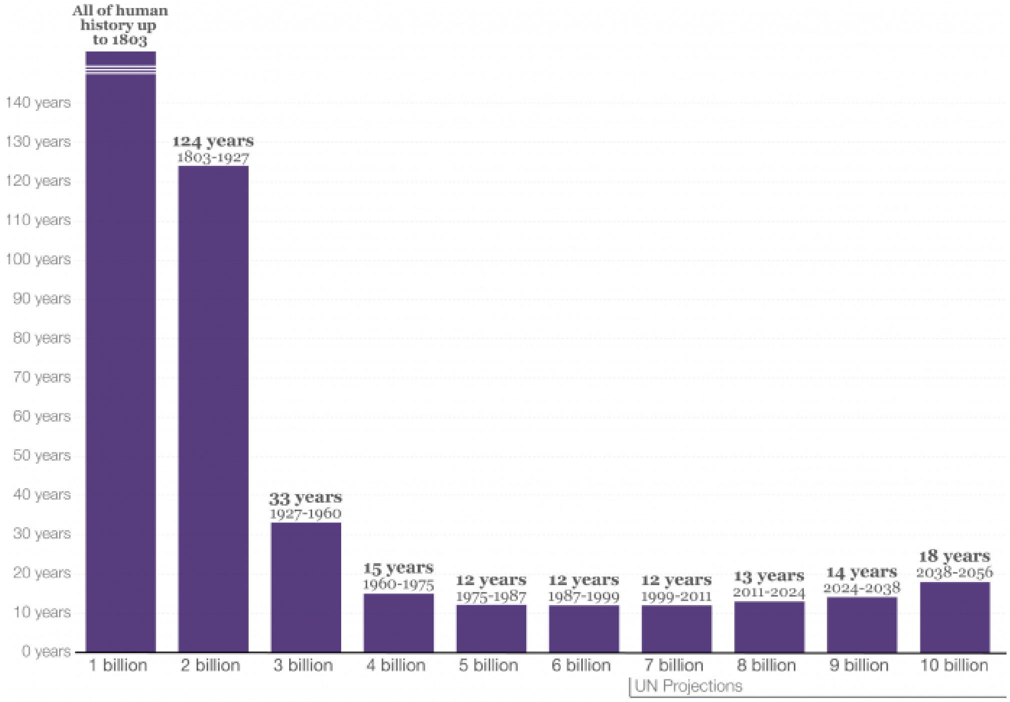
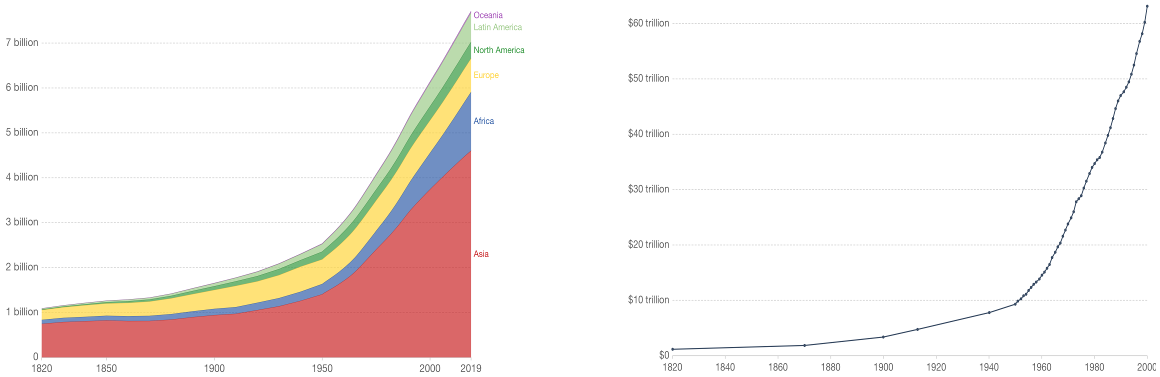
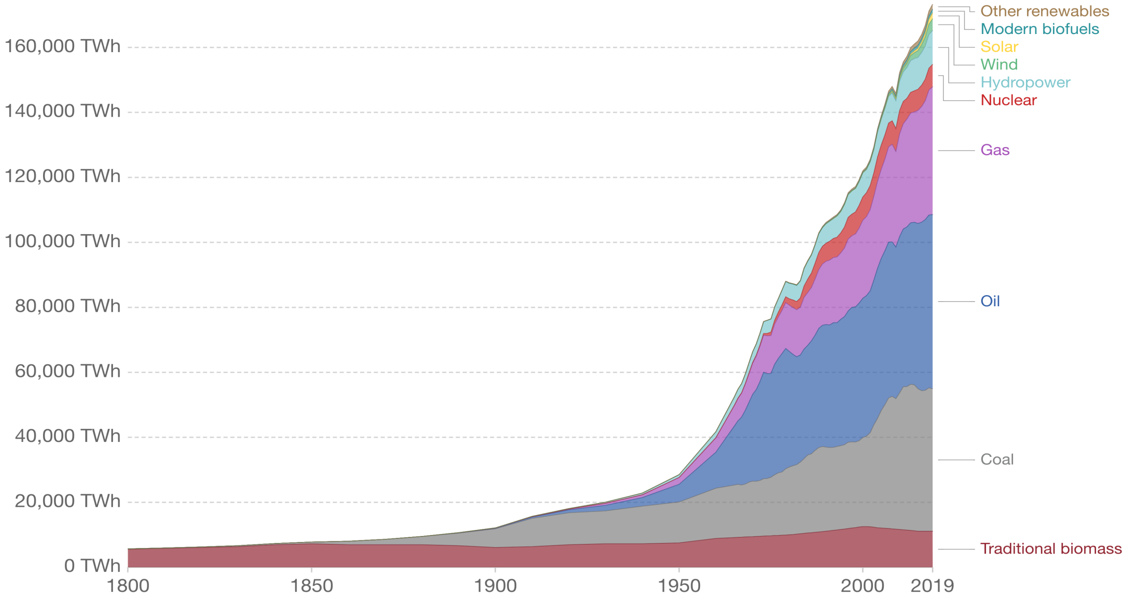


Figure 1.1: Time for the population to increase by one billion with UN future projections
Source: Our World in Data

The above graph hints that some sort of correlation between population growth and energy consumption may exist. Indeed, if we go more in-depth it stands clear that energy, together with medicine development, played a crucial role in boosting the population numbers all over the world. The graphs presented in Fig. 1.2 put in perspective the clear correlation between these two variables and stretch even more to see resemblance with GDP growth.



(a) World population size by region (b) GDP of the World ($ 2011)

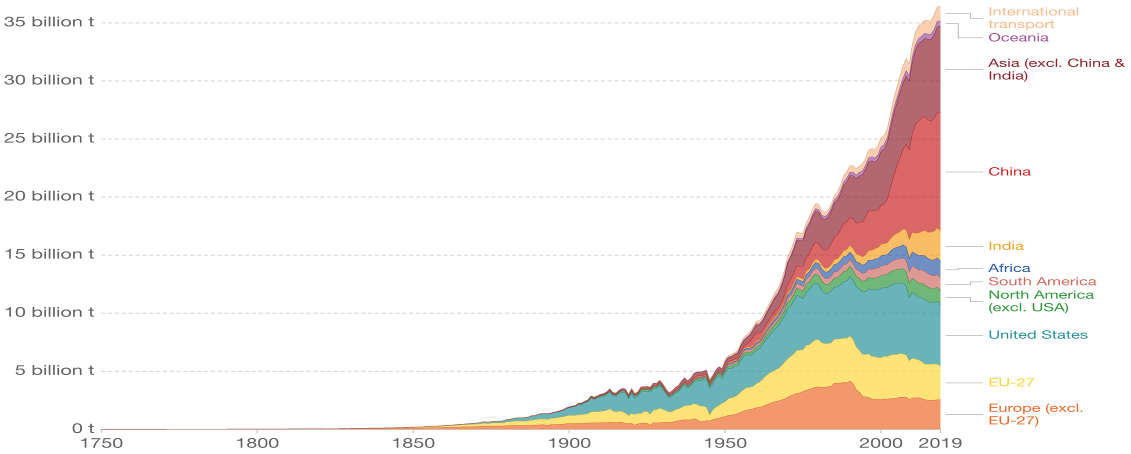


(c) Energy consumption of the World

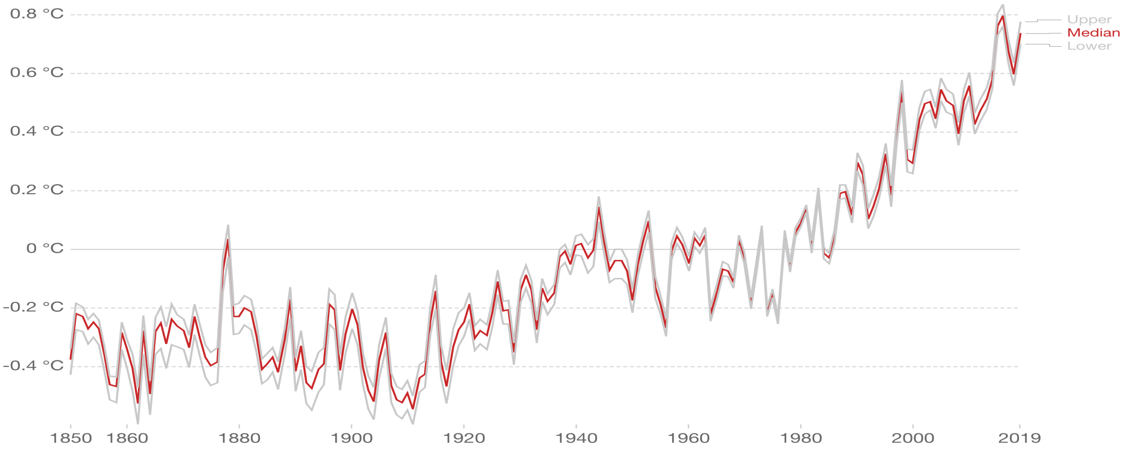
Figure 1.2: World population, GDP and energy consumption comparison (1800s onward)
Source: Our World in Data

All of the three graphs presented above have the same exponential trend. In particular, we can appreciate a significant trend acceleration during the 1950s. Indeed, in a post-War world, society reaped the benefits of living in a war-free climate, which spurred significant innovation and technological advances. In just 50 years, the world GDP was six times the one in the 50s and the same can be said for energy consumption. Population grew at a slower rate but nonetheless more than doubled in the 2000s in respect to its 1950s value. For such matter, the most important key takeaways to be drawn are the following: (i) population, energy consumption and GDP are strictly intertwined together (ii) energy consumption has increased people's quality of life (iii) energy has become a central pillar of humanity progression and evolution.

The constant need to consume and the appeal of living higher quality standards of life left untreated the disastrous consequence linked with the impressive increase of energy consumption. It was only in the 1970s that national policies surrounding energy started to look at the environmental aspect. This concerns gained rapid traction due to the potential correlation found between the increasing presence of carbon dioxide in the atmosphere and global warming (as observed in Section 1.1). he graphs in Fig. 1.3 show the increase of carbon dioxide due to the burning of fossil fuels on the left and the increase of average global temperature on the right.



(a) Annual world total CO_2 emissions by region



(b) Global average temperature anomaly

Figure 1.3: Comparison of CO_2 emissions with the increase of average global temperature increase

Here, the first thing we can appreciate is that the curve in Fig.1.3a follows the similar evolution seen in the precedent GDP, population and energy consumption graphs. This is not unexpected seeing that the more energy is consumed the more one shall emit in the atmosphere. On the other hand, Fig. 1.3b shows the increase of average global temperature. From these main takeaways, governments all over the world started including the environmental facet in their energy policies (i.e. the way in which they deal with issues of energy development including energy production, distribution and consumption).

In the scope of what will be addressed in this thesis, it feels important to specify that the policy instruments developed to tackle this problematic can take up two shapes. It can be either reactive or proactive. A reactive policy (e.g. a tax) is developed in response to a concern, problem, or emergency. It is often the quickest policy development, as problems are more urgent. A proactive policy (e.g. investments) is designed to prevent a problem from occurring. It is a cumbersome process as it is difficult for lawmakers to commit money to a problem that has not yet occurred. Both forms have been applied by countries all over the world and we shall have a deeper understanding of the differences further along in this work.

1.3 Energy and climate policies in Europe

EU climate change policy is based on the EU's long-term target to limit global temperature increases to a maximum of 2°C above pre-industrial levels. It has been derived a $20 \div 30$ cut from the IPCC Fourth Assessment Report recommendations and as a consequence the EU has already put in place, since 2005, the most important carbon trading system in the world, the EU Emission Trading System (EU ETS).

In order to achieve the medium-term GHG emissions reductions required by developed countries, the Council of the European Union formally adopted an integrated climate and energy package in 2009. The package aims to tackle the problems of reducing greenhouse emissions, increase the share of renewable energy sources and decrease the primary energy consumption or, in other terms, increase energy efficiency. This objectives are generally referred as the "20-20-20 by 2020":

1. an absolute emissions reduction objective of 20% in greenhouse gases from 1990 levels;
2. a binding target to reach a 20% share of renewable energy sources in primary energy consumption;
3. a 20% reduction of primary energy consumption (non-binding).

To implement these general targets, the climate and energy package contains appropriate key elements:

1. a revised EU ETS;
2. an "effort-sharing" Decisions that sets legally binding GHG emissions reductions targets in respective EU member states for all sectors not covered by the EU ETS;
3. a Directive for the promotion of renewable energy sources;
4. a Regulation to reduce average CO_2 emissions of new passenger cars;
5. new environmental quality standards for fuels and biofuels;
6. a regulatory Framework for carbon capture and storage (CCS).

