Politecnico di Torino

Master Degree in Engineering and Management

Climate risk and real estate: influence of weather-releated events on real estate and market response

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SUMMARY

FIGURES

ABSTRACT

Nowadays Climate Finance has become a disputed topic, since climate change started to affect our everyday lives. Natural catastrophes have produced several negative consequences to the development of humankind in developing countries, with the result of displacement, migrations and the need to search for valid alternatives in order to restrain the economic and social effects.

Investors have also become more aware of the large impact Climate Change can have on financial markets. Particularly, they started to acknowledge the causal link between the occurrence of catastrophic events and the change in the perceived value of assets, therefore resorting to financial instruments to cover themselves from risks deriving from climate change.

Climate Finance was first introduced in the 1970's by Nordhaus, whose innovative research and work paved the way for thinking about the interaction of the physical process of climate change with the real economy.

Climate Change is an empirical phenomenon, whose knowledge is often incomplete and based on past observations and future projections. There is, however, a relation between GHG (greenhouse gasses) emissions and the rise of global temperatures, but most of the effects will be on the long term since the rise of temperatures is an irreversible phenomenon, leading experts to take into account the evolution of the system. According to Nordhaus in fact, Climate Change is the result of economic anthropogenic activities (Nordhaus 1993). That implies choosing economic policies which would balance a stable growth with wealth creation and climate sustainability. An important issue regards the first best option Governments may decide to adopt is that of taxing CO2 emissions in a way to reduce them. This would cause a significant slowdown in production and overall growth, and as a matter of fact, those most affected by this policy such as developing countries would not internalize the benefits. Along with higher growth rates, developing countries record higher CO2 emissions and because fossil fuels still represent the cheapest and most reliable energy sources and resorting to alternatives is still not economically feasible, they would have far fewer incentives.

A second-best option entails a comprehensive approach which considers

mitigation, adaptation and monitoring, as well as technological innovation to reduce CO2 emissions, in a way to redistribute resources.

Financial markets indeed play a crucial role by aggregating information to elaborate a response, by sharing and diversifying the risks and by mitigating climate changes through the transfer of resources to a more sustainable production. This paper aims at analyzing the existing literature to explore the causal link between financial markets and the risk deriving from climate change, with a particular focus on both commercial and residential real estate market, despite results for residential real estate being consistent for commercial real estate as well. The inspiration for this thesis stems from a lecture held by Stefano Giglio, young winner of the 2020 Carlo Alberto Medal to be awarded to a young Italian economist under the age of 40 for his/her outstanding research contributions to the field of Economics.

The thesis is structured in the following way: the first chapter introduces climate change from an economic perspective and reports all major historical milestones in addressing this negative externality. It concludes with a hint to carbon neutrality and the negative emissions technologies to achieve. The second Chapter is dedicated to the link between American real estate market as well a brief overview of the most impacting climate change hazards. It explores the existing literature illustrating the statistical relationship between house prices and catastrophe occurrence and it provides a deep understanding of the significance of the results. This chapter briefly mentions why the Italian real estate market is not suitable for such analysis, despite the lack of significant literature thereupon. Four types of hazards are included, namely floods, hurricanes, sea level rise threat and wildfires. Third Chapter is dedicated to the unwinding of market factors affecting house market values which sometimes cause a decrease in significance of previous findings. Moreover, it sheds light on how investors should discount climate change mitigation efforts based on real estate term structure[1] of discount rates for risky

[1] The term structure of interest rates, commonly known as the yield curve, depicts the interest rates of similar quality bonds at different maturities.

assets, i.e., housing and how this is correlated to consumption. Conclusions point to a hedonic cost of climate risk which is borne by real estate market players.

CHAPTER 1

Climate Finance and Climate Change from an economic perspective

1.1 Climate Finance: an overview

In order to fully comprehend the phenomena behind the markets for green bonds and several other climate change- related financial instruments, it is essential to capture the concept of Climate Finance and where do we currently stand in history.

According to the definition provided by The UN Framework Convention on Climate Change (UNFCCC), adopted and opened for signatures in 1992 in Rio de Janeiro, Brazil, Climate Finance refers to "local, national or transnational financing—drawn from public, private and alternative sources of financing—that seeks to support mitigation and adaptation actions that will address climate change"[2].

During the the 1992 Rio Earth Summit, a fundamental principle was established; that of "common but differentiated responsibility and respective capabilities", which entails developed countries must commit in order to help developing countries reduce their greenhouse gasses emissions through mainly financial resources and instruments[3].

This academic definition encompasses two salient aspects, those of mitigation and adaptation respectively.

Mitigation refers to the reduction of the flow of heat trapping greenhouse gases into the atmosphere.

[2] https://unfccc.int/topics/introduction-to-climate-finance

[3] https://unfccc.int/kyoto_protocol

This can be achieved either by reducing source of these gasses (for example, the burning of fossil fuels for electricity, heat, or transport) or enhancing the so-called "sinks" of these gasses (such as the oceans, forests, and soil).
Adaptation involves adjusting to actual or expected future climate. The goal is to reduce our risks from the harmful effects of climate change[4].
It also includes making the most of any potential beneficial opportunities associated with climate change (for example, longer growing seasons or increased yields in some regions).

1.2 Economic perspective: carbon tax and cap and trade

As mentioned in the introduction, William Nordhaus has been one major contributor to research and findings in the field of Climate Economics. He investigated climate change from an economic perspective, i.e. that of inducing an externality, as well as the reasons behind human failure to cope with it. Climate change urges scientific research and policymakers to search for sustainable alternatives in a way to abate GHG emissions. It thus contributes to the production of valuable knowledge as a positive spillover. Pollution and environmental matters make up the negative externality[5] instead, whose cost or is not captured by market prices.
Nordhaus (1977) debates that "climate change mitigation (CCM) is a global public good"[6]. This is due to the fact that if one specific country undertakes mitigation efforts to reduce its GHG emissions, it cannot "exclude" another one from reaping the benefits of its efforts, regardless of whether the latter reciprocates with a similar policy. However, the costs are borne solely by the country implementing

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[4] https://energiaclima2030.mise.gov.it/index.php/il-piano/obiettivi

[5] An externality is a cost or benefit caused by a producer that is not financially incurred or received by that producer [https://www.investopedia.com/terms/e/externality.asp]

[6] Public goods are, by academic definition, non-rival - that is- the cost of extending the output to an additional individual is virtually zero- and non-excludable, it is impossible to exclude others from enjoying them [https://www.investopedia.com/terms/p/public-good.asp]

the green policy. Furthermore, the "non-excludable" nature of climate change mitigation produces a free-rider problem, in which a country gains the benefits of lower GHG emissions without bearing any of the costs. A country that implements a green policy bears the full cost - either in the form of adopting low-carbon technologies or other short-term transition costs for shifting to cleaner energy - but garners fewer benefits, since the benefits of climate change mitigation spill over national borders due to the global nature of the atmosphere.

Climate Change is a global negative externality, or “public bad” due to GHG emissions as its impact spreads around the World. Due to their resistance to market and national government control, global externalities differ from local or national public goods since they require strong Governance and effective management as part of a common collective global effort.

“However, under current international law, there is no legal mechanism by which disinterested majorities of countries can require other nations to share in the responsibility for managing global externalities”[7] (Nordhaus 2018). This spillover effect is called free riding problem and it motivates countries to undertake national objectives, rather than global ones, whose benefits eventually do not extend beyond the country’s borders.

From a theoretical point of view, the solution to externality problems has been known to economists since Pigou's (1920) contribution: the efficient public policy is to increase the cost of all greenhouse gas emissions (e.g. by imposing a tax on emissions) so that it reflects the social costs. This approach, known generically as carbon pricing (literally "putting a price on carbon dioxide"), can be deployed in various ways, including the imposition of a tax on emissions (carbon tax) or the imposition of a cap on emissions, with an associated market to buy or sell permits to emit (cap and trade). The only way for states to guarantee effective climate-

[7] Prize Lecture, December 8, 2018 by William D. Nordhaus

Yale University, USA.

change policies is by jointly creating, implementing, and enforcing those policies on a global scale.

Through a carbon tax, the regulator directly sets the price of emissions by defining a tax for each tonne of greenhouse gas emitted. For example, a carbon tax of EUR 50 per tonne of greenhouse gas in the transport sector would result in a tax of approximately 10 euro cents per litre of petrol. In this particular case, the optimal tax is one that aligns the cost of fossil fuels with the externality they cause. An extensive econometric literature has developed over the last decade with the aim of estimating the size of the greenhouse gas externality. Also known as the "social cost of carbon" in technical jargon, it thus provides guidance on the level at which to set the carbon tax although carbon taxes raise many practical design and implementation questions (Parry, I. W. 2012).

1.2.1 Dynamic Integrated assessment modeling

Climate change requires an array of disciplines to fully spread knowledge and develop ad-hoc policies. Game theory, political science, economics, climate science are good examples. Integrated assessment models (IAMs) helped in this direction. Nordhaus (1992) came up with the DICE model (Dynamic Integrated model of Climate and the Economy) which underwent some changes to the basic settings, as variables and factors were integrated in the original model. The DICE model estimates the path of the economy that optimizes consumption (W=welfare), emissions, and climate change.

The DICE model can be represented as a flowchart showing the interrelation between phenomena and consequences. Beginning in the upper-left box, where economic expansion and distorted pricing signals cause CO2 emissions into the atmosphere to rise quickly. The arrow then advances to the box in the upper right, where rising CO2 levels and other factors are having a significant impact on the climate system. The effects of the changing climate on both natural and human systems are then shown in the box on the lower right. The box on the left's lower third displays societal reactions to the threat of climate change. The arrows show the linkages between politics, climate science and economics. Dashed arrows can be interpreted as a lack of direct connection because no link yet exists. Figure 1 represents a scheme relative to the dice model.

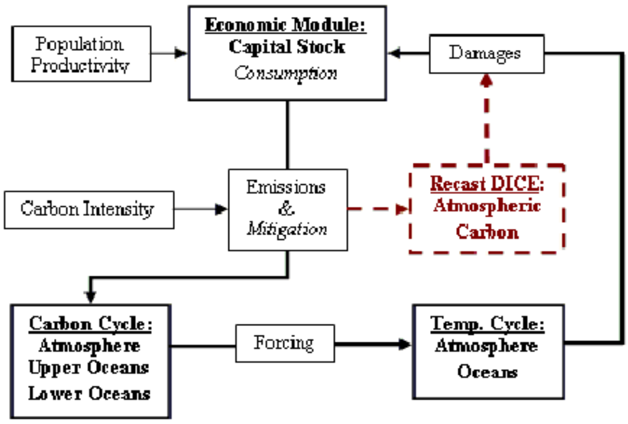

Figure 1-Representation of the DICE model [Rezai, Armon. (2010). Recast the DICE and its Policy Recommendations. Macroeconomic Dynamics. 14. 275-289. 10.1017/S1365100510000428.]

1.2.2 Mathematical Interpretation

The DICE model can also be mathematically represented through a constrained non-linear dynamic optimization model with an infinite horizon (1) the so called-social welfare function-, subject to a constraint (2).

$$(1) \qquad \max \mathrm{Wc(t)}{=}\max[\int_0^{\infty} \mathfrak{U}[c(t)]e^{-\rho t}dt]$$

$$(2) \qquad \mathrm{c(t)} = \mathrm{M}[y(t); z(t); \alpha; \varepsilon(t)]$$

In the equations, c(t) is consumption; y(t) are other endogenous variables (such as global temperature); z(t) are exogenous variables (such as population); α are parameters (such as climate sensitivity); ρ is the pure rate of time preference; and ε(t) are random variables (noise). The most challenging part is to solve equation (2).

Without delving into the details about the many advantages and disadvantages of the model, one them being surrounding the concept of impacts, the key finding of the DICE model are shadow prices and "*the social cost of carbon*".