The EU ETS has been EU's key tool in cutting GHG emissions and uses carbon pricing in the form of a cap-and-trade scheme: it caps the total GHG emissions from the covered sectors and allocates allowance to emit. These allowances can, then, be traded within the scheme. The need to revise this system stemmed from a number of teething problems encountered in the 2005-2007 pilot phase. The most severe deficiencies of this phase included over-allocation, intensifying the effects of free allocation, distorting allocation between member states and generating windfall profits for the power sector. The revised version proposed radical changes:

- A single EU-wide cap to substitute the previous system of national caps;
- Power companies will have to buy allowances at an auction (instead of free allocation) and harmonised allocation will be implemented to those still given away for free.

In this third phase (2013-2020), the EU ETS has been able to limit emissions from 11,000 power plants and manufacturing facilities as well as over 500 aircraft operators flying between EEAA's airports. The sectors covered by the EU ETS are all energy intensive such as power plants and other combustion plants with >20MW of thermal rated input, oil refineries, iron and steel, petrochemicals, etc. The allowances put in circulation annually for both the stationary installations and the aviation sector are bound to linearly decrease each year by a 1.74% factor reaching in 2020 a toll of 1.816 billions for the stationary installations and 35 million for the aviation. Although most of them have been auctioned, a significant part has been given for free to those industrial installations at risk of carbon leakage. Of the defined number of allowances put in circulation annually, approximately 60% have been auctioned while the remainder given for free. In addition to the allocation of free permits due to carbon leakage, a New Entrants Reserve (NER) was implemented with the goal of funding new installations and installations significantly increasing capacity. From this programme 300 million allowances were deducted in order to create the NER300, whose aim was to fund innovative low-carbon energy demonstration projects and to which, as a result of two round calls, approximately EUR 2.1 billion were allocated. The remainder undisbursed budget will be used in combination with the monetisation of at least 450 million allowances to fund the new Innovation Fund set to launch in 2020. This is part of the next phase 4 (2021-2030) and it will support, on a competitive basis, first-time market development and commercial scale demonstration of innovative technologies and breakthrough innovation in sectors covered by the EU ETS, including innovative renewables, energy intensive industries, carbon capture and utilisation (CCU), and energy storage. Furthermore, it has been permitted to participants in the EU ETS to use, until the end of 2020, the international credits derived from the previous Kyoto Protocol's Clean Development Mechanism (CDM) and Joint Implementation (JI) in order to fulfil their obligations. The credits, Certified Emission Reductions and Emission Reduction Units respectively, are financial instruments that represent a tonne of CO_2 removed or reduced from the atmosphere as a result of an emissions reduction project. To sum up the different methods on how the permits are allocated, a comprehensive table follows:

Auctioning
Free allowances (carbon leakage)
Free allowances (NER)
Free allowances (10c)[4]
International credits exchanged

Table 1.1: Composition of permits allocation in phase 3
Source: DG Climate Action

The auctioning is governed by the Auction Regulation and mainly operates from the European Energy Exchange (EEX) platform. In 2018, EEX auctioned 89% of the total amount, on behalf of 27 EU Member States, and the Intercontinental Exchange (ICE) the remainder 11% on behalf of the UK. An overview of the auction clearing prices during phase 3 can be appreciated in Figure 1.4:

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[4] Modernisation of the electricity sector in lower income EU Member States

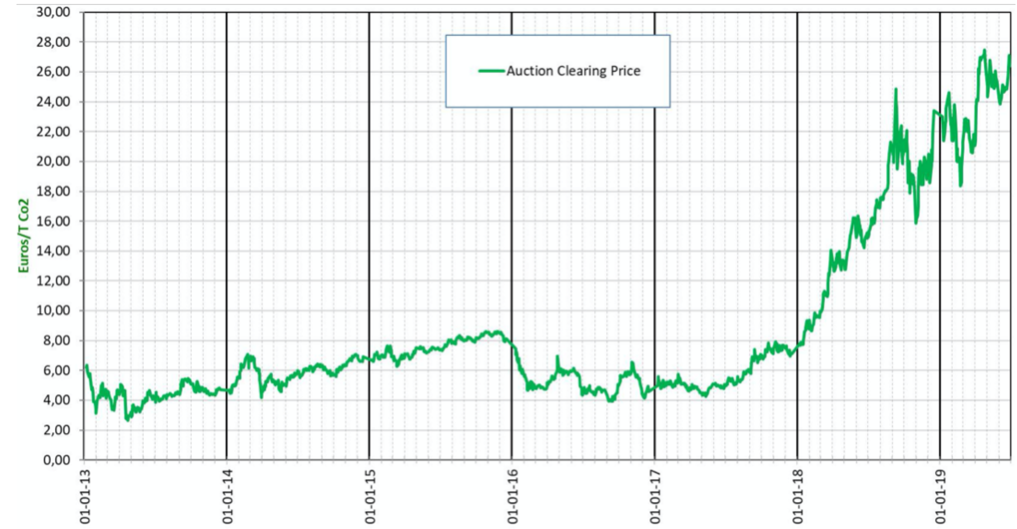

Figure 1.4: Clearing price for general allowances auctions during phase 3
Source: EEX

The total revenues from this auctioning exceeded EUR 42 billion. In 2018 alone, auctioning generated EUR 14 billion. Of this overall amount, during phase 3, approximately 80% was reinvested for climate and energy purposes with a solidarity aim. The implementation of the EU ETS revised was able to yield astonish results, in particular in the electricity and heat production sectors, as we can observe in the following Table. 1.2.

Year	2013	2018
Verified total emissions	1908	1682
Change to year	NA	-11,8%
Verified emissions from electricity and heat production	1125	913
Change to year	NA	-18,8%
Verified emissions from industrial installations	783	769
Change to year	NA	-1,8%
Real GDP Growth Rate EU28	NA	11,0%

Table 1.2: Verified emissions (in million tonnes CO2 equivalents)
Source: EUTL,Eurostat

These results pave the way for the next EU-wide targets policy and objective of the 2030 climate and energy framework. Seeing that reduction from GHG emissions is bound to surpass it's 20% goal of 2020, the new target has been set to at least 40%. Following suite, the share of renewables has been increased to 32% and the decrease of primary energy consumption to 32,5%. To achieve these objectives, a new EU ETS has been revised, in 2018, for it's next phase 4 (2021-2030). The revised EU ETS will enable this new medium-term strategy through a mix of interlinked measures:

- Strengthening to 2.2% the annual factor of allowances decline;
- Free allocation to sectors with high risk profile of carbon leakage will be prolonged;
- Reinforcement of the Market Stability Reserve (MSR)[5];
- Two new funds: the Innovation Fund, to extend support to the NER300 programme, and the Modernisation Fund, to help modernise the power sector and wider energy system.

The adoption of evermore stringent policies and ambitious goals is done with the objective of driving progress towards a low-carbon economy and build an energy system capable of ensuring affordable energy, security of energy supplies, independence of energy imports, growth through new job opportunities and environmental benefits i.e. reduce pollution. Ultimately, the European Union has envisioned as their long-term strategy the goal of transiting to a truly carbon-neutral economy by 2050.

1.4 Energy and climate policies in Italy

Italy shares the European community goal of overcoming the struggle to decarbonise the economy and promotes a Green New Deal which deals with climate neutrality. This is envisioned as a green pact with the local business and the people to include the environment as the economic driver of the Nation. However, it is important to remark that Italy's commitment has been strong for the last past ten years. Support for renewables and energy efficiency has significantly increased over time. In 2018, €13.3 billions have been used to subsidises the electric bill (PNIEC 2019).

Before delving into the details of what Italy has planned to do for the next thirty years, it feels useful to stress on how the national energy system structure and the corresponding CO_2 emissions evolved (Fig. 1.5)

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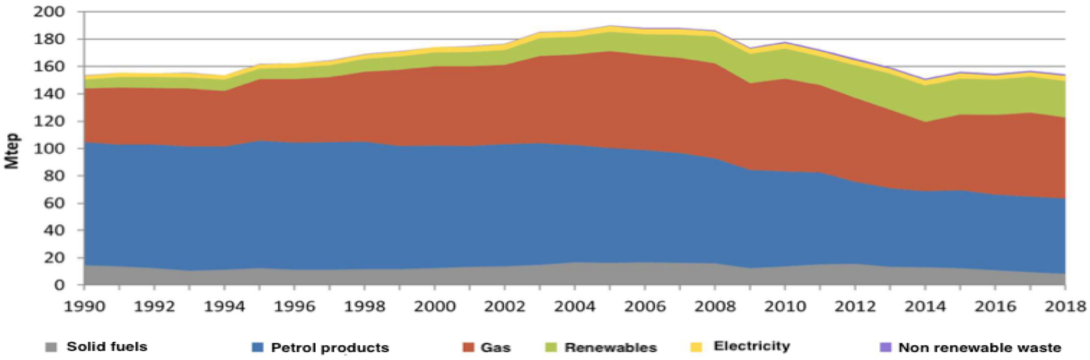
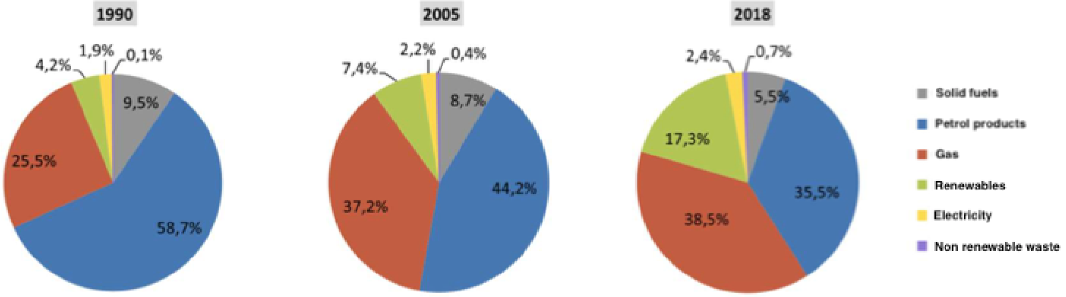
[5] Mechanism to reduce the surplus of allowances in the carbon market and improve EU ETS resilience by adjusting the supply of allowances



(a) Italy gross inland energy consumption divided by source (Mtep)



(b) Italy gross inland energy consumption mix by source (%)

Figure 1.5: Italy gross inland energy consumption, 1990-2018
Source: Eurostat

The first thing to notice is that Italy has been increasing its renewable share over the past thirty years and has been substantially decreasing its dependence on both petrol products and solid fuels. Conventional resources dropped from 93.7% in 1990 to 79.5% in 2018. Italy has essentially worked to substitute its previous preponderant conventional sources (i.e, solid fuels and petrol products) with gas, which is deemed to be the transitioning fuel. Nowadays, the figure is quite different from the early 90s as gas and renewables cover almost 60% of the gross inland domestic consumption. It is interesting to compare this data with how the nation performed from an economic point of view. As described in Section 1.2, the way a country prospers economically is most often positively correlated with the increase of energy consumption. However, Fig. 1.6 tells a different story.

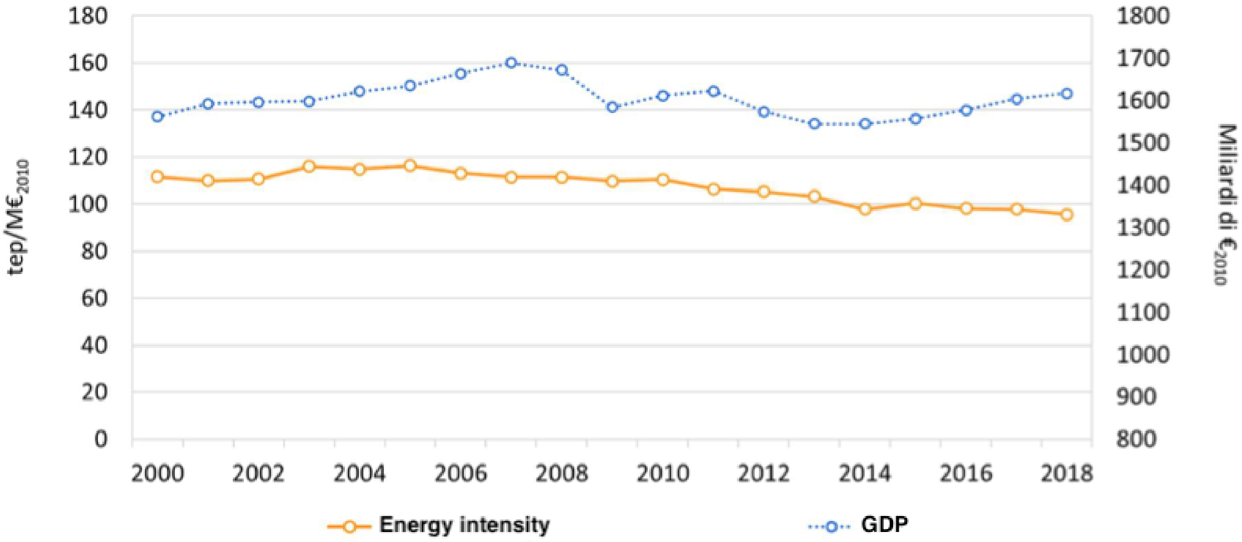


Figure 1.6: Italy's Energy intensity (tep/ Bln €2010) and Gross Domestic Product (Bln €2010), 2000-2018
Source: Eurostat

Indeed, in the analysed period we can observe a constant decoupling between economic growth of the country and its consumptions. In particular, in 2018, the nation's energy intensity index (i.e. the ratio between gross inland consumption and GDP) has seen roughly a 20% drop compared to its beginning of the century levels. This entails that the country has been able to prosper by reducing its energy needs instead of increasing them. A similar result has been seen from a demographic point of view. In 2018, the pro-capite energy demand (2.5 tep/inhabitant) was 17% lower than 2000s levels but population saw an additional 4 million people, bringing its absolute value to 60 million. These numbers show the good country's performance as it is one of the best in the Eurozone. However, this means that further reducing these metrics becomes a harder challenge.