One of the computations' auxiliary byproducts in this model is an assessment of the impact of an additional ton of emissions on optimized consumption. Not only does the optimization problem produces primal variables but also shadow prices (the impact of a unit change in emissions on the objective function). These shadow prices are the effective carbon prices, or carbon taxes which aim at offsetting the negative consequences of emissions. They internalize the carbon externality.

1.2.3 Social cost of carbon (SCC)

The most relevant concept in Climate Economics is the so-called social cost of carbon - “the change in the discounted value of economic welfare from an additional unit of CO2-equivalent emissions” (Nordhaus 2017). It plays an essential role in determining regulatory policies that involve greenhouse gas emissions. The DICE method and its many declinations helped estimate the SCC, by taking into account the full range of impacts, through the carbon cycle and climate change as well as economic damages. Solving for 1 and 2 leads to a path of all variables, the SCC at time t:

$$SCC(t) \equiv \frac{\partial W}{\partial E(t)} / \frac{\partial W}{\partial C(t)} \equiv {\partial E(t)}/{\partial C(t)}$$

the numerator is the marginal welfare impact of emissions at time t, and the denominator is the marginal welfare impact of a unit of aggregate consumption in period t. Current estimates suggest 31 $ per ton of CO2 for the year 2015 and a steady 3% annual growth through 2050 (Nordhaus 2017).

TABLE 1
Annual social cost of carbon values
2007 dollars per metric ton of carbon dioxide

Year	5 percent average discount rate	3 percent average discount rate	2.5 percent average discount rate	High impact—95th percentile at 3 percent
2015	$11	**$36**	$56	$105
2020	$12	**$42**	$62	$123
2025	$14	**$46**	$68	$138
2030	$16	**$50**	$73	$152
2035	$18	**$55**	$78	$168
2040	$21	**$60**	$84	$183
2045	$23	**$64**	$89	$197
2050	$26	**$69**	$95	$212

Source: Interagency Working Group on Social Cost of Greenhouse Gases, *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (U.S. Government, 2016), p. 25, appendix A, available at https://www.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf.

Figure 2- Social cost of carbon values for different disocunt rates scenarios[epa.gov/sites/production/files/2016-12/documents7sc_co2_tsd_august_2016.pdf.]

1.3 Carbon neutrality: an introduction

The increasing global industrialization and over-exploitation of fossil fuels has induced the release of greenhouse gases, leading to an increase in global temperature and causing environmental issues[8].

Evidence from historical records shows that the global average atmospheric concentration increased from 285 ppm of the pre-industrialization era to the 419 ppm in 2022[9] .

There is, therefore, an urgent need to achieve carbon neutrality and several Countries (124 during the COP 26 in February 2021 in Glasgow), committed to this goal by 2050. Carbon neutrality, a state of net-zero carbon emissions, can be achieved by balancing the total amount of carbon dioxide or greenhouse gas emissions produced directly or indirectly by a country, company, product, activity, or individual over a certain period via carbon offset or removal initiatives.

Carbon can indeed be removed through natural sinks such as trees, oceans, able to absorb it and store and in a way to “seize” it from the atmosphere, a phenomenon called “carbon sequestration” (Eckley, 2019).

Another way to reduce emissions and to pursue carbon neutrality is to offset emissions made in one sector by reducing them somewhere else mainly through investments in renewable energy, energy efficiency and other clean, low-carbon technologies.

During the COP 26 in Glasgow, considerable emphasis was placed on mobilizing finance and providing funding to implement effective strategies, as well as providing assistance to developing countries. Governments are expected to provide greener, more climate-resilient infrastructure development and support technological innovation. Describing in detail the strategies implemented by each country is outside the scope of this thesis. A few virtuous cases will be mentioned.

In China President Xi Jinping announced some further commitments for 2030, China will lower its carbon dioxide emission per unit of GDP by over 65 percent from the 2005 level, increase the share of non-fossil fuels in primary energy

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[8] https://www.enelgreenpower.com/learning-hub/energy-transition/climate-change-causes-consequences

[9] https://www.noaa.gov/news-release/carbon-dioxide-now-more-than-50-higher-than-pre-industrial-levels

consumption to around 25 percent, increase the forest stock volume by 6 billion cubic meters from the 2005 level, and bring its total installed capacity of wind and solar power to over 1.2 billion kilowatts. These announcements not only provide guidance and blueprint for China's green and low-carbon development, but also contribute and inject strong impetus on China's proposals for other countries to jointly meet the challenge of global climate change[10]. Nordic countries, on the other hand, pioneered the placement of Pigouvian taxes to account for the negative externality induced by pollution to the detriment of society.

Norway was one of the first countries in the world to introduce a carbon tax, in 1991. The tax is levied on all combustion of gas, oil and diesel in petroleum operations on the continental shelf and on releases of CO_2 and natural gas. For 2022, the tax rate is at NOK 1.65 per standard cubic meter of gas or per liter of oil or condensate[11] .

According to Klein et al. (2007), there must be a certain overlap between adaptation and mitigation strategies under the form of synergies to attain an overall higher co-benefit. An interesting example of the net benefit is that of distributed solar power which contributes to lowering carbon emissions and, at the same time adapts to climate change since it is more resilient power supply system than over the ground grids, often vulnerable to storms and temperature changes. One could also mention forests which do not only serve as sinks by capturing and storing carbon but provide a protection against natural disasters.

Improving agricultural practices (the literature mentions agroforestry[12], regenerative agriculture, and polyculture) through reduced forest conversion to agricultural land helps mitigating climate change through the lowering of GHG emissions as already mentioned and also contributes to the improvement of food security thanks to resilient crops and a higher water efficiency. A transition from

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[10] https://unfccc.int/sites/default/files/NDC/202206/China’s%20Achievements%2C%20New%20Goals%20and%20New%20Measures%20for%20Nationally%20Determined%20Contributions.pdf

[11] https://www.norskpetroleum.no/en/environment-and-technology/emissions-to-air/

[12] Agroforestry refers to cultivation and use of trees and shrubs with crops and livestock in agricultural systems. Agroforestry seeks positive interactions between its components, aiming to achieve a more ecologically diverse and socially productive output from the land than is possible through conventional agriculture. [Gold, Michael A. "agroforestry". Encyclopedia Britannica, 15 Dec. 2017, https://www.britannica.com/science/agroforestry]

a linear to a circular economy, in which items and end of life goods enter second life scenarios rather than being directly disposed to a landfill, is essential in lowering the amount of carbon emissions to the atmosphere.

Additional examples of agricultural, economic, and building sector methods that work in tandem and assist both mitigation and adaptation include genetically enhanced crops, funding net-zero carbon regulations, and geothermal energy use. As for the transportation sector promoting public transportation, increasing vehicle efficiency, electrifying transportation, and encouraging car-sharing services are all approaches to mitigate and adapt to climate change in the transportation sector. These measures will also lead to cost and energy savings, thereby increasing economic and energy resilience and thus enabling adaptation. Additionally urban design has a major impact according to the paper. Compact urban development decreases land demand, avoids risky locations, and is less susceptible to intense heat events than urban sprawl. The literature suggests trade-offs between adaptation and mitigation strategies be accurately meditated, given that negative consequences may occur. For instance, constructing a hydroelectric power plant will reduce greenhouse gas emissions due to its renewable energy source. However, a hydroelectric power plant will increase competition for water with local communities, compromising adaptation.

On the other hand, building a dam can secure a safe and reliable water supply thus benefiting a community (adaptation); dam construction requires a great amount of cement and steel thus negatively affecting mitigation. The paper also cites lack of finance, collaboration, implementation, transparency, and public engagement as constraints to synergies, as well as an ineffective community awareness. Besides, governments should resort to a formal technical committee to advise on scientific issues and possible solutions, but they rarely succeed in doing so. In Europe, only a quarter of the climate change action plans considered an in-depth analysis of the mitigation and adaptation synergies (Abarca-Alvarez et al. 2019)

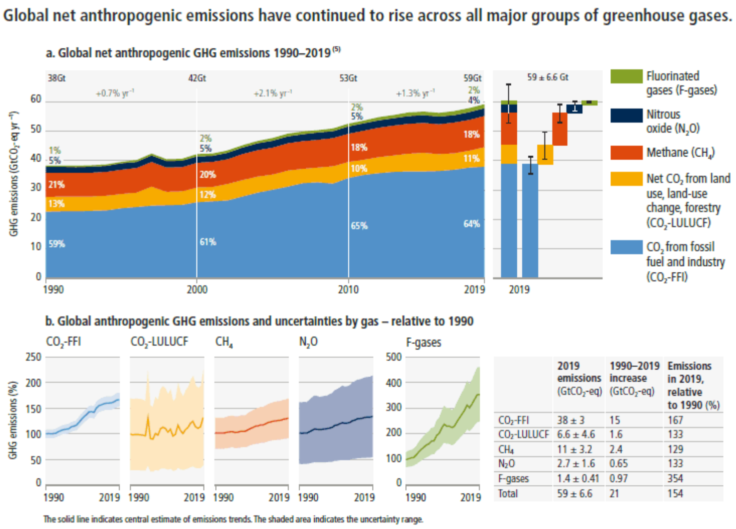

Figure 3-Global net anthropogenic emissions 1990-2019 by type of gas-[IPCC 2019]

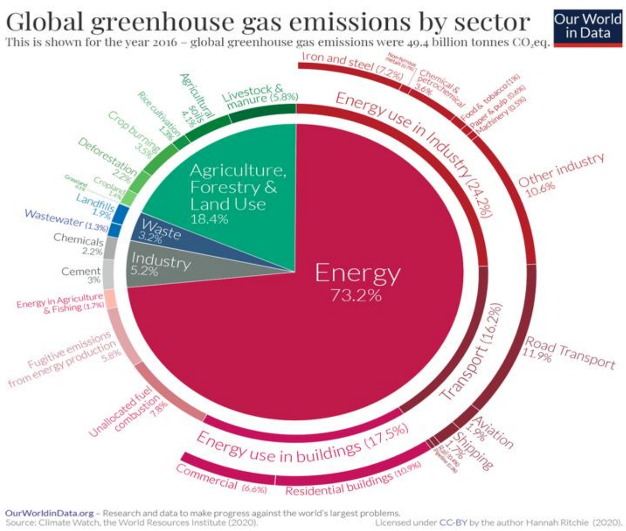

Figure 4-Global greenhouse gas emissions by sector [visualcapitalist.com]

1.3.1 Direct and indirect carbon emissions

According to the GHG Protocol (IPCC[13], 2022) there are three scopes to account for the different nature of emissions.

The GHG Protocol provides the latest tools and training for counting carbon emissions which are used by a variety of entities such as governments, industry associations, NGOs, businesses, and other organizations.

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[13] IPCC The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change.

Scope 1 includes all direct emissions stemming from the activities of an organization or under their control. This includes fuel combustion on-site such as gas boilers, fleet vehicles and air-conditioning leaks.

Scope 2 includes indirect emissions from electricity purchased and used by the organization. Emissions are created during the production of the energy and eventually used by the organization. Scope 3 emissions cover all other indirect emissions from activities of the organization, occurring from sources that they do not own or control. These are usually the greatest share of the carbon footprint, covering emissions associated with business travel, procurement, waste, and water.

As for scope 1 emissions, literature suggests improving insulation systems to avoid leakages and energy losses, as well as introducing environmentally friendly vehicles in a company's fleet, such as hybrid or electric vehicles. Scope 2 emissions can be reduced by purchasing alternative energy from utility providers with clean energy options.

1.3.2 NET (Negative Emissions Technologies)

Below is a discussion of the main technologies and perspectives for achieving carbon neutrality, stressing advantages and disadvantages of each technology. The focus is set on NET (negative emissions technologies) which include renewable energy sources, carbon capture and storage (CCUS).

The causal link between energy and Real Estate market lies within the possibility to build environmentally friendly "smart homes" and the attention towards sustainability which is growing in this direction.

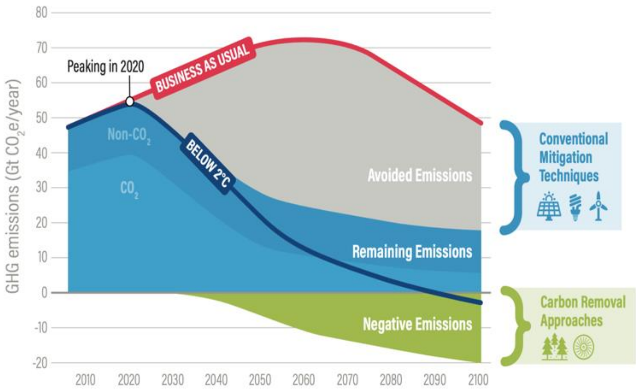

Figure 5-The impact of negative emission technologies [https://circularcarbon.org/market-report/]

1.3.3 Renewable sources and energy storage

There is a clear link between energy conservation and climate change mitigation. Renewable sources can provide more than 3000 times the current global energy demand. Therefore, these types of resources will have a significant share in the future global energy portfolio, much of which is now concentrating on advancing their pool of renewable energy resources (Ellabban et al. 2014).

Among clean energies, renewables, such as solar energy, wind power, and ocean energy, are regarded as some of the most important and efficient means to achieve carbon neutrality. Solar energy for example is being harnessed through photovoltaic technology and represents an inexhaustible, ubiquitous, and clean energy. Due to their high-power conversion efficiencies and notable operational stability, conventional thin-film solar cells made of inorganic semiconductors like silicon, gallium arsenide (GaAs), copper indium gallium selenide, and cadmium telluride (CdTe) materials have been extensively industrialized. Research is now pointing towards organic solar cells, perovskite solar cells, quantum dot solar cells to improve power conversion efficiency: the average is 18% percent according to Ansari et al. 2018. Another source which is often mentioned is wind energy. Wind results from the motion of air due to uneven heating of the Earth’s surface by the Sun. Site location, cost of installation as well as the unpredictable nature of wind greatly affects the adoption of this choice and amongst the challenges cited are noise generation, collision between wind turbines and birds, disruptions, habitat destructions. Biomass is a renewable source of energy that originates from plants.

The most important sources of biomass are agricultural and forestry residues, biogenic materials in municipal solid waste, animal waste, human sewage, and industrial wastes.

Biomass provides 13%–14% of the annual global energy consumption. There are many processes to convert biomass into energy including thermochemical conversion through gasification, pyrolysis and combustion. Amongst the issues are the high cost of transporting the biomass to the site for bioenergy production through various conversion processes and the sustainability of the production of bioenergy feedstocks[14].

Recently, there has been a lot of interest in hydrogen energy since it can be utilized to create an entirely renewable energy system that functions similarly to an electricity grid, providing the sector integration required for an energy system transition and decarbonizing energy end-uses. Hydrogen is mainly produced via water electrolysis which is relatively cheap and can be easily stored in solid, liquid and gas state, though not in large amounts as to scale up costs. In addition most hydrogen is up to now almost entirely supplied from fossil fuels, with 6% of global natural gas and 2% of global coal going to hydrogen production [IEA, 2021].

Another technology exploiting hydrogen is that of hydrogen fuel cell which have developed particularly in the passenger cars market and heavy-duty vehicles, trains, and ships. The main issue now is to reduce the cost while maintaining an acceptable level of durability and efficiency.

Nuclear energy is one of the main contributors to carbon reduction, avoiding 1,7 Gt CO2 emissions a year globally. It is mainly generated through nuclear fission, while nuclear fusion is currently at the R&D phase. The main advantage of fusion is that it produces no long-lived waste [IEA, 2019]. The future of nuclear fission energy is, however, very questionable for several reasons, including escalating costs, problems with the disposal of radioactive spent fuel, safety concerns within the plants, and threats to the proliferation of nuclear weapons. Major attention is nowadays placed on molten salt reactors (MRS) which use high temperature

[14] http://www.worldbioenergy.org/uploads/201210%20WBA%20GBS%202020.pdf

molten salt as a coolant and provides a greater heat storage capacity. Studies confirm that an MRS can also be applied to high temperature electrolysis hydrogen production thanks to a 700 °C outlet temperature. Therefore, MRS could accelerate the transition to achieve carbon neutrality (Peña et al. 2022).

A challenge which hinders the widespread adoption of renewables is the intermittent and random electricity produced. Batteries, as energy storage enablers play an essential role in the improvement of the stability and reliability of the electric output. Amongst the many applications, the car market is directing its efforts towards the development of reliable and sustainable lithium-ion batteries as part of the transition towards smart mobility. The challenges lie in the high cost and limited supply of lithium, whilst the main advantage is the desirable electrochemical performance in both capacity and power density.

Other alkali-based batteries do not deliver the same performance and are therefore limited to market niches or small-scale applications (Gao et al. 2022).

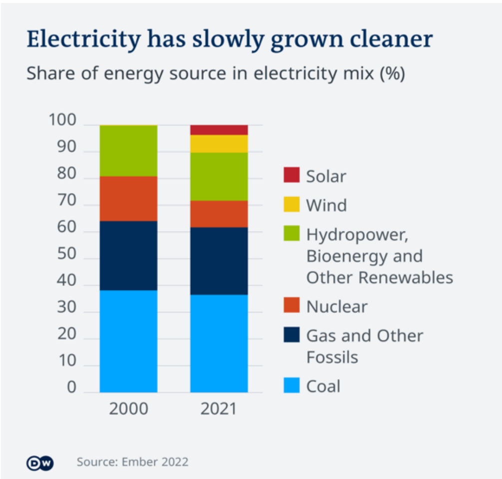

Figure 6- growth of renewable sources in electricity production mix[Ember 2022]

1.3.4 Technologies for CO2 capture and utilization

Separating CO2 from the emission sources, converting and using CO2, transporting, and subterranean storage with long-term isolation from the atmosphere are the three processes that make up the CO2 capture, use, and storage (CCUS) technology. CCUS is paramount in order to achieve the emission reduction target set as part of the Paris Agreement. Research highlights that 19%

of global CO_2 emissions must be captured and stored to keep global temperature rise below 2°C by 2050 (IEA, 2021).

Currently, post-combustion capture, pre-combustion capture, and oxygen-fuel combustion are the main technical routes for CO_2 capture. One of the simplest methods for recovering CO_2 in energy systems, post-combustion separates CO_2 from the exhaust gas.

To lower the energy consumption of CO_2 separation, post-combustion separation research is now focused on finding effective absorbers and streamlining the separation procedure. The low CO_2 concentration in the tail gas, however, is the primary cause of the post-combustion separation's high energy consumption. It is challenging to significantly lower the energy used for separation by just enhancing the absorbers and streamlining the procedure. The way to separate CO_2 before combustion is called pre-combustion.

This technology is carbon intensive since the initial concentration of carbon is higher in the gasified fuel-which is the byproduct of a chemical absorption reaction. A portion of the flue gas is returned to the system for circulation after the fuel is burned in an atmosphere including oxygen and carbon dioxide. The primary methods for producing the necessary oxygen are air separation, pressure-swing adsorption, and cryogenic technologies. The benefit of oxygen combustion is that the flue gas is mostly made up of CO_2 and vapor, requiring almost no energy for CO_2 separation (Wu et al. 2018).

More research is required to reduce emissions from food systems and improve sinks of carbon and other crucial nutrients (i.e., nitrogen, potassium, phosphorus amongst others) because unsustainable management practices in food systems continue to account for a sizable portion of GHG emissions, ranging from the production and application of chemical fertilizers to waste landfilling and burning (i.e., nitrogen, potassium, phosphorus amongst others). Concerning the latter, it would be possible to lessen the need for chemical fertilizers and sustainably support human activities by developing novel techniques for further optimizing waste recycling and nature-based processes in agroecosystems.

The term "*CO2 chemical utilization*" refers to procedures that, under specific temperature, pressure, and catalyst conditions, transform CO_2 into other high-

value compounds. The direct conversion and consumption of CO2 can be achieved through CO2 chemical utilization, which also has a certain direct emission reduction effect. This type of technology pursues CO2 conversion through mostly thermochemical processes, such as the now commercialized *thermochemical catalysis*. The latter aims at producing valuable chemicals by integrating CO2 into certain organic substrates to form new C-X bonds (C–H, C–O, C–N) in catalytic sequences (Roy et al. 2018). Other technologies will not be further investigated as they lie outside the scope of this thesis.
In the area of satellite observation and Digital Earth technology, the support for C neutralization includes the rapid monitoring of global GHG concentration, ground land cover change, and the spatial analysis of global natural C sink, which plays an important supporting role in the assessment of when to achieve the peak of C emissions and the potential of a natural C sink (Wang et al. 2021). This monitoring is performed through satellite remote sensing and Digital Earth. The latter is able to "integrate a massive amount of data mainly from satellite observation, and develop models, simulate or predict current or future global ecosystems at multiple resolutions in space and time, and then visualize the results" (Fu et al. 2020).

1.4. Slowing climate change according to economists

William Nordhaus provides us with the perspective from economists and suggests three ways to significantly cut emissions and slow climate change

The first possible solution is "abatement," or reducing emissions of CO2 and other GHGs primarily by reducing combustion of carbon fuels. The second solution is "carbon removal," or removal of CO2 from the emissions stream or from the atmosphere. And lastly Plan C is "geoengineering," or more precisely solar-radiation management, which would offset global warming by increasing the reflectivity of the earth. As mentioned above, carbon removal is expensive and energy intensive, geoengineering does not seem to be a viable solution and poses a threat to eco-system. Abatement is by far the most realistic option but remains costly when considering targets to reach.

Experts do not anticipate any remarkable technological advances that could significantly lower abatement costs in the foreseeable future, despite the intense research. “New technologies – particularly for energy systems, which have massive financial and physical investments in capital such as power plants, structures, roads, airports, and factories – take many decades to develop, commercialize, and deploy” [IEA, 2021].

For the scope of the thesis, it is paramount to understand how the market selects the most suitable discount rate to value climate change policy investments and assess their feasibility and profitability, and the value they can deliver to society in terms of welfare. Last part of chapter three is dedicated to the parallelism between climate change policy and real estate as both are “risky assets” and how discount rates can be inferred from the latter.

1.4.1 Climate Change and discount rates

The choice of discount rate is essential to assessments of climate change policy. It is a much-debated topic and it has led to disagreements over which one to be employed from a conceptual stand point. On the one hand Stern (2008) points to ethical considerations and a prescriptive consumption discount rate, unrelated to estimates of opportunity cost of capital, or implied interest rates.
Nordhaus (2007), in contrast, provides an interpretation based on empiricism: the appropriate discount rate ought to stem from market interest rates.
Different approaches lead to significant different results. The Stern Review on the Economics of Climate Change (2007) brings up a radical solution to climate change reduction, proposing a far-fetched 3% gas emission reduction per year, employing a consumption discount rate of 1.4%. He even mentions a loss of 5% global GDP as a result of no immediate action. Nordhaus (2007) argues that this value is very low and reflects a strict and aggressive climate policy, which does not reflect today’s marketplace real interest rates and saving rates. He proposes

a more modest approach as part of his DICE model and suggests a 4,3% discount rate. Lawrence & Williams (2012) contribute by introducing two types of consumption discount rates. They discern between a social-welfare-equivalent discount rate that is suitable to determining whether a given policy would enhance social welfare (according to a postulated social welfare function) and a finance-equivalent discount rate that is appropriate for determining whether the policy would lead to potential Pareto improvement[15]. It is necessary to point out that most studies among the existing literature refer to a consumption discount rate rather than a utility discount rate. This is because ethicists, including Stern agree that future utility should not be discounted- that the well-being of future generations should count as much as that of the current generation in a social welfare function. This implies a very low or even null level for the social rate of time preference (or pure rate of time preference as indicated in 1.2), defined as the trade-off within an individual's intertemporal welfare function.
Indicated by the Greek letter ρ, it takes the value of 0.001 in the *Stern Review*, to confirm the assumptions by ethicists. Consumption discount rates, in contrast, translate values of future consumption into equivalent values of current consumption (in terms of social welfare). From the equation (1) from 1.2.2, the social welfare function, the social welfare equivalent discount rate r_{sw} as the rate which translates a marginal change in consumption at some future date t into the social-welfare-equivalent marginal change in consumption at time 0. It must satisfy

(3) $\frac{\delta W_0}{\delta W_0} = (1+ r_{sw})^\wedge t \frac{\delta W_0}{\delta C_t}$

By replacing (1) into (3) and rearranging for r_{sw}

(4) $(1 + r_{sw})^t = (1 + \rho)^t \frac{\delta U_0/\delta C_0}{\delta U_t/\delta C_t}$

[15] Pareto improvement occurs when a change in allocation harms no one and helps at least one person, given an initial allocation of goods for a set of persons.[https://www.investopedia.com/terms/p/paretoimprovement.asp]

This equation shows that there are two distinct reasons for discounting: time preference (represented by the first term on the right-hand side) and the difference in marginal utility of consumption between the two time periods (the second term). It is possible to approximate the second term of (3) with the rate of growth of consumption g since marginal utility of consumption declines as consumption rises.