On this note, Italy has developed its own Integrated National Energy and Climate Plan (2018) which revolves around five pillar dimensions:

- Decarbonisation → Accelerate the transition from traditional fuels to renewables sources by gradually phasing out non renewables sources of electricity generation.
- Energy efficiency → Reduce energy consumption of every sector and focus especially on exploiting the potentiality of the building sector.
- Energy security → Become less dependent on primary energy resources imports and diversify the type of source used.

- Internal market → Improve the degree of market integration in the Union by easing the cross-border interconnections and market coupling between Member States.
- Research, innovation and competitiveness → Development of processes, products and knowledge that have an outlet in improving the decarbonisation paradigm.

Italy's target for reduction of GHG emissions are set at a European level for the sectors falling under the ETS scheme (e.g. energy sector). In Italy, the share accountable to the energy sector was around 81% (MISE 2019). Here, the country is expected to reduce its emissions by 20% and 43% for 2020 and 2030 respectively. Instead, for the non-ETS sectors, an Effort Sharing Regulation (ESR) has been developed and for which Italy's has set an internal target of 13% (2020) and 33% (2030) reduction. In 2016, Italy was already on track with the ESR having emitted 18% less than 2005.

It is important to underline that Italy's process to obtain this target is bound by tackling multiple variables and goes beyond the Emission Trading System. The point is that the complete closure of the "emission gap" can be reached by implementing different options, even cumulative between each other. Whatever the path followed, it stands clear that each assumption made – technical, economic, social or operational – must be diligently respected and, thus, the appropriate investment must be deployed to reach the goal (i.e., climate neutrality). On a related note, we shall briefly recount the three main spheres on which the nation has decided to focus on:

- Energy demand → The aim is to reduce drastically the final consumption by at least 40% compared to the current one. This objective is in line with the European mantra of "energy efficiency first" and the effort must be concentrated on the residential/commercial sector. This reduction must be accompanied by an important recomposition of the energy vectors covering the final consumption. Electricity now covers more than 50% of the final demand and is bound to increase in the medium-term. However, all this would not be possible without some critical enabling factors. Citizens must be available to renovate significantly the buildings and adapt certain aspects of their daily routines to less polluting gestures.
- Energy supply → To meet this incumbent change of demand, the supply must adapt accordingly. Approximately 95%÷100% is the desired range of renewables covering the demand. In particular, Italy is planning to reach this target through a mix of offshore, solar and storage (either in the electrochemical or hydrogen form). Indeed, roughly 25% ÷ 30% of forecasted "overgeneration" (i.e. when supply is more than demand)

is supposed to be converted through electrolysis in hydrogen. Despite this ambitious program, which will completely revamp the energy flux picture, some residual emission will remain, mainly attributable to a small quota of gas in the industrial sector.

- Non-Energy sector → This is the most difficult sector to ameliorate as not much can be accomplished through technology. The margin improvements are in the order of 20% and are mainly obtained by a better management of stock with the strengthening of historical absorption sinks. Potential could be found in the implementation of carbon-capture storage systems but further technology leaps should happen to concretely realise the adoption. Even here, the change in people's eating habits plays a substantial role to reduce emissions coming from the livestock.

This section brings to an end the first chapter, where we had the opportunity to elaborate the main problem by linking it to its root causes (i.e the way energy has been implemented in our society). This made possible to give a glimpse of what both Europe and, more specifically, Italy have been doing till now to overcome this problem. In the following chapter, we shall try to unravel what past authors have come up with to deal with the issue and to understand if carbon pricing could be the solution to these carbon emission troubles.

Chapter 2

Literature Review

2.1 Climate-based policies

Climate change shifted from a scientific problematic to political one only in the mid-1970s. The first political debate on this argument was held in Stockholm during the United Nations Conference on Human Environment (1972). Since then, policy regulators all over the world enforced, using different domestic approaches, policies to tackle this climate issue.

The most renowned is the command and control regulation. The *command* part implies that a certain standard or target drawn out by a government authority must be complied with. The *control* is the part of monitoring if non-compliance events arise and in what measure should they be sanctioned. In the environmental policy dome, the CAC relies on three main standards: ambient, emission and technological. The authority can issue that a certain technology must be used e.g. electrical appliances must have a minimum standard of efficiency or maybe specific industries must bear their fair share of reducing pollution e.g. a performance standard to regulate thermal efficiency in power stations. While it has been deemed to be largely effective in reducing pollution, this policy approach leaves little flexibility. Tietenberg (1990) empirically showed that the costs of implementing a command and control regulation could become $6 \div 22$ times more costly than the least-cost alternative, in which firms abate only up to the marginal cost. Here the point stressed is *de facto* that the financial burden imposed by the CAC policy on firms would put most at a competitive disadvantage. It is for this reason that in the 80s a surge for an alternative form of enforcing rose.

On the journey of finding a cheaper alternative, market-based policy seemed to be the answer. These methods rely on using pricing instruments. In doing so, a new market is born. The underlining idea is to stimulate, rather than impose, pollution reduction by leaving more flexibility in how and where emissions reductions actually take place. Leaving this freedom ensures that each firm will pursue the route which at most is equal to the marginal cost. If, for example, the government decides to implement a tax on emissions, the regulator expects that each party will endorse the strategy that reduces emissions to the point that the marginal cost is equal to the tax. This means that firms with opportunities of implementing technology to abate pollution at low cost will prefer doing so while the remaining who do not have such chances will choose to emit and pay the tax. This higher degree of freedom, which shifts the choice to the entity, make market-based instruments the desired cost-effective option. However, much debate spurred on the capability market-based instrument has in fostering innovation. Despite theoretical literature showing that market-based systems are superior in promoting innovation than regulation, Kemp and Pontoglio (2011) have observed that this is true only for low-cost improvement innovations but does not appear to be true for radical innovations. Evidence appears to be in favour of regulation when it comes to promoting radical innovation. Here the weakness of pricing instruments comes from the same strength: flexibility or, moreover, less stringency. Market-based instruments weaken innovation by offering a cheap way out. Driesen (2003) elaborately states that, under emission trading, only innovations costing less than the marginal cost of additional reduction facilities can find a market. This resonates with what has been said till now. The point he stresses is that design considerations such as stringency and monitoring may matter more than the mere discussion between trading and non-trading programs. The creation of more dynamic economic incentives that stem from the basic emission trading scheme can encourage competition, simulating what the free market does between firms. Negative economic incentives (revenue decreases or cost increases) can fund positive economic incentive (revenue increases or cost decreases). The combinations implemented by governments to address the problematic and find the optimal solution have been numerous. For such matter, due to its heterogeneity, it feels necessary to give a general taxonomy of these instruments:

- Carbon tax → Emitters pay a fixed price for every unit of emissions released into the environment. Ideally, if the regulator knew *ex ante* the marginal abatement costs for all polluters, it could know with certainty what level of pollution will result from the application of any particular echelon of tax. British Columbia and different Northern European countries are noteworthy examples of places where a form of carbon tax has been implemented.

- Emissions tradable permit → Overall cap on emissions from a sector of the economy (or perhaps the entire economy) and allocation of permits, equal to the size of the overall cap, to emitters included in the scheme. The permits are available for trading, so that firms exceeding their requirements can sell them to other firms. Having acquired market value, permits emit a similar abatement signal as the pollution tax. The advantage permits hold over the tax is that the regulator knows beforehand the level of pollution that will result. What remains unknown, however, is the price at which the permits will trade. Operating in such fashion allows substantial flexibility for the regulator to shift costs between regulated entities. The European Union is foremost the most blatant example of emissions cap and tradable permit.

- Tradable emissions performance standard → Involves a requirement that firms outreach a level of emissions intensity (emissions per unit of output) set by the regulator. This scheme works similarly as the emissions cap and tradable permit except for the fact that permits are linked to emission intensity. For this reason, the regulator will not known the overall level of emissions that will result. Diverse are the examples of single-sector tradable performance standard such as the U.S. lead phasedown or California's Low Carbon Fuel Standard.
- Subsidies → It provides an incentive to adopt particular technologies or to reduce emissions. A subsidy leverages market forces in a similar fashion as a pollution tax. However, there are some dissimilarities. First of all, a subsidy lowers a firm's average cost and thus increases profits. This means that either new firms will enter the market or intra-marginal ones will up their activity level, both options increase pollution. A regulator must set a performance benchmark beyond which firms are able to access a subsidy. This is no easy task and, usually, the level is set such that some firms qualify for the subsidy without any change in behaviour. They are known as free-riders and share similar characteristics with the concept of the adverse selection problem, seeing that the regulator does not know which firms actually require the subsidy to change behaviour and which not. A tangent example of subsidy is tax exemptions for electric vehicles and, sometimes, hybrid vehicles adopted all over the globe.

From this overview, we can better observe how different each strategy is in terms of incentives and how the choice of the design attributes of a policy can have a large influence over its environmental effects and economic impacts. By manipulating the design elements, it can be possible either to correctly address or to worsen the concerns on climate change. For example, how permits, in the emissions cap and tradable permit scheme, are allocated can yield different outcomes. We shall now have a look on what literature tells from both a theoretical and empirical point of view concerning the two types of market based policies: re-active (e.g, carbon tax) and active (e.g, subsidies).

2.1.1 Re-active policies

Under this scope, we find the first three instruments previously described: carbon tax, emission tradable permit and tradable performance standard. Despite each having their own differences, the underlining main objective stands to be the same which is internalising into entities in some form the social burden of carbon dioxide emissions.

Before Coase (1960), the only known way to deal with emissions was through the negative externality dilemma which directly tax each unit of carbon emission equal exactly to the marginal social damages[1](Pigou, 1920). Hence, the supposed cost-effectiveness of the method. However, after Coase (1960), a new way of looking at the problem based on the concept of property rights arose. If one could successfully clarify the rights of resource's ownership then a new class of permits could be traded on the market. A few years later, Crocker (1966) and Dales (1968) came up with the idea of transferable discharge permits that addressed this exact issue. This is the view that will lead to the most renown "cap and trade" mechanism.

These two instruments may seem radically different but still hold quite the similarities (Stavins 1997; Goulder and Schein 2013). To better understand the two mechanism, we shall recount what are considered to be the main points of parity and of difference:

- **Similarities**
  - Emission reductions → If the same time-paths and scope of coverage are chosen for either the tax or the trade then they will achieve the same reductions[2].
  - Abatement costs → Entities will abate up to the marginal cost of either the tax rate or permit price. In theory, they will foster the same innovation if the trading system is structured with auctioned allowances (Milliman and Prince 1989; Jung, Krutilla, and Boyd 1996) or that neither of them will come on top (Fischer, Parry and Pizer 2003).
  - Revenue raising → Intrinsically a carbon tax raises money for the government, which could be used to lower the overall net social cost of the policy[3] (Bovenberg and Goulder 1996). If a cap-and-trade is articulated with an auction mechanism the same outcome can be accomplished (Goulder and Schein 2013). Here, the

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[1] With the assumption of an efficient carbon emissions control.

[2] This holds true in the event that no uncertainty exists.

[3] Generally, this happens by making cuts to already imposed taxes on either firms or people.

only obstacle is the need to include an environmental committee on top of the financial one making the process more cumbersome.

- Firm's economic burden (accounting for revenue-raising) → Revenues raised can significantly change the associated cost burden a firm must sustain. Recycling trough cuts in payroll taxes, individual income taxes or corporate income taxes could potentially lead to respectively 15%, 26% and 67% lower net costs[4] (Goulder and Hafstead 2018). This is true for both a carbon tax regime and a cap-and-trade with auctioned allowances.
- Allocation strategies → A cap-and-trade system with auctioned allowances has a lot of common ground with a carbon tax as we have seen up till now. Furthermore, an emission trading system with free allowances has similar impacts of a carbon tax with tradable tax exemptions (i.e. the tax is collected only above a determined amount of carbon emissions) (Goulder and Schein 2013).
- Household impact → It depends on the degree of free emissions conceded and the use of revenue raised. Based on these two elements, the design interests both the expenditure (prices of goods and services) and the income side (wages, capital and transfers). On the consumption part, implementing a carbon pricing technique is regressive (revenues raised are ignored due to price adjustments on goods and services) (Goulder and Hafstead 2018). On the source part, the results are progressive especially if revenue is allocated through lump-sump[5]. Overall, Goulder and Hafstead (2018) have shown that progression exists in any case once both source and use side are taken into account since income changes trump the consumption side consequences.
- Competitiveness → A particular worry of economic policy where countries are afraid that imposing a carbon pricing mechanism on certain industries will place at an advantage firms in the same industry but operating in a country absent of the same policies. This phenomenon is also known as "carbon leakage" of both economic presence and of carbon emissions. Aldy and Stavins (2012) show that countries reducing their conventional resource consumption will drive down fossil fuel prices which in turn will lead to an increased use in nations without similar policies. Introducing a border adjustment with a carbon tax or an output-based requirement with a cap-and-trade on imported goods from countries with absent climate policies could help reduce the competitiveness loss (Fischer and Fox 2008).

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[4] This study has been conducted in the United States and does not take into account the "Tax Cuts and Jobs Act" of 2017. The effect such reform could have is of lowering the corporate income tax efficiency gains.

[5] This is true both for a carbon tax and for a cap-and-trade with auctioned allowances.