Let g represent the growth rate of C, such that

(5) $C_t = (1+g)^t C_0$

By substituting that into (4) and simplifying:

(6) $(1+r_{SW})^t = (1+\rho)^t (1+g)^{\eta t}$

By taking the natural logarithm:

(7) $r_{SW} \approx \rho + \eta g$

The social-welfare equivalent depends on the social rate of time preference and the product between the growth rate of consumption and the sensitivity of marginal utility of income with respect to changes in consumption η (the utility function).

Some important considerations can be drawn from these formulas. r_{sw} is always positive since marginal discounting of future utility is close to zero but still positive (ρ) and η, which reflects the fact that with increased consumption, marginal contribution of social welfare decreases is positive as well. Relatively small differences in the consumption discount rate imply large differences in the discounted values attached to events in the distant future. By varying ρ from 0.1% as implied by Stern, to 3% in the case of Nordhaus Dice model, the carbon tax resulting for the maximization problem is significantly different, as well as the percentage of emission reduction: 14 % was the value obtained for 2015 Nordhaus when 4.3% is used, versus a 53% in the same year for Stern (corresponding to a

1.4% discount rate). The carbon tax for Stern amounts to 360$/ton against 35 $/ton for Nordhaus (Lawrence & Williams, 2012).

We define r_f as the financial rate that equates future and current consumption. In other words, this is capital's marginal product (or marginal opportunity cost). The rate r_f shows how consumption levels are linked across time: if society foregoes one unit of consumption in any given period to increase the capital stock, the amount available for consumption in the next period will increase by 1 + r_f (Lawrence & Williams, 2012). The social welfare function underlying the use of r_{sw} provides a normative basis for policy analysis, and thus r_{sw} can be used to recommend some policy options while rejecting others. However, the Kaldor-Hicks[16] criterion that underpins the use of r_f has a normative basis: most people would agree that satisfying the Kaldor-Hicks criterion increases the appeal of a policy option, all else being equal. As a result, r_f and r_{sw} can be used prescriptively. However, it should be noted that, by definition, the use of r_{sw} provides a broader assessment of a policy option's social welfare implications. When the net benefits of a policy are calculated using r_f, their potential benefits are measured using a criterion (the Kaldor-Hicks criterion) that ignores the distribution of impacts and other potential determinants of social welfare. Uncertainty does affect discounting and r_{sw} depends on ρ, η , and g, each of which is uncertain. r_f is equally affected. The general approach is that when discounting over very long-time horizons, this certainty-equivalent discount rate equals the lowest possible discount rate. It is generally better to separate the two issues, that of discounting and risk by using a risk-free discount rate and incorporating risk into the analysis by using certainty-equivalent benefits. To summarize, the choice of either discount rates should be based on the specific evaluation metric in assessing a climate policy. r_{sw} points to more ethical considerations, while r_f better reflects observed behavior.

[16] The Kaldor-Hicks efficiency under which a change is efficient if the gains to the winners of any change in allocation outweigh the damage to the losers [https://www.investopedia.com/terms/p/pareto-efficiency.asp]

1.5 Historic background

Significant worldwide commitments were taken during several summits, which are briefly listed below. Following treaties helped seal these commitments and represent milestones in combating Global Warming and Climate Change.

- 1997 Kyoto Protocol which operationalizes the United Nations Framework Convention on Climate Change by committing industrialized countries and economies in transition to limit and reduce greenhouse gases (GHG) emissions in accordance with agreed individual targets.
  The Convention itself only asked those countries to adopt policies and measures on mitigation and to report periodically.
- 2009 Copenhagen Accord solidified global efforts, setting a target of mobilizing US$100 billion a year by 2020 from a wide variety of sources for developing countries to put in place mitigation strategies in order to cut carbon emissions.
- 2010 Cancun Agreements where the Green Climate Fund (GCF) was established as a key delivery mechanism for climate change finance and the 2020 target.
- In Doha, Qatar, on 8 December 2012, the Doha Amendment to the Kyoto Protocol was adopted for a second commitment period, starting in 2013 and lasting until 2020.
- 2015 Paris Agreement reinforced the target and required countries to effectively implement their national climate plans, as well as increase their ambition over time. It also recognized that climate change funding should be enabled from a 'wide variety of sources, instruments and channels', including the public and private sectors.

1.5.1 Kyoto Protocol (1997)

Kyoto Protocol, in full Kyoto Protocol to the United Nations Framework Convention on Climate Change, entered into force in February 2005, 90 days after being ratified by at least 55 Annex I signatories that together accounted for at least 55 percent of total carbon dioxide emissions in 1990.

The protocol called for reducing the emission of six greenhouse gases in 41 countries plus the European Union to 5.2 percent below 1990 levels during the "commitment period" 2008–12.

The protocol provided several ways for countries to reach their targets. One approach suggested was to make use of natural processes, called "sinks," that remove greenhouse gases from the atmosphere, such as planting trees.

Another one was the use of CDM (Clean Development Mechanism) which encouraged developed countries in making sustainable investments in developing countries in order to gain carbon credits toward their actual obligations. A third approach was that of emission trading which enabled countries to buy and sell emissions rights and thereby placed an economic value on greenhouse gas emissions.

The protocol spared ratifying developing countries of any obligations . This meant China and India for example were not supposed to intervene. The United States, the world's second emitter of greenhouse gases did not ratify the protocol. The resulting reductions never met the target mentioned above and this led academics and experts to question its real effectiveness[17].

1.5.2 Paris Agreement

The Paris Agreement set out to improve upon and replace the Kyoto Protocol, an earlier international treaty designed to curb the release of greenhouse gases. It

[17] Britannica, The Editors of Encyclopaedia. "Kyoto Protocol". Encyclopedia Britannica, 8 Sep. 2022, https://www.britannica.com/event/Kyoto-Protocol.

entered into force on November 4, 2016 and has been signed by 195 countries and ratified by 190 as of January 2021[18].

The objective was no less than a binding and universal agreement designed to limit greenhouse gas emissions to levels that would prevent global temperatures from increasing more than 2 °C (3.6 °F) above the temperature benchmark set before the beginning of the Industrial Revolution.

Most economists and academics agree on the ineffectiveness of these worldwide agreements due to the collective effort required and the lack of incentives and penalties.

Scott Barrett, an economist expert in Global Affairs as well as vice dean of Columbia University’s School of International and Public Affairs, argues that, despite the name-and-shame structure of the agreement, in which governments would periodically review each other’s pledges, the actual effort was much less than they had promised [16].

He, furthermore, mentions a free-riding problem (see also Nordhaus (2015)): regardless of how much a single country contributes to CO2 emissions reduction, a global outcome is sought after, that is enjoying the benefit of a global scale intervention without having to significantly reduce the emissions on a country basis. Moreover, as previously mentioned, there is not a regulatory body to keep countries accountable whenever they do not honor the agreements, meaning that countries are not subject to any fines nor sanctions at all. Another criticality which is often highlighted is the generalized nature of the accords, which do not target specific industries. Barnett then suggests that governments implement smaller, more technical agreements focusing, for example, on emissions cuts in particular industries. This option is far from pursuing the same objective as those discussed in the Paris Agreement, rather it would lead to small-scale and incremental improvements. Ultimately, in the event of unilateral abatement by a single country, global emissions could even remain unchanged if that country's companies decided

[18] Britannica, The Editors of Encyclopaedia. "Paris Agreement". Encyclopedia Britannica, 28 Oct. 2022, https://www.britannica.com/topic/Paris-Agreement-2015.

to relocate their production to countries with a less stringent climate policy a phenomenon known as carbon leakage.

Along with the Kyoto Protocol and the Paris Agreement, the European Union's main instrument for achieving decarbonization targets is the European Union Emissions Trading System (EU ETS), a cap-and-trade system to control pollutant emissions from large power plants, industry, and the commercial aviation sector, which together account for about 40 per cent of the EU's pollutant emissions. The ETS has been complemented by sectoral measures with varying targets in the Member States, and investment in research and development of new technologies for carbon dioxide capture and storage (CCS).

In 2019, the EU presented the European Green Deal containing proposals to revise and tighten the regulation of the ETS and non-ETS sectors, as well as the imposition of ambitious targets for energy efficiency and renewable energy use.

In order to monitor the path towards achieving the objectives set by the Paris Agreement, EU Member States are required to send a ten-year planning document to the European Commission, providing indications of the national objectives and the measures needed to achieve them. Despite their 10-year horizon, the targets and policy actions must be in line with the achievement of zero emissions by 2050, as already indicated in the *European Green Deal* (CAN Europe 2022).

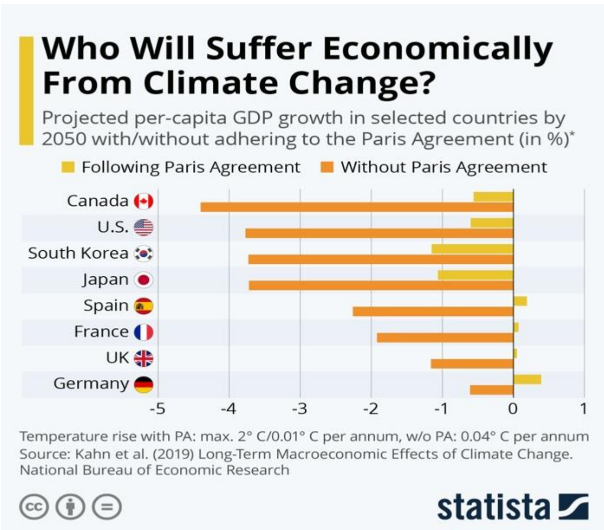

Figure 7-Projected per capita GDP growth in selected counties with/without the Paris agreement[https://www.statista.com/chart/21619/gdp-losses-climate-change-paris-agreement/]

Furthermore, as a way to stimulate the investments necessary to reach the 2020-2030 targets, the EU has decided to allocate about one third of the *NextGenerationEU* budget13 to investments aimed at achieving the objectives outlined in the *European Green Deal*. These funds should also be mobilized through the issuance of green bonds by the European Commission.
In Italy, climate goals are summarized into the PNIEC, prepared by the Ministry of Economic Development in the beginning of 2019. The PNIEC covers the following topics: energy efficiency and renewables, emission reduction, internal market and interconnections, research, and innovation. It encompasses a considerable reduction in greenhouse gas emissions compared to 2005 (-43 per cent in ETS-regulated installations and -33 per cent in the remaining sectors), a rise in the share of renewable energies (30 per cent of total gross energy consumption and 22 per cent of consumption in transport), a reduction of primary energy consumption by 43 per cent (Albino et al. 2022).

Nevertheless, the energy crisis triggered by the Russian invasion of Ukraine forced both temporary deviations from the decarbonization path and a strengthening of the related medium- to long-term targets. Against the backdrop of the energy emergency, Member States intervened with a series of temporary measures to support businesses and consumers, including in some cases increasing electricity production from coal-fired power plants.

Considering recent developments, such as the aforementioned conflict and previously, the energetic and raw material crisis caused by posthumous Global Covid-19 Pandemic, there is an ongoing search by for alternatives to Russian gas for electricity production as well as heating. To this purpose, significant effort was put into the drafting and approval of a *National Recovery and Resilience Plan (PNRR),* which foresees investments amount to 70 billion euros as part of the "*Green revolution and ecological transition*"[19]

[19] https://www.mef.gov.it/en/focus/The-Recovery-and-Resilience-Plan-Next-Generation-Italia/

1.5.3 Overall considerations

Efforts towards renewables are both directed to the generation of heat and power - vital to human activities- as well as the production of hydrogen and biofuels from biomass, as is suggested by the current literature. Energy storage seems the apparent solution to the intermittency of some of the renewable energy sources such as wind and solar energy. However, the scalability and cost-effectiveness of energy storage are subject to many constraints and limitations. As the largest carbon sinks on Earth, terrestrial and marine ecosystems could help reduce climate change by boosting carbon sequestration. These policies should be strengthened to encourage reforestation, afforestation, and the use of C-negative materials to protect terrestrial ecosystems. CCUS technologies are still relatively immature and are hindered by the limits of thermodynamics and kinetics, let alone the high cost and energy consumption.

CHAPTER 2

Literature review: climate change and real estate

2.1 Introduction

Every area of the real estate market is being impacted by the advances and effects of climate change, from price increases to a loss in the appeal of particular regions. Increases in extreme weather patterns and large-scale events, such as flooding and wildfires as well as powerful hurricanes and hurricane-force storms, are correlated with rising temperatures. These occurrences are making it more difficult to control the costs and condition of property on an annual basis in the real estate market. Hurricanes have had a large impact in the North Atlantic. Coastal communities are frequently the hardest damaged since flooding seriously compromises the structural integrity of buildings, not to mention the fact that sea levels are rising along the coasts as a result of warming temperatures. By the year 2050 the annual expected losses from floods are predicted to exceed 1 trillion USD [OECD, 2016]. Homes and millions of acres of land are being destroyed in the Western United States by larger, hotter, and more catastrophic wildfire on a more regular basis. While real estate prices and rentals rise in surrounding neighborhoods that are unaffected by these influences, repair bills become more regular and insurance rates begin to soar. Properties start to lose their popularity in these areas and tenants become more reluctant to inhabiting weather-plagued locales, threatened by natural disaster. Prices eventually drop and homes lose value. This ultimately leads to a hedonic social cost which is borne by real estate players and prospective buyers.

Previously only a minor issue for many real estate players, climate change is now at the top of the list. Real estate leaders have taken on a role of critical importance in the climate transition, the time frame from now through 2050 during which the globe will experience both the physical repercussions of climate change and the

alterations in economic, social, and governmental structures required to decarbonize.
Real estate players now have new obligations to revalue and future-proof their portfolios as a result of the changing climate, but they also have new opportunity to generate new sources of value.

The physical dangers of climate change combined with this economic transition have increased the potential of mispricing real estate across markets and asset classes. A Mckinsey survey on a diversified equity portfolio found that, absent mitigating actions, climate risks could reduce annual returns toward the end of the decade by as much as 40 percent. Real estate players will need to figure out which of their assets are mispriced, as well as the direction of this phenomenon, use their knowledge to drive informed investments and manage their assets effectively. In the real estate sector, developing climate intelligence is essential to drive value creation and strategic differentiation. However, the opposite is also true: real estate is crucial to international efforts to combat climate change.
Real estate is responsible for approximately 40 percent of total global emissions. Approximately 11 percent of these emissions are generated by manufacturing materials used in buildings (including steel and cement), while the rest is emitted from buildings themselves and by generating the energy that powers buildings .

There are many ways for real estate to help the decarbonization process, through already existing technologies, in a way to achieve profitability. For instance, upgrading to more energy-efficient lighting systems and installing better insulation have positive financial returns. “Today, newer technologies also make low-carbon heating and cooling systems, such as heat pumps and energy-efficient air conditioning, more cost competitive in many markets and climates. These cost-effective upgrades can create meaningful change while also de-risking assets”[20]

[20] https://www.mckinsey.com/industries/real-estate/our-insights/climate-risk-and-the-opportunity-for-real-estate

The climate transition not only poses a challenge for investors, but also an opportunity to achieve cost effective upgrades while allowing assets to de-risk. This shift may also lead to competitive differentiation and value creation.
Climate transition requires investors to:

- Incorporate climate change risks into asset and portfolio valuations. This requires building the analytical capabilities to understand both direct and indirect physical and transition risks.
- Decarbonize real-estate assets and portfolios.
- Create new sources of value and revenue streams for investors, tenants, and communities.

The following paragraphs will provide insights into the factors contributing to both physical climate risk and consumption risk, both of which affect real estate.

2.1.1 Brief overview of American real estate market

In December 2022, U.S. home prices were up 1.3% compared to last year, selling for a median price of $388,060. On average, the number of homes sold was down 36.4% year over year and there were 377,810 homes sold in December this year, down 594,277 homes sold in December last year. The national average 30-year fixed rate mortgage rate is at 6.4% and up 3.3 points year over year. There were 1,317,776 homes for sale in the United States, up 14.6% year over year. The number of newly listed homes was 255,040 and down 29.8% year over year. The median days on the market was 44 days, up 19 year over year. The average month of supply is 2 months, up 1 year over year. 23.1% of homes in the U.S. sold below list price, down 19.8 points year over year. There were only 14.6% of homes that had price drops, up from 7.0% of homes in December last year. There was a 98.1%

sale-to-list price, down 2.4 points year over year[21].

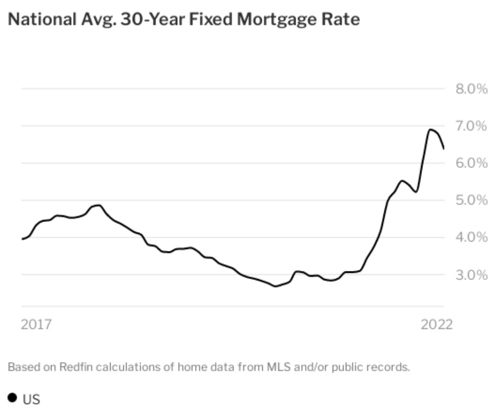

Figure 8-National average 30 year mortgage rate [https://www.redfin.com/us-housing-market]

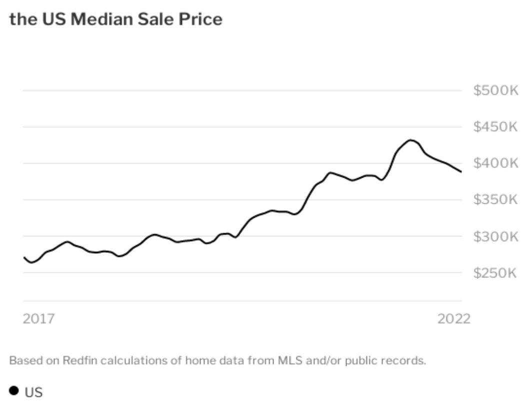

Figure 9-US median house sale price[https://www.redfin.com/us-housing-market]

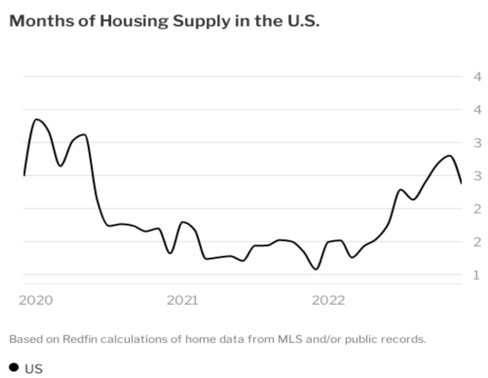

Figure 10-Months of housing supply in the US[https://www.redfin.com/us-housing-market]

[21] https://www.redfin.com/us-housing-market

2.1.2 Incorporate climate change risks into asset and portfolio valuations

Buildings and other assets can be impacted by physical and transition risks either directly or indirectly via their effects on the markets with which they interact. The direct impact for a building lies within the embodied energy of the materials employed in construction, as well as the carbon footprint. The ecosystem in which the building is situated, can add up to the initial impact of the physical asset, depending upon the level of detail of our lifecycle assessment. An example could be a building supplied by a carbon intensive energy grid, or transportation system, which is indirectly exposed to the risk of those systems. This poses a major concern for real estate companies, which have been conducting stress tests on their portfolios and found potential losses escalating in the next years. According to McKinsey direct physical repercussions are significant and noticeable, with a $5 billion depression in the value of Florida properties exposed to climate risk compared to unexposed homes. An article on the Journal of Urban Economics mentions a 7% reduction in housing prices in New York area, following 2011 hurricane Sandy and persisting up to 2018 [see [18]].
This reflects a greater perception of risk by investors. Destructive fires in Northern California led to an annual 60% leap in nonrenewals of insurance by households due to skyrocketing prices.

It is essential for real estate players to anticipate legislative, economic and societal developments, and make commitments to avoid or reduce risks, therefore allowing a reallocation of capital and pioneering a change in the structure of the economy. A salient case is that of 2019 New York City's Local Law 97, which "sets limits on the greenhouse gas emissions of covered buildings starting in 2024 to help New York City reach the goal of a 40 percent reduction in greenhouse gas emissions from buildings by the year 2030 and 80 percent reduction in citywide emissions by calendar year 2050.[22]"

To better comprehend the possible effects of revenue, operating costs, capital costs, and capitalization rate on assets, real estate owners and investors will need to increase their "climate intelligence". Among other things, this entails acquiring the analytical skills necessary to regularly evaluate both physical and transitional threats, quantify risks and opportunities.

- Prioritize risks through portfolio's assets: a risk matrix correlating likelihood, i.e. the probability of occurrence and impact, i.e the severity of the consequences is a powerful standard tool across managerial decisions
- Mapping building exposure consists in determining which buildings are exposed to risk and the degree of exposure thanks to detailed micro-economic and macro-economic modeling, (i.e. the projections of GDP based on the carbon price for a local area's energy mix)
- Quantify portfolio impact consists in gaining an overview of economic metrics of all assets within the portfolio.
- Take action: these capabilities are not directed towards a purely academic assessment but should drive decision processes and investment decisions, considering lease pricing, capital attraction, investor relations, in order to secure a competitive advantage.

2.1.3 Decarbonizing real estate

The embodied carbon footprint is the amount of CO2 per unit mass of material associated with the production of raw materials, semis, transportation, and construction processes.

Decarbonization entails a reduction of the amount of carbon required to design, construct, use, renovate and demolish a building. According to a Deloitte's article,

[22] https://www.nyc.gov/site/sustainablebuildings/requirements/covered-buildings.page

75% of buildings in EU are not energy efficient, and since buildings have a quite long useful life (50 years on average), decarbonization efforts ought to be conveyed towards efficiency, thus on the use phase of the building, the so-called operational carbon footprint[23].

National and European regulations are pushing towards the translation of commitments, policies' objectives into design specifications. New construction regulations are setting targets in terms of energy performance, percentage amount of renewable in the production mix and in terms of emissions per square meter (IEA, 2022). Salient is the case of France's RE2020[24]. Designers and project planners therefore have several options such as Increase the amount of locally-available bio-based materials (such as wood, clay, wool, and even straw), produce energy on site (solar panels), manage BIM technology and make forecasts about future material usage, using modular techniques from the circular economy. Carbon efficiency outcomes mostly depend on decisions taken at the design and construction phases of the lifecycle. However, the use phase requires and consumes energy for the heating and lighting (utilities) and the literature suggests to amortize the impact by extending the useful life of a building, or converting it to another use at the end of its life without major renovations and adaptations. Renewable sources of energy and green energy use, a shift to non carbon heating and cooling sources and the employment of Internet of Things are all valid means in this direction. IoT has the potential to reduce the cost of consumed energy by controlling the lighting and temperature of rooms that are currently not occupied through a mobile phone. Renovations, on the other hand tend to be more carbon intensive since they may require multiple interventions and entail replacement of materials or venting/ cooling systems which does not necessarily allows energy efficiency. Renovating decisions must be thoroughly analyzed. According to estimates from the Waste Framework Directive of the EU, only 50 % of C&D waste is currently being recycled (Zhang et al. 2022). In some regulations re-used and recycled materials are considered carbon-free. The material recovery goals for

[23] https://www2.deloitte.com/ce/en/pages/real-estate/articles/decarbonization-of-real-estate.html

[24] https://www.ecologie.gouv.fr/reglementation-environnementale-re2020

building and demolition waste set forth in EU legislation will be reviewed by the Commission by the end of 2024. The Commission will implement policies to expand platforms for reuse and recycling and encourage a solid internal market for secondary raw materials[25].