- **Differences**
  - Costs uncertainty → Initially, Weitzmann (1974) believed that benefit uncertainty did not have an effect on either of the two pricing instruments. However, Stavins (1996) showed that when marginal benefit and cost are positively correlated then a quantity policy mechanism is more efficient. The opposite holds true with a negative correlation. This concept was furthermore elaborated by Newell and Pizer (2003) when climate change was deemed to be a stock externality[6]. Based on this assumption, the slope of the marginal benefit function would be lower (in absolute values) than the marginal cost one and a tax instrument would be more appropriate. Indeed, it feels more appropriate to compare this marginal cost function with the present discounted value of future stream of marginal damages (i.e. social cost of carbon) (Pizer and Prest 2019). Karp and Traeger (2018) elaborate and show that a positive correlation exists between marginal benefits and costs. This means that a quantity instrument should be preferred or at a minimum they stand to be more efficient in dealing with climate change.
  - Price volatility → Having more certainty in the associated cost of climate policy will reduce the certainty quantity of emissions allowed (Aldy and Stavins 2012). Intrinsically, a cap-and-trade is more exposed to volatility than a carbon tax which could potentially lower the investment in new technologies.
  - Interactions with other climate policies → If some market-failure is present then it may be appropriate to introduce a complementing policy to the pricing carbon regime (Schmalensee and Stavins 2017a). However, if no market failure exists and the new policy is addressing the same issues as the market pricing instrument then differences arise between cap-and-trade and carbon tax. In such situation, with a quantity instrument, a concern regarding "leakage" of emissions and a lowering of permits prices arises because no net reduction of emissions is observed (Goulder and Stavins 2011). This does not happen with a carbon tax but, however, both policies will become not cost-effective.
  - Cost of transaction → In an emission trading system higher compliance cost exist due to the presence of allowances. However, historically and empirically speaking, this cost have not been significant in the observed systems (Schmalensee and Stavins 2017a).

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[6] The derived marginal damage is a function of time, which means that the consequences of emitting would manifest years later (i.e, average increase of global temperature), and will generally be flat for any given period.

  - Administration → The simplest form of a cap-and-trade mechanism will show greater complexity than the simplest carbon tax implementation. This has also been concluded by observing textbook applications by Goulder and Schein 2013.

In Section 1.4, we had the possibility of showing the fine structure details of the Emission Trading System applied in Europe. Here, the literature has been able to amply describe the pitfalls and the success of such implementation. The ETS has moreover functioned as expected after the pilot phase (Ellerman, Convery, and Perthuis 2010). Looking at particular design elements, the following can be appreciated:

- Having no banking provisions could lead to permits price collapse and a changing economy could make a cap not binding anymore. (Stavins 2019)
- Contrasting the competitiveness problem with free allowances has been deemed a failure but an output-based allowance mechanism could alleviate the issue. (Stavins 2019).
- The introduction of ”market stability reserves” can help with the ”waterbed effect” (Stavins 2019) as it is known in Eurozone (Fankhauser, Hepburn, and Park 2010).

Stemming from the European example of a cap-and-trade, it stand interesting to analyze the carbon tax implementation of a few Northern European countries under the ETS regime. These taxes have been introduced to excise particular tax reform initiatives (e.g, cut income tax rates) but the impacts are quite difficult to asses due to the blurred line with the EU ETS (Murray and Rivers 2015). The four countries under review are Norway, Sweden, Denmark and Finland which implemented their tax regimes in the 90s (way before the EU ETS). Norway had an energy coal tax of \$24 per ton of CO_2 (Bruvoll and Larsen 2004) later removed in 2003. The transportation sector was included in 2009 with a \$58 tCO_2 on gasoline and a \$34 tCO_2 on diesel. Sweden saw its carbon tax increase from \$33 tCO_2 (1991) to \$120 tCO_2 (2019) but sectors falling under the EU ETS are exempted. Denmark has a carbon tax of around \$17 tCO_2 since 2005 and Finland of \$28 tCO_2 since 2008. However, industries facing the most loss in competitiveness have been helped financially in all aforementioned countries (Aldy and Stavins 2012). Despite this, Northern European countries have been a good example of revenue recycling to finance spending of the government or lower other taxes (Organization for Economic Cooperation and Development 2001).

The last instrument will shall put under scrutiny is the tradable performance standard (TPS). It works in a similar manner to a cap-and-trade but, rather than fixing the quantity of emissions, it focuses on a pre-specified intensity target. The sum of all emissions from all sources or from a specific source divided by the total output should be less than this target. Even here, a market of permits can be created and be traded based on the performance of singular firms. The consequent equilibrium of trading should lead to an equality between average industry emissions intensity and policy goal (Fischer 2001).

More than often, a TPS is not implemented. It seems inefficient when it comes to abatement as it does not directly deal with curbing the demand. This means that it generally fails to internalize marginal damage of the negative externality (Becker 2020). However, the same Becker (2020) underlines that the analysis of a TPS implementation policy should be done in a dynamic context as the energy intensive sectors are strongly dependent on long-lived capital, which is need of replacement as it ages. Both Amigues (2013) and Coloumb (2019) show that the needed investments for shifting from a dirtier technology to a cleaner one should happen gradually and early on. As this shift slowly happens, average emissions intensity will fall due to an increasing enter of low emitters (which are retiring their dirtier assets thanks to permit's incentives) and the permit's price will fall (Fischer 2001). This leaves space to some policy structure potentiality in regards to tradable performance standards which must be carefully designed. Indeed, the TPS results to be superior to an equivalent cap-and-trade especially when there is a zero emitting fuel and the target intensity is set to zero (Fischer 2001; Holland 2009; Becker 2020).

On this note, we can conclude that this analysis has shown that, in reality, there is no easy choice between the reactive policies but it all boils down to a design structuring process along a policy continuum (Weisbach 2010). Therefore, the way a reactive climate policy is structured becomes far more important than the mere choice between a carbon tax, a cap-and-trade system or a tradable performance standard (Stavins 1997; Goulder and Schein 2013; Goulder and Hafstead 2018).

2.1.2 Active policies

The most common used form of active policy are subsidies, which refer to any manner of preferential treatment granted to consumers or producers by a government. The most important aspect of a subsidy is identifying the types of policy instruments (i.e., the transfers mechanism) employed to distribute the benefits. We shall focus on understanding three main discussions surrounding the application of this instrument for renewable energy sources.

First and foremost, it is adopted by governments to reach three main policy goals. The environmental one is surely the main objective as amply discussed both for the EU and Italy's perspective. Furthermore, sometimes given less emphasis, is the potentiality to create new jobs and industries. ILO (2008) estimated that in 2006 Europe saw an increase of over 2.3 million jobs. The third political motive to use subsidies in the renewable energy sources department is to ensure a security of supply (i.e. avoid supply disruptions). Ölz (2007) shows that the renewable technologies must be accounted for with some sort of advanced grid management and back-up capacity form to successfully deploy RES inside an energy system. All of this motives translate into a policy implementation which seeks to immediately deploy renewable technology to establish as an industry and look to operate them in a cost-effective manner in the medium-term (Beaton and Moernhout 2011).

However, reaching these goals generally entails some important barriers of both financial and non-financial scope (Mendonca, Jacobs and Sovacool 2010). We shall briefly recount the major ones:

- **Financial**
    - Innovation externalities → Under this scope, fall the issue of investing being disincentived due to sharing research benefits without bearing the costs of it. Palmer and Burtraw (2005) evidence that such problem may be solved by introducing intellectual property rights and thus correcting the slow of innovation. The OECD (2010) also underline the issue of investment riskness in such technologies.
    - High capital requirements → Power plants using renewable technologies have high initial capital costs which could disincentivize investments in this area (Beck & Martinot 2004, Martinot 2004). However, they have very low variable costs.
- **Non-financial**
    - Infrastructural and regulatory → Most developed countries have already in place extensive transmission and distribution infrastructures which were thought for a centralised energy production system. The way this system is designed could be a burden for small independent renewable players rather than large ones (Beck and Martinot 2004).
    - Information-related → Beck and Martinot (2004) show that the lack of information on the renewable technologies under all points of view could pose a danger to investment. The same goes for a wrong judgment of technology performance

(Mendonca 2010). Finally, the social aspect still plays an important role in some countries. One of the most discussed concern is the landscape impact of installing new wind or solar power plants.

Governments have developed various mechanism to subsidise renewables. They are generally divided as income or price support (e.g, feed-in-tarrifs), revenue foregone (e.g, tax breaks) or direct and indirect transfer of funds (e.g, direct spending) (Beaton and Moernhout 2011). Each of them share some common ground but manifest some point of difference generally on who can be eligible, what is the lifetime of the supporting mechanism and to what degree does this support extend. The IEA (2008) suggest that a decreasing mechanism is implemented over time in the appropriate subsidy scheme to mirror the cost abatement of renewables as they mature.

An extensive literature surrounding a comparison between the aforementioned subsidy schemes exist. In an ex-poste analysis of subsidy policies in the European countries it has been found that tradable green certificates and tendering, which are part of the income support category, have been the most cost-effective (Menanteau, Finon and Lamy 2003). However, the European Wind Energy Association (2005) later showed that only feed-in-tarrifs or feed-in-premiums are capable of fostering the deployment of renewable technologies. The European Comission (2008) will later confirm such conclusion but that that the FIT scheme must be adapted to really outperform. An interesting aspect would be to compare the subsidy mechanism against other policies interventions on climate change. Few studies exist on the subject. One of which is the Palmer and Burtraw (2005) ex-ante analysis on a renewable standard portfolio (income support), tax credits (revenue foregone) and an emission trading system. Here, the best performance in terms of new installed renewable capacity were obtained by the renewable standard portfolio and the ETS scheme.

Chapter 3

Methodology

3.1 Energy-economy models overview

Since the 1970s, economists and policy analyst have been using energy-economy models to comprehend climate change policy effectiveness. This has spurred the development of two school of thoughts: the top-down and the bottom-up approach.

The bottom-up approach analyzes the individual base elements of the disaggregated energy-economy and specifies them in great detail. In this particular case, these base elements are generally the representation of current and emerging technologies, which linked together to form larger subsystems, are used to satisfy the energy demand. This approach advocates that certain technologies, when their financial cost is converted into present value, appear to be profitable once market dominance is achieved and thus, leading to a significant environmental improvement related to the way energy is used. However, this approach has been largely criticized by many economists because being too focused on technology which conceals the macroeconomic effects of policies, especially the changes in energy prices and costs. Furthermore, this models ignores consumer preferences falling short in providing a useful estimate of a policy on the well-being of society.

The top-down approach, on the contrary, breaks down the system into smaller parts by working in a reverse engineering fashion. In our energy-economy scenario, it means evaluating the aggregate relationship between relative costs and market shares of energy. These factors are, then, linked to sectoral and total output in a broader equilibrium framework. The key role parameters, in this approach, are the elasticities of substitution which determine the substitutability between any pair of aggregate inputs and between energy forms. These parameters are said to successfully show actual preferences of consumers and businesses, implicitly incorporating their respective losses and gains, because derived from real and historical market behaviour. The shortfall of this approach is mainly due to the limited flexibility of these parameters. Values extrapolated from past experience do not guarantee validity in the future and it's fixed nature may not show the full adaption of firms and household to policies, leading to high cost estimates for policies looking to abate energy-related emissions.

Each model falls short where the other one shines. Bottom-up models lack the capability of showing macro economic implications and depicting society well-being. Top-down approaches, instead, suffer the absence of technological detail in most sectors and where it is included, technologies are typically assumed to be perfect substitutes for one another. No clear superior models exist and the choice resorts on the application.

3.2 Computable general equilibrium

Since the 1980s, the most used form of top-down approach in policy analysis has been the computable general equilibrium model (CGE). Largely based on the neo-classical spirit, a basic model relies on the concept of circular flow of income in society. In the most simple representation of circular flow, we only have two agents: households and firms. The households are bestowed with the factors of production which are rented to firms in exchange of income. The firms use these factors to produce goods which they will then sell to the households in order to generate revenue.

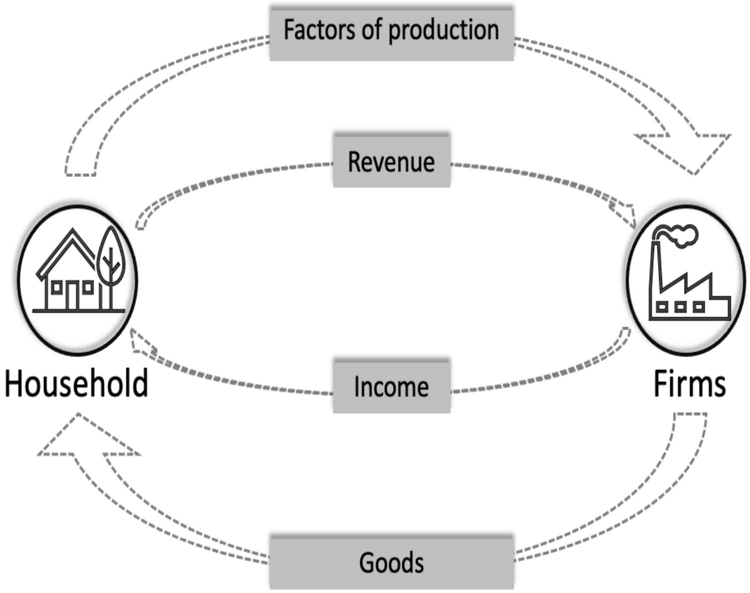

Figure 3.1: Visual representation of circular flow

Figure 3.1 well shows how the flow of goods and money is balanced. This concept represents the equilibrium of the economy. This first equilibrium is known as the market-clearance condition and it generally refers to the fact that any commodity produced in the economy must equal the quantity demanded. Together with this condition, we find two other in order to reach the general equilibrium of the economy. The closed nature of the loop indicates that the revenue generated by the firms must be spent on obtaining the factors of production (i.e. zero profit condition). Finally, we have the budget balance condition which shows that the whole income levied by households must be spent on acquiring goods.

Once all three conditions are met, the economy is said to be in general equilibrium. The computable, which derives from the fact that it can be programmed, general equilibrium model exploits all of the aforementioned conditions. The perks of adopting this modelling technique lies in the possibility of capturing the intricate linkages that exist between markets depicted. This characteristic becomes extremely useful especially when dealing with policy analysis because it helps uncover indirect impacts a policy can have on the sectors not covered by it. The partial equilibrium technique, in contrast, fails to capture this linkages as it focuses on a sector in isolation. Indeed, when debating about climate change policies it stands not possible to isolate the effects to a single sector as green house gases have an impact on the economy as a whole. Therefore, a computable general equilibrium approach can leverage insights that could easily be missed by implementing a partial equilibrium.