2.2 Real estate exposure to consumption risk and the yield curve of real estate discount rates: average return rates and long-run discount rates

To start with, real estate is an asset and it can be purchased through monetary investment and put up for rent to provide stable income on a regular time basis as cash flows. This insight is fundamental to understanding further considerations in this dissertation.

To show that real estate is sensitive to consumption risk, one should account for their index price changes during periods of crisis and welfare deterioration. According to Giglio et. al (2021), house prices rise on average three years before a crisis, peak just before the crisis, and fall by as much as 7% in the three years following the crisis's onset. This drop in house prices during crisis periods (such as global financial crisis), which are typically marked by high marginal utilities of consumption[26], justifies the riskiness of real estate as an asset. Similar conclusions are drawn for consumption disasters (Barro, 2006). Moreover, Giglio et al. (2020) discover a positive correlation between house prices and consumption by analyzing a database of twenty countries detailing house transaction series across history. This backs up evidence that real estate is indeed a risky asset: low payoffs in states of falling consumption and higher marginal utility of consumption. Furthermore, an analysis concerning expected rate of returns in average terms point to quite high results (5.5% to 7.4%), a result which should be cautiously taken since it clashes with the downward slope of the yield curve for housing discount

[25] https://single-market-economy.ec.europa.eu/news/eu-construction-and-demolition-waste-protocol-2018-09-18_en

[26] In Neoclassical economics, consumption is defined as the use of goods and services by a household. It is a component in the calculation of the Gross Domestic Product (GDP). Macroeconomists typically use consumption as a proxy of the overall economy [https://corporatefinanceinstitute.com/resources/economics/consumption/]

rates. Two methods are used: *the price rent approach* and the *balance-sheet approach*. The former starts from a price- rent ratio estimated in a baseline year and constructs a time series of returns by combining a house price index and a rental price index (suppose the housing stock pays dividends –i.e. rents). It then subtracts depreciation and maintenance costs and adjusts the expected rate of returns to match inflation. The latter consists in obtaining data on the value of the residential housing stock from countries' national accounts, i.e. price and the dividend as a net capital income for several countries including the US, the UK and Singapore. Despite the methods used, which won't be analyzed in detail, a 6% per year is found to be a robust result for expected rates of return. Growth rate o f rental income (indicated by g) is often below 1% and is subject to inflation. Long run housing discount rates were estimated in Giglio, Maggiori, & Stroebel (2015). They were able to unravel the value at which households discount future cash flows accruing over hundreds year horizon. This horizon is not random, indeed, it is the same amount of time it takes for benefits from climate change abatement measures to produce significant outcomes. Residential properties trade in these real estate markets as either freeholds, which are perpetual ownership contracts, or leaseholds, which are prepaid and tradable equity contracts with finite maturities, whose maturity may lats between 99 and 1000 years. The study estimates the present value of owning a freehold after the leasehold contract expires by comparing the respective prices of leasehold and freehold contracts for otherwise equivalent properties. This present value is therefore an indication of the long-run discount rate for real estate. They surmise that leasehold price discounts are inextricably linked to contract maturity and that discount rates of around 2.6% (meaning households are willing to pay less for a leasehold, all else equal) are required for cash flows over than 100 years in the future to match the data from both countries. The average rates of return for the housing market together with the long-run discount rates examination through ownership contracts help explain the shape of the term structure of discount rates (also known as yield curve) for housing asset which is downward sloping, unlike other types of asset and securities. The curve needs to be low at the long end, in order to match the 2.6% discount rate applied to the long-term housing claims. But it needs to be high enough at the short end to imply an average discount rate of 6%. In other words, the term structure of discount rates for the housing asset needs to be downward sloping in order to explain the data (Giglio et al. 2021).

2.3 Hedonic price model

The Hedonic Price Model approach, derived mainly from Lancaster's (1966) consumer theory and Rosen's (1974) method, implies that goods are characterized by their constituent properties; consequently, the value of a product can be calculated by summing up the estimated values of its individual properties. Since HPM offers a basis for estimating demand and prices for composite products, the method can be applied to estimate house prices considering the specific characteristics of housing units. Indeed, the heterogeneous nature of housing properties justifies the use of HPM to estimate their demand and value.

For this reason, HPM has been widely used in real estate and residential market research in the recent past. The application of HPM is further justified by the fact that the quantity and number of distinctive features of a particular housing unit influences the quality of the services provided. This composite extended model consists in three factors determining house prices, namely the structural characteristics, spatial attributes and temporal dynamics. In order to ensure producing non-distorted estimates, the model includes independent, identically distributed stochastic errors. Monocentric theory states that land value and distance from central business district within an urban context are the main variables affecting real estate market value. This theory assumes that all neighborhoods have the same characteristics. Multicentric theory has overcome the previous one and allows for spatial heterogeneity and autocorrelation. It indeed introduces spatial dependency between localization and district distinctive features and without special characteristics, the model would lead to inconsistent and distorted results. The inclusion of the temporal dimension makes it possible to capture the temporal dynamics of markets as well as volatile prices generated by a persistent trend in the economy or cyclical patterns. The conventional regression equation of the hedonic price, as far as the real estate market is concerned, consists of either the rent or the value of the house in relation to the characteristics of the housing units that influence the rent or the value respectively. The basic assumption of regression analysis also applies to this study, i.e., that the determinants of the dependent variable, i.e., rent, price or, in this case, value, are known precisely. The hedonic regression equation can take the form of a linear, semi-logarithmic (semi-log) or logarithmic (log-log) function. The most common is the semi-logarithmic (semi-log) form, which offers the advantage that the coefficient estimates are price proportions directly attributable to the respective characteristics (Cassel and Mendelsohn, 1985). The advantage of the logarithmic form is that the hedonic regression equation estimates elasticities with respect to each individual characteristic under consideration. However, no evidence shows the superiority of any functional forms. The variant of the model found to well approximate all the literature so far analyzed belongs to Freeman (1993), who defines the Hedonic function, HP as a combination of three vectors for location-specific environmental amenities (E_i), structural characteristics of the house (H_i) and characteristics of the neighborhood (L_i). Accordingly, the model can be written as:

$$HP = f(H_i; L_i; E_i)$$

(H_i) includes characteristics such as size of the property, number of bedrooms, availability of swimming pool, while L_i includes attributes such as accessibility to public services and recreational centers. E_i finally encompasses pollution level and distance from the risk area.

The model can be expressed in the general form:

$$HP = \beta_i \mathcal{X}_i + \mathcal{E}$$

With $\mathcal{X}_i$ being a vector of explanatory variables, β_i is the vector of coefficients which describe the implicit prices of the explanatory variable, and Ɛ is the “noise”, or error term. Subscript “i” refers to the single home sale transaction.

Dummy variables are used to capture temporal dynamics with which transactions occur. For example, if the list of residential transactions refers to the period from

1990 until 2010, the dummy for a house that was sold in 1990 takes the value 0, the dummy for a house that was sold in 2000 takes the value 10, and so on.

Ordinary least squares (OLS) is a linear regression technique widely used to estimate parameters in these models. The method relies on minimizing the sum of squared residuals - “distances” - between the actual and predicted values.

The signs of the estimated coefficients (also called parameters) could be positive if the characteristic has positive impacts on property values and negative if the characteristic contributes to reducing the house values.

2.4 Hazard exposure and evidence on asset values

In this chapter, the evidence from the literature based on asset exposure to specific climatic dangers or perils is summarized. In particular, literature concerning the link between housing market, commercial properties and floods, hurricanes, with a special mention to Hurricane Sandy, wildfires and the threat of sea level rise will be analyzed.

2.4.1 An introduction to floods

This brief introduction to flood hazard, he types, causes, and occurrence of floods in the United States and their unsustainable economic and social costs will help readers gain a better understanding of the phenomena treated in this dissertation. Evidence shows that around 40% of the 35,000 U.S. disaster events, in the United States only between 1980 and 2022 were major floods and related storms. U.S. national government spending on extreme weather is significant—about US$400 per household in an average year. Since 1983, national government disaster spending has topped US$1 trillion. Globally flooding is one of the most common, widespread, and destructive natural calamities, affecting approximately 250 million people each year and causing USD 40 billion in losses [NOAA, 2023][27]. Flood

[27] NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2023).https://www.ncei.noaa.gov/access/billions/, DOI: 10.25921/stkw-7w73

costs are typically not covered by homeowner insurance, and insurance usually pays only half of the damages. Overall, disasters impose a financial burden on taxpayers who finance disaster relief and subsidized government insurance, as well as individuals and businesses directly affected, as they have to pay for what insurance does not cover. Historically, emergency management has focused on the immediate and urgent aspects of a disaster, such as the response function of police, fire, emergency medical services, and civil defense personnel, preparedness, which includes advance planning and training required for emergency operations when a flood event occurs, and the post-disaster recovery period, during which damage is repaired. However, there is a fourth phase to emergency management: mitigation. The latter is defined "as actions taken to reduce risk to human life and property before the occurrence". Mitigation consists of structural, brick-and-mortar projects or nonstructural, chiefly land use actions which include planning and zoning, risk awareness education, and insurance. *Storm surge* is an unusual rise in water level in coastal areas above and beyond the regular astronomical tide caused by wind, waves, and low atmospheric pressure generated by a severe storm. *Storm surge* is extremely dangerous due to its potential to flood large coastal areas. Extreme flooding can occur in coastal areas, especially when storm surge coincides with normal high tide, resulting in storm tides of 20 feet or more in some cases. *Storm surge* frequently poses the largest threat to life and property from a thunderstorm along the coast. In the past, the rise of the ocean associated with many of the major hurricanes that have made landfall has resulted in high death tolls. Hurricane Katrina (2005) is a perfect example of the damage and devastation that can be caused by surge. At least 1500 persons lost their lives during Katrina and many of those deaths occurred directly, or indirectly, as a result of storm surge.

Climate change-related sea-level rise exacerbates hurricane damage and has devastating cumulative effects on communities. *Storm Surges*, also known as *Major flooding* mostly affects South Eastern US States, with Florida and North Carolina, being the most vulnerable. Another type of flood event is "*nuisance flooding*" or *coastal flooding* which is inundation that is becoming more common due to tides rather than weather. Low-lying roads, high tides, erosion, and flooded waterfront areas are becoming more common, with significant property damage. This type of hazards results in water damage to basements, automobiles, and public infrastructure, as well as contaminated groundwater. A flash flood is caused by a large amount of rain in a short period of time, usually less than six hours. *Flash floods* are typically defined by raging torrents that rip through riverbeds, urban streets, or mountain canyons following heavy rains. They can happen within minutes or hours of heavy rain. They can also occur even when no rain has fallen, such as after a levee or dam failure or a sudden release of water caused by a debris or ice jam. Most times, damage is exacerbated not only by heavy rain, but also by changes to the earth's surface caused by humans. In addition to rapid urbanization, farming and deforestation boost runoff, which floods areas that wouldn't otherwise flood. Careless construction in flood-prone areas, poor watershed management, and other human actions all contribute to increased flood damage.

Since 2000, riverine floods have indeed represented approximately 73% of all floods, flash floods for nearly 16%, and coastal floods for slightly less than 2% (the remaining 9% were not classified)[28]. Many flooding events, however, are difficult to categorize because they may entail more than one type of flooding (e.g. a tropical cyclone may cause coastal flooding as a result of wind-driven sea surge, flash flooding due to heavy precipitation accompanying the cyclone and potentially riverine flooding as the accumulated water enters the river system).

Although climate change will affect the occurrence, intensity, and frequency of floods as well as increase the pool of properties with vulnerability, the risk of flooding to homes and commercial properties (businesses) is not a new concern. Growing population and the concentration of assets in flood-prone areas have resulted in a significant increase in built-up areas vulnerable to flooding, as well as the magnitude of the impacts resulting from flood disasters. According to some estimates, more than half of the world's population will live within 100 kilometers

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[28] https://www.nssl.noaa.gov/education/svrwx101/floods/types/

of the coast by 2030 (McMichael et al. 2020). Furthermore, urbanization is to blame for the worsening of his condition since Rainfall absorption capacity deteriorates, and water runoff increases dramatically above what is expected on natural terrain. A key concept is that there are several channels through which property value is affected.

Large flood occurrences can also result in significant financial and economic repercussions for the government, businesses, and households due to indirect effects such as business interruption, loss of employment and output, and reduced tax revenues. In addition, impacts on businesses may consist in disruptions to supply chains, infrastructure services for water and power production, loss in demand for goods and services. Flood water in urban areas can become polluted with sewage, posing additional health risks and potentially higher clean-up costs. Damage to crops can impact food security in a country or region, even affecting global trade [FAO, 2015].

Moreover, the tourism industry may also be negatively affected by flood occurrences. Scott et al. (2012) wrote a paper about how residential holiday properties in the Caribbean (CARICOM) would resent the aftermath of 1 meter sea level rise resulting in inundation in the absence of adequate mitigation measures. The study concluded that up to 50% of these properties would be struck by this phenomenon.

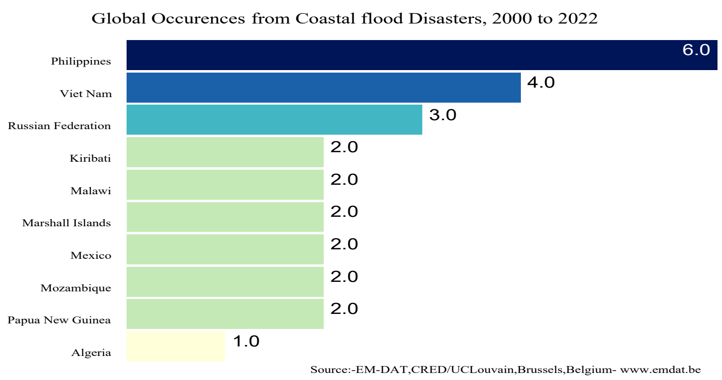

Figure 11-Global occurrence form coastal flood disaster , 2000-2022 [www.emdat.be]

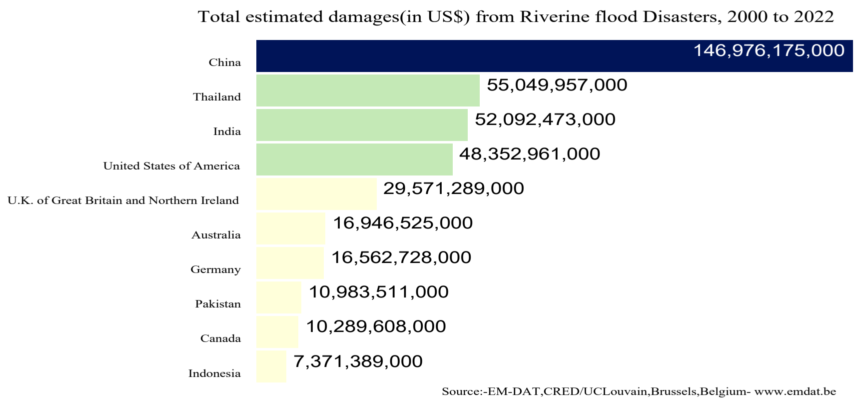

Figure 12-Total estimated damages in US $ from rivierine floods 2000-2022[www.emdat.be]

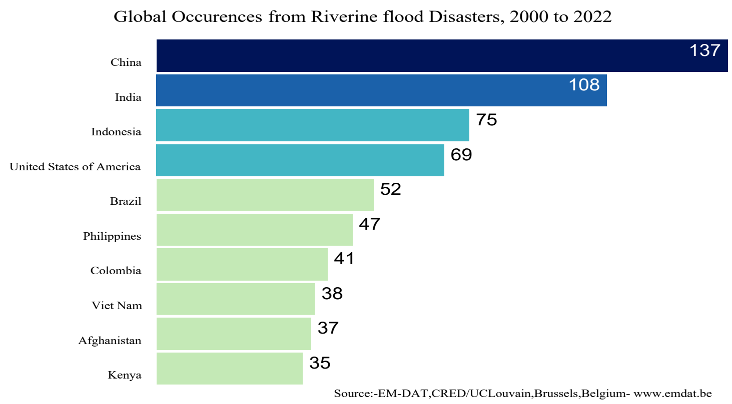

Figure 13-Global occurrence of rivierine floods from 2000 to 2022[www.emdat.be]

2.4.2 Analysis of existing literature regarding floods and residential/commercial market value

The greatest contribution for commercial properties in areas affected by floods are given by Bhattacharya-Mis et al. (2015). Their efforts are concentrated towards the indirect effect of flooding on affected communities in terms of economic downturn for the affected businesses, as well as the psychological and social drawbacks for the stakeholders (business holders). They stressed the cognitive and emotional processes within human behavior and investigated the flood risk perception of stakeholders as a driver for vulnerability of value. Vulnerability is defined as the capability of a system of restoring its initial condition, following the occurrence of a major event. Their research focused on linking the impact of flood risk on utility, desirability and marketability related to vulnerability of commercial property value in flood risk areas across England (Wakefield and Sheffield were considered). Both affected and un-affected respondents were surveyed using a *Likert style*, 16 statements- questionnaire, with scale agreement range of 1 to 5 where 1 indicates strong disagreement, 3 shows neutral attitude and 5 reflects strong agreement with the respective statement.

They proceeded to compute the median, as a central value indicator from the responses obtained with reference to the statements as well as an agreement index to show consistency amongst the answers, where ${S_x}^2$is the observed variance in ratings and ${\sigma_e}^2$is the variance of the population, from which the sample is extracted.

A spatial vulnerability model was applied to their answers to illustrate the distribution of vulnerable properties values on a GIS (Geographic Information System) platform.

$$r_{WG} = 1 - \; S_x^2 / \sigma_E^2$$

r_{WG} greater than 0,7 is an indicator of good agreement.

The model then transforms the responses into measurable criteria, which are weighted against each other and normalized to be unitless. A ranking of factors affecting vulnerability of commercial properties 'value is the final output.

To summarize, the study concludes that the vulnerability of value is well approximated by direct exposure to risk and expected direct impacts and, although cognitive factors are not always reflected by current market behavior, they are fundamental in understanding an asset performance in the long term.

There is however a deep knowledge gap between property holders and experts using more sophisticated tools to determine factors affecting assets' value.

In the context of flood risk valuation, two main criticalities arise. One is related to individual perception of risk which strongly differs from the objective probability of a specific risk.

This is named "perception bias" and leads individuals to overestimate low probability events and underestimate willingness to pay for risk. Revealed preference method is almost useless in this type of analysis.

Owing to this, Daniel et al. (2009) resorts to a meta-analysis performed on 19 studies and 117 point estimates, to investigate the impact of exposure to flood risk in terms of the implicit price differential of a house located in a flood zone. They discovered that a 0.01 increase in flood risk each year corresponds to a difference in selling price of an otherwise comparable residential property of -0.6% based on examination of the outcomes of pre- and post-flood incidents.

Another problem which is highlighted is "that there is a real danger of confounding positively valued water-related amenities with negatively valued exposure to flood risk. The way in which these countervailing effects have been incorporated and identified in valuation studies has to date been rather underdeveloped".[29]

The study also helps modeling the willingness to pay to reduce exposure to environmental hazards, which seems lower for wealthier residents.

Beltrán et al. (2018) focuses on residential properties and examines 37 studies ranging from U.S. and European markets. He found a range of price impacts from a -75,5% discount to a 61% premium for residential properties located in floodplains. "In an efficient housing market the price of property located inside the floodplain ought to be lower than the price of equivalent property outside.

"This price discount is interpreted as a measure of the benefits of a reduction in flood risk" (Beltrán et al. 2018).

However, the hedonic price function (HPF) analyzing transactions omits many aspects and tends to point towards a price premium rather than a discount for properties located in floodplains and coastal regions. This is why Beltran e al.

decides to extend the results of a meta-analysis performed by Daniel e al (2009), increasing the sample size of transactions and considering additional research papers. Moreover, Beltrán et al. (2018) resort to meta regression to consider the time elapsed since previous flood events, since the consequences of flooding may still be present and severely affect the analysis. This produces a considerable explanatory power to existing variables. By excluding coastal regions, whose amenity effect significantly distorts findings under the form of bias, they are able to capture a point estimate for the discount within a 100-year floodplain. The results show that properties trade at a -2,9% discount before the catastrophic event and down to -6,9 % after the catastrophic event, when dealing with inland flooding. On the other hand, as for a 500-year floodplain, properties are discounted at - 5,2%. Coastal regions are deemed unreliable as the amenity effect given by proximity to water leads to acute inconsistency (+37% premium).

Another aspect which emerges from the study is the magnitude of the discount immediately after the flood has occurred, with respect to a decay when time has elapsed.

Lamond et al. (2019) shift their attention on how different international regulatory regimes pursue flood risk mitigation for commercial property through the tool of insurance. Furthermore, they intend to prove the consistency of international approaches to the valuation of commercial property at risk." The availability of insurance is a material factor in the valuation of commercial assets" (Lamond et al. 2019).

Five countries (Australia, China, Germany, the USA and the UK) were selected and 72 local researchers from these countries with expertise in the field of environmental risk and flood risk management were interviewed.

Australia does not provide a clear definition of floods and, being a federal State, with autonomous national laws, it fails to produce a common mitigation strategy since all States have different risk profiles.

In China the law does not require a mandatory insurance against flooding and it is available at private insurers but seldom purchased.

"Germany adopts an all-risk policy covering direct damage to assets as well as losses due to business interruption" (Surminski & Thieken, 2017). "Flood insurance penetration in Germany has increased strongly in recent years, but is still low in comparison with other countries such as the UK "(Lamond et al. 2019).

Private businesses offer commercial property insurance in the UK, which is optional. All sorts of flooding are often covered by standard plans, and flood damage can also be covered by "business interruption insurance.

The US National Flood Insurance Program (NFIP[29]) provides that, "both commercial and residential properties located in the administratively-defined 100-year floodplain are required to carry flood insurance, with the cost of that insurance dependent on the elevation of the structures relative to the base flood elevation (BFE) and any mitigation that has been implemented."[National Flood Insurance Program-FEMA]

Interviews revealed that commercial property is more likely to self-insure and has a lower penetration of insurance compared to residential property. Commercial property is also less likely to have comprehensive coverage for flood risk. Professionals struggle with having a unified picture of risk due to heterogeneity in the commercial property sector and the importance of business location in some sectors. Investors may need to be aware of the volatility associated with such valuations because there is no standard methodology that valuation professionals employ to evaluate flood risk within or across national markets. When considering purchases, large UK investors are increasingly conducting due diligence on flood risk, according to Pottinger and Tanton (2014). This trend is being pushed by tightening regulations and the recurrence of major flood catastrophes.