However, there are still some disadvantages that loom over the computable general equilibrium model. First and foremost the most argued problematic is the one regarding the calibration. One must define the functional relationship inside the model describing technological and agents preferences. More importantly, due to the fact that the majority of computable general equilibrium model rely on restrictive functions, the results one can infer from adopting this technique are broadly limited by these impositions. The second issue arises when the step of populating with numbers the functional relationships arrives and is subject to a two-step process. The first stage deals with the necessity of choosing a reference scenario, or benchmark data, which refers to a "snapshot" of the economy in equilibrium. This hypothesis is most of the times a stretch as the economy is in a continuous state of change. Thus, the choice of the reference scenario greatly influences the results of the model. Last but not least, even when one could argue appropriate the choice of the benchmark data, it will still persist the issue regarding the choice of the parameters defining the flexibility of the agents in moving away from this equilibrium. These are, generally, chosen empirically and based on historical data. However, when there is a lack of them in literature, they are more often decided based on judgment. This introduces a further degree of error in the model results and even when empirical ones are used it may not always be true that they will still hold in the future (Norton, Costanza and Bishop 1998)

When applying a computable general equilibrium model to analyse the effects of a policy, and more specifically an environmental policy, an ulterior problematic must be held into account. The utilisation of a top-down approach lacks the capacity of correctly detailing the technological changes. Technology is aggregated and highly generalised inside the production function through a parameter known as the elasticity of substitution, which abstracts the concept of marginal rate of technical substitution and summarises the substitutability between inputs. The adoption of such parameter leads to two major overlooks. Firstly, the method is not suited to analyse policies which deal with technological stimulation such as subsidies. Furthermore, the production function fails to include eventual price jumps, due to the nature of relationship between relative prices and volumes, caused by a technological tipping point and this means that non-linearity of prices are missed. Even when one can move beyond this problems, an ever green obstacle will still remain. The computable general equilibrium model is of complex comprehension and most of the policy makers find hard to interpret the results. This is due to the heavily intricate linkages that lie behind the model and are often referred as "black boxes". The fact that even the same authors find difficulties in intuitively explaining the results has made the greatest strength the CGE holds also its biggest weakness. Partial equilibrium model, on the other hand, are more appreciated as interpretation of a sector in isolation from its neighbouring environment is more intuitive.

Therefore, before delving more in detail on the potentiality of a computable general equilibrium model in the climate change scenario, we will try to untangle the complexities that lie beyond the so called "black box" by analysing a simple model of a two-firm and one household scenario. As one can imagine, even analysing a basic setting such as the former still implies a fair understanding of calculus.

3.2.1 Mathematical development

The scope of this section is to unravel the mathematics behind how firms decide which inputs to use and consumer which goods to consume. In other words, an overview of the basic economic calculus of the computable general equilibrium model is given.

To begin with, we shall look at the general hypothesis made. First and foremost, consumers and firms are believed to act "rationally" in their decision process. This means that consumers maximise their utility function based on an imposed external budget and that firms maximise profits based on input and output prices (Mas-Colell, Whinston and Green 1995) In addition, the curve of the utility function must be convex which means that consumer will not reach saturation at high level of consumption but nevertheless any marginal increase in consumption will subsequently correspond to a smaller increase in utility. Secondly, markets are competitive which means that any agent operating in it is considered to be price "takers". The third hypothesis refers to the firms having a constant returns to scale, which implies that in order to double the output they must also double the input. To conclude, the competitive general equilibrium is classified as Pareto optimal which implies that the marginal rate of technical substitution is equal for all producers and the marginal rate of substitution is equal for all consumers, which in turn corresponds to the marginal rate of transformation of producers.

As previously stated, the model studied is a simple two-sector and one household. The choice of not analysing a more complex one relies on the aim of helping understand what is the computable general equilibrium made off. Moreover, one of the sector is deliberately chosen as the aggregated of energy intensive industries and the other one as the rest of the economy[1]. This choice resonates with the scope of creating a model that can be easily utilised in dealing with energy related policies.

Firms - Production function

The existence of firms in the setting is solely based on the scope of maximising profits by influencing outputs through inputs. The firms only inputs available are labour and capital, which are supplied by the household. Labour is believed to be mobile across the two firms analysed while capital is fixed and sector-specific. The production function that relates inputs and outputs, when only the primary factors are included and there is only one output, is the Constant Elasticity of Substitution (CES) one and elopes as follow:

$$X_i = A_i \cdot [a_i \cdot LD_i^{\rho} + (1 - a_i) \cdot KD_i^{\rho}]^{\frac{\upsilon}{\rho}} \tag{3.1}$$

The Eq. 3.1 is referred to a generic firm i and is of complex management due to the over abundance of parameters to estimate based on judgement or on empirical data. The assumption previously made of constant rate of return (υ equals one) lets us simplify it but

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[1] In reality, this over simplification is not that far-fetched as it can be supported by the Walras Law as we will better see later.

for the purpose of this analysis it still far too complex. A special case of the CES function shall be utilised and more precisely the Cobb-Douglas one. The latter is obtained when ρ approaches zero in the limit[2] and is preferable due to its isoquant flexibility.

$$X_i = A_i \cdot LD_i^{\alpha_i} \cdot KD_i^{\beta_i} \tag{3.2}$$

Here the only parameters we find are the α_i, β_i and $\mathrm{A_i}$, which respectively refer to the output elasticities and the total factor of productivity. The output elasticities are however dependent on each other due to the constant return hypothesis and one can be rewritten in function of the other. The Cobb-Douglas function becomes:

$$X_i = A_i \cdot LD_i^{\alpha_i} \cdot KD_i^{(1-\alpha_i)} \tag{3.3}$$

We can now proceed in using Eq. 3.3 in a more general two-sector (i,j) view by correctly using the respective labour and capital expressions:

$$\begin{cases} X_i = A_i \cdot LD_i^{\alpha_i} \cdot KD_i^{(1-\alpha_i)} \\ X_j = A_j \cdot LD_j^{\alpha_j} \cdot KD_j^{(1-\alpha_j)} \end{cases}$$

In the previous system equations, LD and KD, with the respective suffixes, refer to the labour and capital demanded as inputs. In this scenario, the firms have been deemed to be "price takers" as per definition of a competitive general equilibrium and thus will recur to the profit maximisation theory. In mathematical terms, this translates to:

$$\pi_i = P_i \cdot X_i - wLD_i - r_iKD_i \tag{3.4}$$

A similar equation can be written for the other sector and both can be resolved using the first-order condition, which consist in imposing to zero all the first derivatives relative to each of the variables studied. However, before proceeding to the resolution, let us substitute the output of the "representative" firm with its Cobb-Douglas equivalent:

$$\pi_i = P_i \cdot A_i \cdot LD_i^{\alpha_i} \cdot KD_i^{(1-\alpha_i)} - wLD_i - r_iKD_i \tag{3.5}$$

Then, the first order condition will lead to the following two equations:

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[2] A more detailed explanation goes beyond the scope of this thesis but can be found in the original paper that introduced the CES function to the world, *Capital-Labour Substitution and Economic Efficiency* by Arrow, Chenery, Minhas and Solow (1961)

$$\begin{cases} \frac{\partial \pi_i}{\partial LD_i} = P_i \cdot A_i \cdot \alpha_i \cdot LD_i^{\alpha_i - 1} - w = 0 \\ \frac{\partial \pi_i}{\partial KD_i} = P_i \cdot A_i \cdot (1 - \alpha_i) \cdot KD_i^{-\alpha_i} - r_i = 0 \end{cases}$$

We shall, then, solve in respect of the rent and wage variables. This will lead to:

$$\begin{cases} w = \alpha_i \cdot \frac{P_i \cdot X_i}{LD_i} \\ r_i = (1 - \alpha_i) \cdot \frac{P_i \cdot X_i}{KD_i} \end{cases}$$

By proceeding to solving the system equations, we easily find the following binding solution:

$$\frac{r_i}{w} = \frac{(1 - \alpha_i) \cdot LD_i}{\alpha_i \cdot KD_i} \tag{3.6}$$

The Eq. 3.6 shows that the ratio of input prices is proportional to the marginal rate of technical substitution between labour and capital. If this was not true, a firm could easily reduce unit costs simply by choosing a different combination of inputs. Therefore, if we substitute the result of Eq. 3.6 in the first Cobb-Douglas equation, we can determine the outputs of labour and capital demanded (in general form, without any suffix):

$$\begin{cases} LD = \frac{X}{A \cdot [\frac{r}{w} \cdot \frac{1-\alpha}{\alpha}]^{(1-\alpha)}} \\ KD = \frac{X}{A \cdot [\frac{w}{r} \cdot \frac{\alpha}{1-\alpha}]^{\alpha}} \end{cases}$$

The relations found hold for both the sectors (i,j).

Household - Consumer function

The study of the household function derives from consumer theory, which elaborately shows the household preferences between the two goods produced by the firms. It is supposed that this relationship is depicted by a utility function. As it was for the production function, even the utility function can be expressed as a Constant Elasticity of Substitution (CES) form but contrary to what we have seen before the ρ does not approach zero in the limit. Therefore, the utility function is:

$$U = [\gamma \cdot X_i^{\rho} + (1 - \gamma) \cdot X_j^{\rho}]^{\frac{1}{\rho}} \tag{3.7}$$

In the previous equation, we have one new parameter. γ is the "distribution parameter" and $\rho = \frac{1}{1-\sigma}$, where σ is the rate at which relative demand change with relative prices change or just the curvature of the utility function ("elasticity of consumption substitution"). The household in question does not have unlimited funds and will operate in its decision process under a budget constraint. Moreover, it will try to choose between each good in a manner that leads to a maximisation of the utility function. Thus, given the following budget constraint:

$$B = P_i \cdot X_i + P_j \cdot X_j \tag{3.8}$$

and knowing that the household will maximise utility up until budget exhaustion, we can impose the problematic as follow:

$$\theta = [\gamma \cdot X_i^{\rho} + (1-\gamma) \cdot X_j^{\rho}]^{\frac{1}{\rho}} + \lambda \cdot (B - P_i \cdot X_i - P_j \cdot X_j) \tag{3.9}$$

Then, the first order condition will lead to the following two equations:

$$\begin{cases} \frac{\partial \theta}{\partial X_i} = \gamma \cdot X_i^{\rho-1} \cdot [\gamma \cdot X_i^{\rho} + (1-\gamma) \cdot X_j^{\rho}]^{\frac{1}{\rho-1}} - \lambda \cdot P_i = 0 \\ \frac{\partial \theta}{\partial X_j} = (1-\gamma) \cdot Y_i^{\rho-1} * [\gamma \cdot X_i^{\rho} + (1-\gamma) \cdot X_j^{\rho}]^{\frac{1}{\rho-1}} - \lambda \cdot P_j = 0 \end{cases}$$

We shall, then, solve in respect of both goods. This will lead to:

$$\begin{cases} \lambda \cdot P_i = \gamma \cdot X_i^{\rho-1} \cdot [\gamma \cdot X_i^{\rho} + (1-\gamma) \cdot Y_i^{\rho}]^{\frac{1}{\rho-1}} \\ \lambda \cdot P_j = (1-\gamma) \cdot X_j^{\rho-1} \cdot [\gamma \cdot X_i^{\rho} + (1-\gamma) \cdot X_j^{\rho}]^{\frac{1}{\rho-1}} \end{cases}$$

By proceeding to solving the system equations, we easily find the following binding solution:

$$\frac{P_i}{P_j} = \frac{\gamma}{(1-\gamma)} \frac{X_j^{\frac{1}{\sigma}}}{X_i^{\frac{1}{\sigma}}} \tag{3.10}$$

Similar to what has been seen with the producer function, the utility relation shows that the rate of substitution between the two goods must equal the ratio of the respective prices. We can now substitute this result in Eq. 3.8 and find the household demand functions[3]:

$$\begin{cases} X_i = \frac{B}{P_i + P_j \cdot [\frac{\gamma \cdot P_j}{(1-\gamma) \cdot P_i}]^{\sigma}} \\ X_j = \frac{B}{P_j + P_i \cdot [\frac{(1-\gamma) \cdot P_i}{\gamma \cdot P_j}]^{\sigma}} \end{cases}$$

It has now come the time to bring together the results and find the equilibrium equations.

---

[3] Known as the Walrasian demand function or uncompensated, which relates to the fact that the income is not adjusted to hold the household on the same indifference curve i.e. utility will change

Assembling - Equilibrium equations

The complete model can now be derived by piecing together the equations we have found previously. In particular, we must satisfy the three conditions mentioned above. The first we are going to deal with is the market clearance. In our case, we have four markets that must be balanced: Labor, Capital, Good $\mathrm{X_i}$ and $\mathrm{X_j}$.

For what concerns labor, we consider that it is mobile across sector and fixed. The clearance condition that must be satisfied is the following:

$$LD = \sum_{i,j}^{N} LD_k = LD_j + LD_i \tag{3.11}$$

and by substituting the respective sector equation found when resolving the production function, we obtain the following first market clearance equation:

$$LD \geq \frac{X_i}{A_i \cdot [\frac{r}{w} \cdot \frac{1-\alpha_i}{\alpha_i}]^{(1-\alpha_i)}} + \frac{X_j}{A_j \cdot [\frac{r}{w} \cdot \frac{1-\alpha_j}{\alpha_j}]^{(1-\alpha_j)}} \tag{3.12}$$

The same procedure can be applied when dealing with the second market clearance equilibrium. Capital is supposed to be fixed in terms of supply and for simplicity of the case we can consider equal rent in both sectors i,j ($\mathrm{r_i}$ = $\mathrm{r_j}$ = r). The clearance condition that must be satisfied is the following:

$$KD = \sum_{i,j}^{N} KD_k = KD_j + KD_i \tag{3.13}$$

and, thus, the second equation will look like this:

$$KD \geq \frac{X_i}{A_i \cdot [\frac{w}{r} \cdot \frac{\alpha_i}{1-\alpha_i}]^{\alpha_i}} + \frac{X_j}{A_j \cdot [\frac{w}{r} \cdot \frac{\alpha_j}{1-\alpha_j}]^{\alpha_j}} \tag{3.14}$$

The next equilibrium equations are the one regarding the market clearance of both sectors (i,j) goods. Here an important remark must be made. When dealing with the equilibrium of the good's market, there is only need to elaborate one equilibrium. This is possible thanks to the Walras Law, which clearly states that if one market is in equilibrium all the other n -1 markets will be in equilibrium as a consequence. Therefore, one of the four equations is redundant and the third one analysed will be as follow:

$$X_j \geq \frac{B}{P_j + P_i \cdot [\frac{\gamma \cdot P_j}{(1-\gamma) \cdot P_i}]^{\sigma}} \tag{3.15}$$

Now that we have sift through the market clearance equilibrium, we can move on to the zero profit conditions. For this condition, only the two sectors (i,j) are required to meet the equilibrium. The development just takes into consideration the profit equation and substitutes for each sector the respective formulas. This will lead to the following zero profit equations:

$$\frac{w}{A_i \cdot [\frac{r(1-\alpha_i)}{w\alpha_i}]^{1-\alpha_i}} + \frac{r}{A_i \cdot [\frac{w\alpha_i}{r(1-\alpha_i)}]^{\alpha_i}} \geq P_i \tag{3.16}$$

$$\frac{w}{A_j \cdot [\frac{r(1-\alpha_j)}{w\alpha_j}]^{1-\alpha_j}} + \frac{r}{A_j \cdot [\frac{w\alpha_j}{r(1-\alpha_j)}]^{\alpha_j}} \geq P_j \tag{3.17}$$

Thanks to Walras Law and to the fact that equations are linear , we can talk about relative level of prices rather than absolute ones, which means that magnitude does not matter, and that we can fix one commodity price to be the numeraire. By fixing the commodity price (i.e. use 1 as a benchmark), all other price changes observed will be relative to the one fixed. Finally, we have arrived to the third of the equilibrium conditions: the budget balance. Here we just need to meet the requirement of budget exhaustion, which means that budget at household disposal must be equal to the factors of endowment used (e.g. capital and labour).

$$B = r \cdot KD + w \cdot LD \tag{3.18}$$

We have now found all the equations needed to run a simulation of a model for this simple two sector and one household scenario. The resulting equations are six in six unknown variables, which are: rent (r), wage (w), $\mathrm{P_j}$, $\mathrm{X_j}$, $\mathrm{X_i}$ and B. The six equations are recounted as follow:

$$\begin{cases} LD \geq \frac{X_i}{A_i \cdot [\frac{r}{w} \cdot \frac{1-\alpha_i}{\alpha_i}]^{(1-\alpha_i)}} + \frac{X_j}{A_j \cdot [\frac{r}{w} \cdot \frac{1-\alpha_j}{\alpha_j}]^{(1-\alpha_j)}} \\ KD \geq \frac{X_i}{A_i \cdot [\frac{w}{r} \cdot \frac{\alpha_i}{1-\alpha_i}]^{\alpha_i}} + \frac{X_j}{A_j \cdot [\frac{w}{r} \cdot \frac{\alpha_j}{1-\alpha_j}]^{\alpha_j}} \\ X_j \geq \frac{B}{P_j + P_i \cdot [\frac{\gamma \cdot P_j}{(1-\gamma) \cdot P_i}]^{\sigma}} \\ \frac{w}{A_i \cdot [\frac{r(1-\alpha_i)}{w\alpha_i}]^{1-\alpha_i}} + \frac{w}{A_i \cdot [\frac{w\alpha_i}{r(1-\alpha_i)}]^{\alpha_i}} \geq P_i \\ \frac{w}{A_j \cdot [\frac{r(1-\alpha_j)}{w\alpha_j}]^{1-\alpha_j}} + \frac{r}{A_j \cdot [\frac{w\alpha_j}{r(1-\alpha_j)}]^{\alpha_j}} \geq P_j \\ B = r \cdot KD + w \cdot LD \end{cases}$$

3.3 The Calliope model for energy scenarios

On the other side of the energy-economy modelling spectrum, we find the bottom-up approach. Contrary to top-down, bottom-up focuses on the energy sector and not the economy as a whole. This sector is made up of demand (industrial, residential, commercial, and transport) and supply (mainly the delivery of energy products). Stemming from this, mitigation scenarios can be developed based on either different energy end uses or new technologies to meet demand or, even, a combination of both. Greenhouse gases can be included at any point in the energy supply chain (e.g, when electricity is produced). In doing so, GHG can be accordingly taken into account during development of a suitable scenario. To build up for an appropriate assessment, it is required to know the technical (e.g, engineering or physical) and financial aspects of the energy system under study. Most commonly, the energy system is assembled based on a reference year for which the energy demand, the specific technologies and the imports-exports flows are known.

The reference year becomes the starting point for the analysis. Future projections can be made on the technologies to be included, the improvement on energy efficiency or gross domestic product growth for the end-uses or, even, the appropriate potentiality for imports and exports. Once each parameter, data and assumption has been duly screened, the integrated analysis can be carried out. This analysis is, generally, implemented through an energy system model (albeit an optimisation one). Serial alternative scenarios can be developed to analyse the impacts of different policies, technologies or mix of end-uses. The outcomes of each scenario should be followed by a detailed assessment on both a qualitative and quantitative plane.

As previously introduced, one of the most common means to conduct the integrated analysis is through energy system models. These are, more than often, linear optimisation models which rely on minimising an objective function. The objective in discussion is the total cost of delivering energy products to meet demand, discounted by an appropriate interest rate. Based on this concept, two aspects are to be underlined: (i) the function is constraint by the physical necessity of meeting supply with demand, and (ii) trade-offs will be inevitably be made on which technology should be used to cover the end-uses. Furthermore, these models incorporate an inter-temporal structure which could either be static (i.e, run on a single designated year) or dynamic (i.e, time paths are part of the parameters). These models permit the inclusion of macro-economic factors. These are found either when making the end-uses demand forecast (e.g, GDP annual growth) or when implementing an additional constraint (e.g, limiting foreign energy imports). Interesting enough, these model allow the inclusion of GHG emissions, which could be adopted as an alternative objective to minimise or given a weight in minimisation problem.

Energy system models come to the aid, as an alternative tool to top-down approach, in analysing environmental policies. This holds especially true when dealing with long-term scenarios involving technology stimulation. What was previously aggregated becomes now highly disaggregated and the focus is shifted from an economy wide view to a more specific, sectorial one. Clearly, the sector in question is the energy one which accounts for the largest share of emissions worldwide. In particular, the main activity of every energy sector is the production, transmission and distribution of electricity. These models are even capable of accounting for some macro-economic aspects. For example, as previously said, GDP growth for forecasting demand or capital/operating costs of each technology. Stemming from this a general taxonomy on energy system models is given (Prina, Mazzolini and others 2020). They can be divided in long-term (i.e., multiple time horizons) and short-term (i.e., the horizon coincide with the simulation year). Long-term models are sub-divided in perfect foresight and myopic. Instead, for both short and long-term models, each can be characterised by (i) energy sectors covered, (ii) geographical coverage, (iii) temporal resolution, (iv) methodology and (v) programming technique. Despite this fine disaggregation, energy system model are still bounded by some major flaws.

First, and foremost, studying a sector in isolation means giving up linkage with the rest of the economy. This entails that any change happening in the rest of the economy won't be accounted for and won't have any repercussion on the system under analysis. Indeed, this is an issue studding each bottom-up energy system model. Secondly, going more in the details, four main challenges have been examined specific for each energy system model (Pfenninger 2014): (i) spatial and temporal resolution, (ii) balancing uncertainty and transparency, (iii) accounting for the increasing energy sector's complexity, and (iv) accounting for behavioural economics. The study conducted by Prina, Mazzolini and others (2014) finds that all of these challenges can be summarised in several resolution issues: temporal, spatial, techno-economic detail and sector coupling. To this, a fifth challenge is added known as transparency. The same study (Prina, Mazzoliini and others 2014) analyses several different models available and finds that the model we adopt in this thesis (i.e, Calliope) performs overall extremely well.

Calliope is an open source energy system model (Pfenninger and Pickering 2018) and it uses, under its hood, the Python-based optimisation modelling language (i.e, Pyomo) (Hart, Laird and others 2012). The core capability is to model and solve structured problems. The main difference form other algebraic modelling languages (e.g, GAMS) is the possibility of modelling objects. The framework is especially built to adopt renewable resource inputs with a high degree of spatial and inter-temporal resolution.

3.3.1 Mathematical development

An overview of the basic calculus behind Calliope and, in general, behind any energy system model is given.

As previously stated, each energy system model works on minimising an objective function:

$$min : y = \sum_{z,t} cost(z, p, c_m) \quad \forall m = 1, ..., n \tag{3.19}$$

In Eq. 3.19, z is the location, p is the technology and c_m is the cost. The cost can either be monetary (e.g. classic costs) or non monetary (e.g. carbon dioxide emissions). Stemming from this equation, the model needs to correctly elaborate how much capacity to install for any given technology, which plant to dispatch to cover demand and at what level of transmission capacity and utilisation. Furthermore, it is worth to note that capacities could be fixed and storage could also be included in the picture. Therefore, we shall introduce the main constraint the function is subject to:

$$\sum_{l,p \in Z_i} en_{prod}(k, z, p, t) + \sum_{l,p \in Z_i} en_{con}(k, z, p, t) = 0 \quad \forall i, t \tag{3.20}$$

The Eq. 3.20 is the balance of energy supply and demand. k is the carrier (e.g., gas, petrol or electricity), t are the timesteps and Z_i are the zone of any given set of locations (z). en_{prod} is the energy produced by a model element and en_{con} is energy consumed by any given model element capable of doing so. Transmission links can consume in one zone and produce in another (with or without losses).

The costs minimised for each technology (p) for which they have been defined is a combination of both the capital ($cost_{capex}$) and operational ($cost_{opex}$) costs.

$$cost(z, p, c_m) = cost_{capex}(z, p, c_m) + cost_{opex}(z, p, c_m) \tag{3.21}$$

The $cost_{opex}$ can be further disaggregated in its fixed ($cost_{opex,f}$), variable ($cost_{opex,v}$ and fuel ($cost_{opex,fuel}$) cost as shown in Eq. 3.22. $cost_{opex,f}$ is only dependent on the capacity installed, $cost_{opex,v}$ varies with the amount of energy supplied and $cost_{opex,fuel}$ floats based on the fuel needed to supply that amount of energy in output.

$$cost_{opex}(z,p,c_m) = cost_{opex,f}(z,p,c_m) + cost_{opex,v}(z,p,c_m) + cost_{opex,fuel}(z,p,c_m) \tag{3.22}$$

If one where to include carbon dioxide emission for specific technology (p), the $cost_{opex,v}$ is used. In this case, an appropriate emission intensity parameter for the relative technology has to be included in input. It is worth nothing that carbon dioxide emission are not discounted (i.e. no interest rate is applied). Finally, the model always calculates the levelized cost of energy (LCOE) in any running instance.

$$LCOE = \frac{\sum_{z,p} cost(z,p,c_m)}{\sum_{z,p} en_{prod}(k,z,p,t)} \tag{3.23}$$

The LCOE can be a relevant metric when trying to asses the cost (in present value terms) of producing a single unit of energy output from any given technology (p). Eq. 3.23 formulates the theoretical concept lying behind.

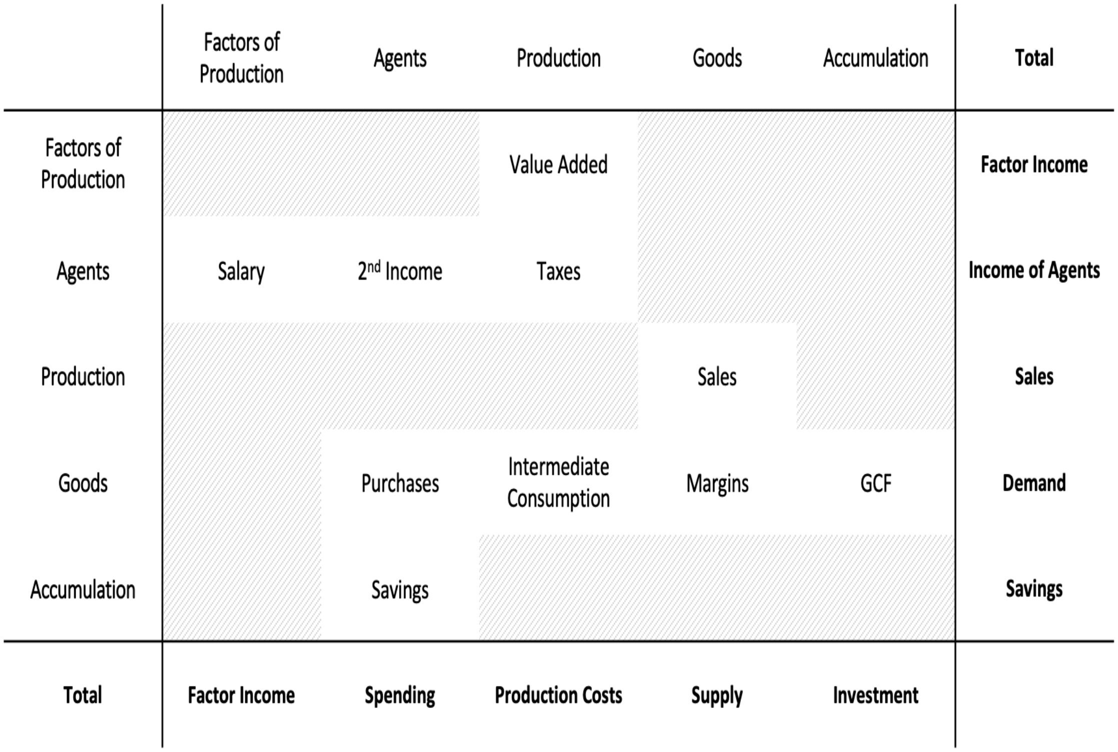
Chapter 4

Results

4.1 Analysis of a carbon tax regime in Italy's economy

Calibration through SAM

The Social Accounting Matrix is a snapshot of the economy-wide transactions of a country usually for a reference period of a year. It is nothing more than the balance of their circular flow, accounting for income and spending. This view can be better eloped as a double-entry book keeping like Input-Output (I/O) table. A SAM takes into consideration the transactions that happen between agents of a country's economy. Each agent will have both a row account and a column account. The sum of the row account will reveal the total income levied and the sum of the column account will reveal the total spending. Therefore, a SAM will result to be a squared matrix and it will be deemed balanced once total spending is equal to total income for each agent across the table.



	Factors of Production	Agents	Production	Goods	Accumulation	**Total**
Factors of Production			Value Added			**Factor Income**
Agents	Salary	2nd Income	Taxes			**Income of Agents**
Production				Sales		**Sales**
Goods		Purchases	Intermediate Consumption	Margins	GCF	**Demand**
Accumulation		Savings				**Savings**
Total	**Factor Income**	**Spending**	**Production Costs**	**Supply**	**Investment**	

Figure 4.1: Basic Structure of a Social Accounting Matrix

For the specific case analysed, a simplified version of a Social Accounting Matrix (SAM) is used to calibrate our basic model. Based on data extracted from the Italian National Institute of Statistics (ISTAT), the Table.4.3[1] shows a simplified structure, where X_j is the aggregate of energy intensive industries and X_i is the rest of the economy.

	X_i	X_j
Capital	700.072	183.562
Labour	520.984	199.117
Total	1221.056	382.679

Table 4.1: Simplified SAM of Italy. All values are in billions of €2019
Source: ISTAT, 2019

Gross Domestic Product (GDP) is the sum of the total final demands (T) or total production costs. However, in this peculiar case, only the value added cost incurred by the factor of productions is considered. For simplicity, the taxes and intermediate consumption has not

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[1] Under the concept of Energy Intensive industries fall the following activities: extraction, manufacturing, distribution of electricity, gas, vapour and air conditioning, water distribution, waste management and construction. All the other activities fall inside the rest of the economy, as do not account a high share of energy intensity.

been considered. From the Table.4.3, one shall see in column T that the household consumed €1221.056 billions from good $\mathrm{X_i}$ while it consumed €382.679 billions from good $\mathrm{X_j}$. The third row shows the consumption of capital for each respective good while the last row shows the consumption of labour for each good. The SAM analysed here clearly confirms the accounting principle aforementioned and meets the requirements of the three equilibrium conditions.

The values found in the SAM are prices per unit multiplied by quantities. Since calibrating the model involves dealing with quantities, one can arbitrarily choose the value for the prices per unit and put them equal to one (1) because it makes no difference to our simple model. This means that the entries of the SAM are exactly equal to the demanded units (i.e. the consumer used up 382.679 units of good $\mathrm{X_j}$ at a 1 €/unit). It is now possible to solve our preceding equations to found the parameters unknown. Parameter α_i can be found from the profit maximisation Eq. 3.6:

$$1 = \frac{(1-\alpha_i)\cdot 520.984}{\alpha_i \cdot 700.072} \tag{4.1}$$

Therefore, $\alpha_i = 0.4267$. This value can be substituted in Eq. 3.3 and find $A_i = 1.9785$. In a similar manner, we can do the same for good $\mathrm{X_j}$ and find out $\alpha_j = 0.5203$ and $A_j = 1.9983$. For the other parameters, an elasticity of substitution for the household must be defined. Seeing that in literature the most used value is $\sigma = 0.5$, that is the one chosen. Then, $\rho = -1$ and $\gamma = 0.9106$ by substituting in Eq. 3.10. Finally, LD and KD will just be equal respectively to the sum of its row values in Table 4.3.

Solution of CGE

Even though an analytical solution can be derived from a simple model such as this, for more complex ones a numerical solution is deemed necessary. In the case under analysis, the first step of finding the parameters value when deriving a numerical solution has already been given. The second step deals with deciding the excess demand for each market. There are four markets (KD, LD, $\mathrm{X_i}$ and $\mathrm{X_i}$) and for each of these markets excess demand is given by demand minus supply. Following an example equation for $\mathrm{X_j}$:

$$\delta_{Xj} = \frac{B}{P_j + P_i \cdot [\frac{0.9106 \cdot P_j}{0.0894 \cdot P_i}]^{0.5}} - X_j \tag{4.2}$$

Furthermore, there are two firms for which one can define the excess profit function. These equations are defined as the surplus of unit revenues over unit costs. Following an example equation for $\mathrm{X_i}$:

$$\delta_{Pi} = P_i - \frac{w}{1.9785 \cdot [\frac{r(0.5733)}{w \cdot 0.4267}]^{0.5733}} - \frac{r}{1.9785 \cdot [\frac{w \cdot 0.4267}{r(0.5733)}]^{0.4267}} \tag{4.3}$$

Finally, the excess consumer income equation must be defined. This one simply develops as follows:

$$\delta_B = 883.6340 \cdot r + 720.1010 \cdot w - B \tag{4.4}$$

For each of these excess functions, it stands clear that they must be equal to zero when in equilibrium. Therefore, the numerical solution of the CGE model elaborated up until now implies a joint minimization of Eq. 4.2, Eq. 4.3 and Eq. 4.4.

For such matter, a numerical solution has been developed through MATLAB. The system of equations under scrutiny are non-linear and manifest a complementarity between prices and excess demands (i.e. excess demands can be negative for zero prices, but need to be zero for positive prices). Therefore, the appropriate solver for these system of equations is one which deals with non-linear complementarity problems (NCP). In general, NCP adopts the Newton algorithm optimization. This method involves a two-step procedure. Firstly, an arbitrary starting solution is chosen (i.e. $\mathrm{x_0}$). Then, the algorithm is set in motion by evaluating the function (i.e. $\mathrm{f_i}$). If the evaluation does not yield zero, a new solution is calculated by incrementing the precedent starting solution by a term equal to the ratio between the recent evaluated function over its derivative (see Eq. 4.5).

$$x_{i+1} = x_i + \frac{f_i}{f_i'} \tag{4.5}$$

This procedure is cycled until a convergence criteria is met, where i expresses the number of iterations made. This formula holds for single-variable equations and is the founding basis for multivariate problems. While a similar calculus applies, in a multivariate problem the partial derivatives are taken in respect of each variable. This leads to the definition of the Jacobian, which is the matrix accounting for all the partial derivatives. Denoting for our case the solution vector as $z = [p_j, w, r, X_j, X_i, B]$, then the respective Jacobian will be:

$$J = \frac{\partial \delta(z)}{\partial z} = \begin{bmatrix} \frac{\partial f(p_j)}{\partial p_j} & \frac{\partial f(p_w)}{\partial p_j} & .. \\ \frac{\partial f(p_j)}{\partial w} & \frac{\partial f(w)}{\partial w} & ... \\ ... & ... & ... \\ \frac{\partial f(p_j)}{\partial M} & ... & ... \end{bmatrix} \tag{4.6}$$

The newly defined Jacobian is used in a similar Newton algorithm's fashion to derive the new solution:

$$z_{i+1} = z_i + J^{-1} \cdot \delta(z_i) \tag{4.7}$$

As seen before, this procedure will iterate until an appropriate convergence criteria is met (i.e. the error between any two of the iterative solutions falls below a certain threshold).

Analysis of a carbon tax implementation

To illustrate the adoption of CGE in energy policies, the model developed until now can be applied to solve a simple policy dilemma. The policy implemented will be a tax on carbon and it will be imposed only on the energy intensive goods ($\mathrm{X_j}$). To account for this introduction, the equations previously elaborated must be modified. In particular, the addition of a tax falls on the price the consumer will pay for the energy intense product (i.e. the price increases by $\tau \cdot \mathrm{P_j}$). Furthermore, it is assumed that the government will give back the revenues raised in a lump sump to the consumer (i.e. the budget formula increases by $\tau \cdot \mathrm{P_j} \cdot \mathrm{X_j}$). The equations are manipulated and become as following:

$$\begin{cases}
720.1010 \geq \frac{X_i}{1.9785 \cdot [\frac{r}{w} \cdot \frac{0.5733}{0.4267}]^{(0.5733)}} + \frac{X_j}{1.9983 \cdot [\frac{r}{w} \cdot \frac{0.4797}{0.5203}]^{(0.4797)}} \\
883.6340 \geq \frac{X_i}{1.9785 \cdot [\frac{w}{r} \cdot \frac{0.4267}{0.5733}]^{0.4267}} + \frac{X_j}{1.9983 \cdot [\frac{w}{r} \cdot \frac{0.5203}{0.4797}]^{0.5203}} \\
X_j \geq \frac{B}{P_j \cdot (1+\tau_j) + P_i \cdot [\frac{0.9106 \cdot P_j (1+\tau_j)}{(0.0894) \cdot P_i}]^{0.5}} \\
\frac{w}{1.9785 \cdot [\frac{r(0.5733)}{w0.4267}]^{0.5733}} + \frac{r}{1.9785 \cdot [\frac{w0.4267}{r(0.5733)}]^{0.4267}} \geq P_i \\
\frac{w}{1.9983 \cdot [\frac{r(0.4797)}{w0.5203}]^{0.4797}} + \frac{r}{1.9983 \cdot [\frac{w0.5203}{r(0.4797)}]^{0.5203}} \geq P_j \\
B = r \cdot 883.6340 + w \cdot 720.010 + \tau_j P_j X_j
\end{cases}$$

These equations have been coded in MATLAB and five scenarios have been studied. Starting from the equilibrium point, where there is no tax imposed, an incremental tax rate of step 10% has been applied on the consumption of the energy intensive good (i.e. $\mathrm{X_j}$) up to the final value of 50%. The results from this five scenarios have been reported in Table. 4.3

Tax Rate [%]	X_i	X_j	$\frac{w}{r}$	B
0	1221.1	382.7	1	1603.7
10	1234.9	368.8	1.003	1641.1
20	1247.9	355.9	1.006	1677.7
30	1258.4	345.3	1.009	1708.7
40	1268.4	335.3	1.010	1739.7
50	1277.1	326.6	1.013	1767.7

Table 4.2: Carbon tax scenarios studied

From this results, some interesting insights can be deducted. As one could have expected, consumption of the energy intensive good is reduced and compensated, due to the general equilibrium principle, by the consumption of the product coming from the other industry. With the highest tax rate, the fall in demand amounts to 14% and, despite this, relative prices still remain rather low. However, what strikes the most from this analysis is the wedge the tax drives between labour and capital. Fig. 4.2 shows how the return on capital is the worst off between the production inputs. Indeed, the higher burden of taxation is mostly absorbed by the capital employed in the energy intensive industry. This leads to the conclusion that workers in that sector will be better off than the owner of capital as a result of the tax imposition.

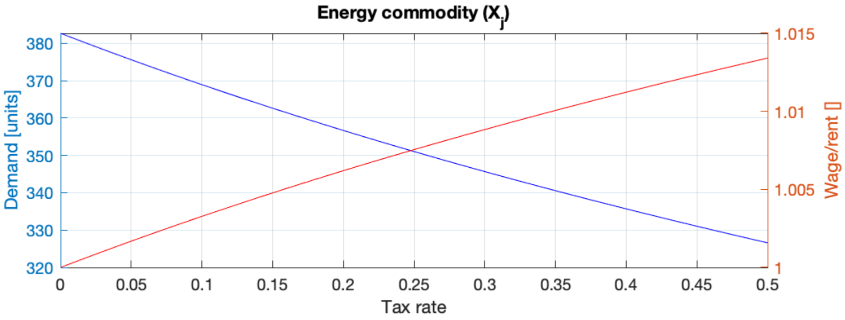

Figure 4.2: Evolution of the energy intensive's demand (Left Axis) and the wage/rent ratio (Right Axis) as the tax rate increase

4.2 Study of the Italian energy system for carbon neutrality

Baseline scenario

The model has been constructed from data referring mainly to the year 2020 and elaborated through the Calliope framework. Some data from 2019 has been used when data was not available and adapted to the year under analysis (e.g. the plant capacities for most technologies). The time series data for wind and solar generation are from the year 2019 and will not change despite the scenario analysed (i.e. not accounting for the possibility of different solar or wind generation profiles). The demand curve is referred to the year 2020 for the baseline scenario while two new demand curves have been developed for the year 2050. An overlook of the data will follow suite, with values summarised in Table 4.3.:

- **Renewable resource**
  - *Wind and solar* → Based off the hourly observations from the NASA MERRA reanalysis (Rienecker 2011) and NUTS2 subdivision of Italy's territory. Wind power plants simulation is obtained through the Virtual Wind Farm model (Staffell and Green 2014). Both utility and rooftop solar plants are elaborated through the BLR model (Ridley 2010) and estimated with the performance model (Huld 2010).
  - *Hydro* → The 2020 installed capacity is based off Terna's data of power plants in 2019 and a five year historical growth trend of 0.75% YoY. Hydro capacity has been divided based on technology (e.g, run-of-river) and allocated only to the six bidding zones. The capacity factor has been estimated based off Terna's supply and demand time series data.
  - *Biological & Geothermal* → In this category fall the power plants adopting the following technology: waste, biomass wood, biogas and bio-fuels. All data has been taken from the 2019 numbers given by Terna and adjusted through a 5 year CAGR of 0.3%. Geothermal is not included because, as of 2020, it has an installed a capacity of less than 1 GW, which does not even account for 1% of total available capacity in Italy. Moreover, Unione Geotermica Italiana (2018) has set a maximum theoretical expansion potential to approximately 2.5 GW by 2050. This makes geothermal not particularly relevant in the quest of decarbonization.
- **Conventional resource**

  The gas, oil and coal installed capacity has been elaborated starting from Terna's 2019 data available and the last five year trend decline of -3%.
- **Italy zone subdivision and connection**

  The Italian territory has been divided in its 21 Regions of which six also cover the bidding zone role: Nord (Lombardia), Centro Nord (Toscana), Centro Sud (Lazio), Sud

(Puglia), Sicilia and Sardinia. The bidding zone is where energy supply and demand is met from a market point of view and consequently dispatched. The transmission lines that connect each bidding zone are the HV overhead cables (Inter-zone), which have a maximum capacity (based off Terna's data) and a given transmission cost. The transmission lines that stem inside a macro-region (e.g, Nord) have been assumed of infinite maximum capacity and free cost. Furthermore, the HVDC cable connecting the Centro Sud with Sardinia (i.e, the SAIPEI) and the one connecting Centro Nord with Sardinia has been modelled based off its technological data. The only cross border connections modelled are the ones with France and Switzerland as they represent 90% of the imported share of electricity. Export is not modelled as it accounts for less than 3% of the final electricity demand. A representation is showed in Fig. 4.3.

Region	Thermal [GW]	PV Roof [GW]	PV Utility [GW]	Wind On S. [GW]	Hydro [GW]	Bio [GW]
Nord (Lombardia)	28	0.5	1.9	-	16.6	0.9
R1 (Piemonte)	-	0.2	1.4	-	-	0.4
R2 (Valle d'Aosta)	-	-	-	-	-	-
R3 (Veneto)	-	0.5	1.5	-	-	0.4
R4 (Trentino Alto-Adige)	-	0.2	0.3	-	-	-
R5 (Friuli Venezia Giulia)	-	-	0.4	-	-	0.1
R6 (Liguria)	-	-	0.1	-	-	-
R7 (Emilia Romagna)	-	0.3	1.8	0.1	-	0.6
Centro Nord (Toscana)	4	0.2	0.7	-	1.1	0.2
R8 (Umbria)	-	0.1	0.4	-	-	-
R9 (Marche)	-	0.1	1.0	-	-	-
Centro Sud (Lazio)	9	0.2	1.2	-	2.8	0.2
R10 (Abruzzo)	-	0.1	0.7	0.3	-	-
R11 (Campania)	-	0.2	0.7	1.8	-	0.2
Sud (Puglia)	12	0.2	2.7	2.7	0.9	0.4
R12 (Molise)	-	-	0.2	0.4	-	-
R13 (Basilicata)	-	-	0.3	1.4	-	-
R14 (Calabria)	-	0.1	0.4	1.2	-	0.2
Sicily (Sicilia)	5	0.3	1.2	1.9	0.7	-
Sardinia (Sardegna)	2	0.2	0.7	1.1	0.4	0.1

Table 4.3: Baseline scenario plant installed capacity. Capacity under 0.1 GW has been represented with "-". Thermal includes CCGT, Gas, Oil and Coal; Hydro includes Run of the River, Basin and Reservoir. These technologies have been aggregated for macro-region.

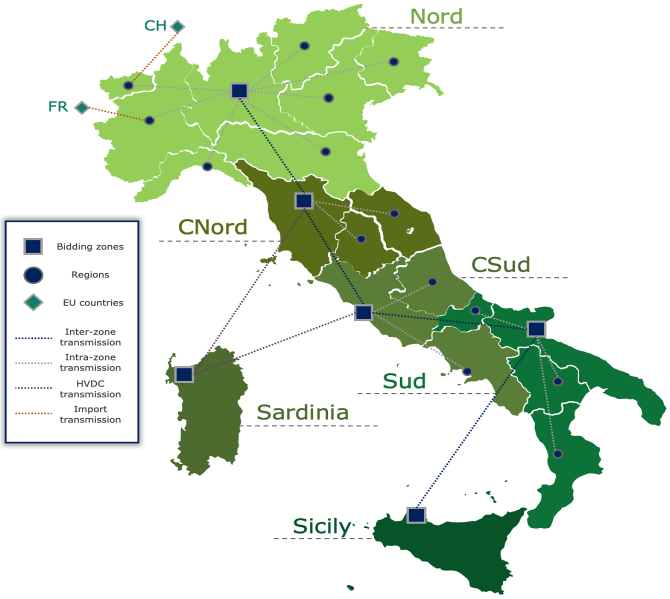

Figure 4.3: Representation of the Italian territory subdivision by 21 regions and relative connections

Forecasted scenarios

Once the model has been populated and the electricity system built, it can be used to evaluate different scenarios. Therefore, we shall now have a look on the two scenarios implemented which come from a forecast of demand made through an open source model of energy profiles (DESSTINEE, Staffell and Green 2015) based off IEA's future development scenarios (i.e, 2DS and 4DS). In both scenarios, no conventional resource is kept and the new electricity system is elaborated cost optimally. For such matter, electricity curtailment[2] has been considered when running the model. Furthermore, we included the same carbon regimes seen before, thus emulating a carbon price.

- **IEA's scenarios**
    - The 2°C Scenario (2DS) → 80% chance of limiting the increase of global average temperature by 2°C. Target of reducing emissions by more than half (compared to 2009). Transformation of the energy system is pivotal. This scenario is quite similar to the WEO 450 Scenario after the year 2035.
    - The 4°C Scenario (4DS) → Limiting the increase of global average temperature to 4°C with significant improvements in energy efficiency. Quite similar to the WEO New Policies Scenario after the year 2035.

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[2] Is a reduction in power output below what could have been produced. More than often, accumulation of energy surplus is more costly than letting it go unutilised.

- **New renewable sources**

  The only new technologies we take into account for the future electricity system are: PV (in both rooftop and utility scale), Wind (in both on-shore and off-shore scale) and Storage (only battery technology). The maximum technical-social potential capacity expansion for each region has been taken from the appropriate elaborated datasets (Trondle and Pfenninger 2019). For the renewable technologies already present, no scope for capacity increase is considered (i.e. hydro and biological). This is due to the fact that no significant expansions is expected, either because of insufficient land available for hydropower (World Energy Council, 2007) or benefits for biomass and etc. (European Environment Agency, 2006). Other technologies (e.g. CCGT with CCS, Pumped hydro storage, CCGT with hydrogen, etc.) have not been considered due to the uncertainty and unreliability of further technological and economical development.

- **Import**

  A sensitivity analysis on the electricity imported from cross-border connections has been carried out. In one case it has been kept to 2020 levels and on the other hand it has been completely removed from the system.

In Table 4.4 we show the assumptions used for the financial parameters relative to the technologies adopted and in Table 4.5 we summarise the results relative to the electricity system future scenarios analysed, compared with a reference one that is the output of the model on the basis of the 2020 demand and the cost optimality scope.

Technology	Capex [€/kW]	Fixed Opex [€/kW]	Variable Opex [€/kWh]	Storage Cost [€/kWh]	Lifetime [Years]
PV Roof	1000	10	-	-	26
PV Utility	600	7	-	-	30
Wind On S.	1750	13	-	-	25
Wind Off S.	2000	7.5	-	-	25
Batteries	100	10	-	400	10

Table 4.4: Summary of new technologies costs.
Sources: RSE, Energy Gov

Scenario (*energy demand*)	Old [GW]	PV Roof [GW]	PV Utility [GW]	Wind On S. [GW]	Wind Off S. [GW]	Batteries [TWh]	CAPEX p.a. [€ bln]	CO_2 [Mt]
Reference (303 TWh)								
With import	87	4	18	11	-	-	-	70
IEA 2DS (482 TWh)								
With import	27	397	61	67	20	5	13	4
Without import	27	414	61	74	27	12	30	5
IEA 4DS (442 TWh)								
With import	27	407	61	70	21	2	8	4
Without import	27	394	61	64	19	8	20	5

Table 4.5: Summary of scenarios main results (Old includes Thermal, Hydro and Bio)

- IEA 2DS → Running a first scenario with 2020 import levels has shown that significant investments must be made in photovoltaic technology. Especially for photovoltaic rooftop which sees the biggest share of new capacity installed. Offshore is largely not developed with only 43% of the potential total installed capacity by 2050. Onshore peeks at 82% of the potential. The other pivotal investment is storage. Batteries play a crucial role in moving to this fully green scenario where emissions drop by 95% in respect to 2020 levels. They also represent the huge chunk of the costs needed to make the transition in the next 30 years. When import is taken out of the electricity system (i.e. being fully independent) costs rise significantly due to the increased storage cost of batteries which more than double. In both instances all the lines have a low load factor except for the HV linking Centro Nord with Nord.
- IEA 4DS → Even here, running a first scenario with 2020 import levels has shown that significant investments must be made in photovoltaic technology. However, fewer ones are required. PV utility always gets developed to its fullest which further underlines the importance of installing photovoltaic resources. Wind offshore is more developed with 46% of the potential installed and the same goes for the onshore. Batteries are mostly present in the Nord macro region with almost none installation in the meridional and insular regions. This situation slightly changes when imported electricity is taken out. Despite this, it strikes to see wind installations go down rather than up. This is mainly attributable to the substantial difference in final demand electrification in respect to the IEA 2DS scenario.

Here, the most important results to underline are the following. Photovoltaic technology is a must have especially at a utility scale, with new capacity between rooftop and utility never going down 14 GW p.a.. Batteries become indispensable during the night and its cost could even battle with wind generation when demand does not reach the high levels of electrification given by the IEA 2DS case. If import levels are kept at 2020 levels, the electricity system becomes decentralized with the high voltage lines having generally low load factor. The situation slightly changes when no import is allowed especially for the line connecting Centro Nord with the Nord. Indeed, the IEA 4DS sees a less aggressive electrification of vehicles (e.g. road) and efficiency in all sectors (e.g. residential). Furthermore, as said above, the import sensitivity has been included to see how costs significantly change when imports are taken out from the equation, with total system costs generally becoming more than double. Overall, system transitioning cost based on the scenario greatly varies going from as low of €8 bln (IEA 4DS - With imports) to as high of €30 bln (IEA 2DS - Without imports) per annum.

Further sensitivity has been conducted on curtailment and across two years, 1989 and 2016. These two years have been respectively classified as the worst weather year and the average reference year for Italy (Lombardi and Pfenninger 2020). Taking out curtailment has shown that more storage capacity and power is needed. In particular, storage power could go up to 10 times more than with the possibility to curtail electricity. Building of renewable power plants goes down across all technologies but overall cost of the system goes up due to batteries cost almost doubling. On the other hand, changing the weather year (for photovoltaic and wind) has shown that having more wind farms installed, especially offshore, could potentially cut the need to install batteries up to half. Potential reductions in installed solar power plants can be appreciated, especially in the reference average year. However, photovoltaic investments still remain substantial not going below 10 GW p.a (roof and utility combined). Accounting for all sensitivity scenarios ran, we find that transitioning cost could go as low as €6 bln (IEA 4DS - With imports and curtailment - 2016) to up to €30 bln (IEA 2DS - Without imports but with curtailment - 2019) per annum.

Chapter 5

Conclusions

An international effort is ongoing with the aim of decreasing global warming through lowering the greenhouse gas emissions due to human activities. One of the likely culprit has been identified in the technologies that countries all over the world adopt to meet their nations electricity final demands. The need to change the core of how electricity is generated has spurred significant political actions in terms of energy policies implemented. We have seen that Europe and more specifically Italy has adopted a mix of reactive policies (i.e. ETS trading) and active policies (i.e. subsidies to foster the deployment of greener technologies) to reach its goal. In particular, Italy seeks to obtain its 95% ÷ 100% through a mix of wind, solar and batteries in order to reach net neutrality of carbon dioxide emissions by 2050.

Then, we have extensively discussed on the aforementioned energy policies that are implemented to counteract climate change worldwide. Here, we have appreciated how no superior reactive policy really exists but it all boils down to how the policy is designed and that inevitably subsidies (especially feed-in-tariffs) have been the most successful in fostering green technology deployment. Therefore, to analyze what this means for Italy, we have recurred to two different energy models to analyse the path to Italy decarbonisation by 2050.

Firstly, through the adoption of a CGE, we have shown that the impact of a carbon tax (i.e, an emission trading scheme with auctioning) is not sufficient to lower demand. Even with a 50% tax regime, demand will fall by 14% and the only result will be making a rather capital intensive industry even more costly. It strikes decisive that having a carbon pricing scheme becomes irrelevant to reducing greenhouse gas emissions in the long term. However, this shall not undermine the importance of having one in place right now, which could potential become the revenue source to fund the real investments needed to transition.

This has lead to analysing what is really needed to fully reach the goals that Italy has set out for in the Integrated Plan for Energy and Climate through a bottom-up energy model (i.e. the Calliope framework). Here, we have shown that moving to a fully decarbonised electricity system means moving towards a decentralised one where the combination of photovoltaic modules on the rooftop and batteries is the only way to go. Curtailing or not electricity significantly influences overall transitioning cost. The need to have more battery power drives up costs, almost doubling, when electricity cannot be left unutilised. Moreover, the reduced need of renewable technologies capacity does not compensate for the increased rated power of batteries. A recent study done from the Solar Energy Technologies Department (2018) came to a similar conclusion where building overcapacity could potentially be better than installing grid storage. Furthermore, cost number go further up when import levels of electricity are brought down to zero from 2020 levels. The need to have more stored energy available causes batteries cost to double in the best case analysed. Introducing a sensibility on different weather years has shown that when more wind farms are installed less batteries are needed and less solar panels are needed when the year was particularly sunny. However, this result does not stand to be statistically significant. Overall, approximately €18 bln should be invested each year to obtain such goals by 2050.

Finally, further studies could be conducted on the curtailment and import scenarios. This two variables have shown to hold quite the weight when deciding which steps to take for a greener future. Europe is investing extensively on building new infrastructures to create new cross border connections (TEN-E 2019) and understanding the optimal balance between future imports and internal production could pave a more cost efficient path. Parallel to this, more research could be carried on the role curtailment holds in the future electricity system. However, the most crucial point to stress research on is the demand. This number tends to go further up the more electrification of final demand is requested and significant efforts should be done from a demand side to keep it under control.

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