Besides, Lamond e al (2019) cites lack of risk awareness of professionals and lack of appropriately detailed information on risk as two further critical barriers, which explains why any discount in market value is rather inconsistent

Hirsch and Hahn (2018) examined how flood risk affected Regensburg, Germany's rental rates and home values. They discovered that both variables were negatively impacted, however rentals were affected less severely than prices. They explained

[29] NFIP: The U.S. Congress established the National Flood Insurance Program (NFIP) in 1968 to help give property owners a way to financially safeguard themselves. NFIP will offer flood insurance to property owners, tenants, and business owners whenever their municipality or city participates in the NFIP. [https://www.fema.gov/flood-insurance]

this by comparing the commitments of owners and tenants to particular properties, with the former having only a temporary interest.

Miller, Gabe, and Sklarz (2019) [32] conduct a thorough analysis of the effect of water proximity on U.S. residential property prices. They examine whether home markets are adjusting to increased climate hazards as climate change becomes more definite by referencing and elaborating on a considerable empirical literature on valuing the amenity (location and/or view) component of waterfront proximity. This study makes use of a distinctive, substantial data set made up of residential dwelling transactions in 19 states with coastal sites between 2000 and 2017, in contrast to many earlier studies that concentrated on places in and around flood plains with a single metro region. The authors confirm that there are sizable premiums for waterfront vicinity, and that the positive amenity premium nets out the drawbacks connected to the potential risk of flooding or other water-related disasters, which vary depending on proximity to the water. They also discover that after significant storms, single-family home prices swiftly return to former macro trends with no long-lasting negative influence on value despite increased climate risk awareness.
One possibility is that insurance settlements might lessen the effect on value. According to the authors, government flood insurance schemes are underpriced and serve to artificially support housing markets that are more vulnerable to losses as a result of climate change. Other authors point to the inclusion of liquidity and prices which allow for adjustment of private assets' markets such as real estate in these studies. For instance, in the greatest risk regions of Baton Rouge, Louisiana, Turnbull et al. (2013) discovered lengthier selling times as well as price reductions for homes.

2.5 Hurricanes

Hurricanes, known generically as tropical cyclones, are low-pressure systems with organized thunderstorm activity that form over tropical or subtropical waters with winds of 119 kilometers per hour (74 mph) or higher. Tropical cyclones form in the middle of the ocean from an atmospheric disturbance, such as a tropical wave or a system of thunderstorms.

Owing to warm ocean waters, typically 80°F/27°C, an unstable atmosphere driven by differences in temperatures, moisture in air and little change in wind speed with height are all conditions to be met for a hurricane to form. Additionally the Coriolis effect causes the storm to spin and reach higher speeds when located at least 200 miles from the Equator. Scientists suggest that the resulting storm surge- is the abnormal rise in seawater level during a storm, measured as the height of the water above the normal predicted astronomical tide- poses a serious threat, especially when the hurricane makes landfall, i.e. when the center of the storm moves across the coast.

The surge is caused primarily by a storm's winds pushing water onshore. The amplitude of the storm surge at any given location depends on the orientation of the coastline with the storm track. Evidence pointing towards an increase in intensity of hurricanes and a decrease in travel speed is mounting and this is due to warmer sea surface temperatures and changes in the atmosphere. Hurricanes are powered by the release of heat when water that evaporates from the ocean's surface condenses into the storm's rain. A warmer ocean causes more evaporation, resulting in more water available to the atmosphere. A warmer atmosphere can hold more water, allowing for more rainfall. More rain translates into more heat released, and stronger winds consequently. Higher wind speed and more intense rainfall is one of the consequences of global warming, the other being higher surge resulting from higher sea levels. The water height is relentlessly increasing, and the resulting surges may be higher as more water is pushed onto land (Mendelsohn et al. 2012). There is yet no clear evidence of an increase in the frequency of these phenomena. Literature surrounding the topic is scarce and mostly stemming from research within US universities, since these phenomena remain limited to the Caribbean and Southeastern United States only. Since 2000, there have been progressively more intense hurricanes, such as the 2005 Hurricane Katrina which caused enormous destruction and significant loss of life. It was indeed responsible for 108 billion dollars damage and approximately 1800 fatalities. Hurricane Sandy occurring in 2012 comes second in the ranking in terms of victims and damage caused, 233 people and 70 billion dollars respectively. The analysis includes effects on hurricane on market factors such as prices, value, insurance premia, associated to both commercial and residential properties and based on investors' perception of risk.

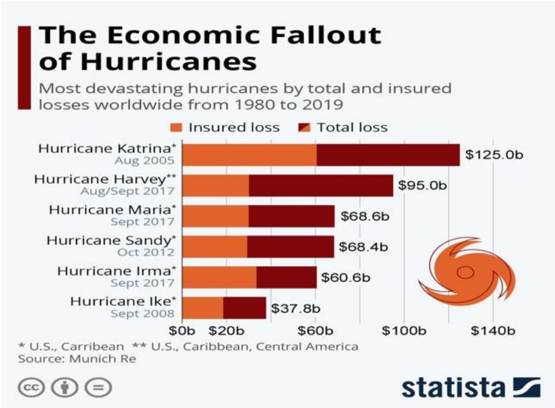

Figure 14-The economic fallout of hurricanes [https://www.statista.com/chart/10845/economic-fallout-of-hurricanes/]

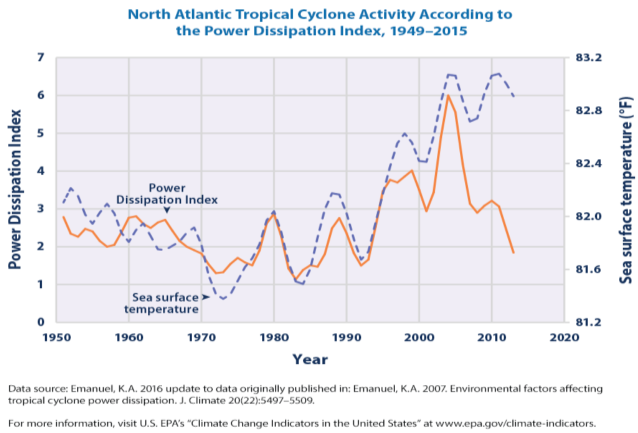

Figure 15-North Atlantic Cyclone activity according to power dissipation index [https://www.epa.gov/climate-indicators/climate-change-indicators-tropical-cyclone-activity]

2.5.1 Literature on hurricanes

An early contribution to how housing prices are negatively impacted by hurricanes is that of Graham et al. (2007). High transaction costs and condensed information flows make real estate goods relatively illiquid, thus lowering real estate prices' capability to capture significant information. This is in net contrast with securities market, more liquid and sensitive to market dynamics. They consider a strike of hurricanes, from 1996 up to 1999 on a Cape Fear Region, North Carolina. "They estimate the impact on the logarithm of real prices from factors such as time (a time series from 1996 extending up to 2002 is assumed) and macroeconomic variables”. Their findings show that, while the first two hurricanes (Fran and Bertha) were perceived as rather random events, leading to no major shocks in the housing market, the latter two (Bonnie and Floyd) significantly affected market expectations and the overall property owners’ perception about catastrophic events. To strengthen this statement, they performed a Chow test, by computing the F-statistic showing whether the difference between the time periods considered in the analysis is significant. The test yields an F-calculated value higher than 2 (2.21, and 2.45) in the period following February 1999 and April 2000, and a p-value of around 0 (0.06 and 0.08). One cannot reject the null hypothesis according to which the structural shift in the house price computation has eventually occurred.

Murphy and Strobl (2009) argue that hurricane strikes lead to a raise in real house prices by approximately 3 to 4 % up to three years after the occurrence. This result is explained by the unavailability of housing stock, which is higher than the displacement effect of residents, driving up housing prices. They also discovered an indirect negative effect, albeit small, on local incomes. They construct a hurricane destruction index taking into account wind speed relative to damage and the lifetime of the storm. Gathering data for housing price index, as well data about income (per capita, local and personal), they found that two major consequences arise. To start with, there is property destruction, with property losses net of related insurance claims being included as one-time effects. The amount of uninsured losses, calculated by the consumption of fixed capital minus business transfers, is subtracted from proprietors' income and rental income in this regard. Natural disasters are also likely to impede the flow of income into the economy since they stop regular economic activities.

Below et al. (2017) conducted a thorough investigation of how housing prices responded to storms along the coast of North Carolina from 1996 to 2012 and discovered a price discount of about 3.8 percent in the first 60 days after a storm, dissipating right after. This is in line with the literature analyzing floods which reveals a temporary negative reaction on housing prices that ultimately disappears as time goes by.

Fisher and Rutledge (2021) gathered data from the National Council of Real Estate Investment Fiduciaries (NCREIF) on 30 years time span (from 1989 until 2019) and on five types of properties, namely office, retail, apartment, industrial, and hotel. They analyzed around 400,000 property observations (cross sectional and time series) across the United States. After taking into account any additional capital expenses for repairs, they discovered that there has been a noticeable difference between locations that were and weren't affected by hurricanes in terms of the value and rates of return for properties located in those areas. Their model encompasses variables for the property square footage, square footage squared, property age, and age squared and it leads to regression results for cumulative property value change eight months after the hurricane. According to the findings, property values climbed by 3.2% per quarter, or 25.9% less than values of properties that were not affected by a hurricane, throughout the eight quarters that followed the hurricane quarter. Up to 3 years (or 12 quarters) after the hurricane, the influence on value is still negative, but after that point, it starts to fade, and values begin to recover 5 years (or 20 quarters) after the hurricane. The study also focuses briefly on the cumulative returns from one to five years after the hurricane, highlighting how retail and apartment properties were more resilient with respect to office, hotel, and industrial still experienced a cumulative negative impact on the capital return.
Once again, the impact extends beyond the direct damage to the property. Institutional investors may be reluctant to allocate capital to an area where the risk of storms is thought to be higher, since it might have a detrimental influence on property values and returns long after the cyclone has passed.

Taspinar and Ortega(2018) examine the impact of Hurricane Sandy on the New York City housing market, starting from a dataset for the 2003-2017 period, providing a difference in differences[30] estimate on properties located in neighborhoods that were directly affected by the storm as well as unaffected ones. Their research shows that the depression affecting housing prices is permanent up to a certain level, which in turn reflects the increased perception of risk from living by the ocean.

This extends to properties which did not suffer direct material damage but are equally at risk of being flooded.

Thanks to accurate information from FEMA[31], they were able to pin down which building structures suffered the most and to what extent in five neighborhoods, Queens, the Bronx, Manhattan, Brooklyn, and Staten Island. Detailed aerial imagery helped determine point-damage estimates and report damage level for all buildings due to flooding (320 thousand observations roughly) and subsequently encapsulate it in a time variant variable "*DMG COMBO*". Another FEMA dataset was used to estimate the storm surge and provide the accurate level of flooding at each point using a geographical breakdown technique. This information is then coded into a variable called "DEPTH".

Furthermore they were able to include the varying threat levels of coastal flooding subdividing the city in 6 evacuation zones, with zone 1 being the one with the highest risk and zone 6 the one with the lowest risk thanks to cartesian coordinates. Since each dataset was based on different systems of geographic coordinates, the merging process was quite challenging as well.

The model used considers a (i,z,t) observation, with i being the individual apartment and z the neighborhood and t, the quarter or year and the purpose is that "to compare the price trajectories of three sets of housing units, before and after hurricane Sandy, to each other and to housing units that were not affected

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30 Difference-in-differences: the difference-in-differences method is a quasi-experimental approach that compares the changes in outcomes over time between a population enrolled in a program (the treatment group) and a population that is not (the comparison group) [https://dimewiki.worldbank.org/Difference-in-Differences]

31 The Federal Emergency Management Agency (FEMA) is an agency of the United States Department of Homeland Security (DHS), whose primary purpose is to coordinate the response to a disaster that has occurred in the United States and that overwhelms the resources of local and state authorities. FEMA was created in 1978 under President Jimmy Carter and it commands an annual budget of roughly 14 billion USD [https://www.fema.gov/it]

by Sandy in any way". The model regresses the natural logarithm of housing prices against the perceived and effective level of damage caused by the cyclone, represented by three dummy variables," *Dam0i, Dam1i, and Dam2i"*. They claimed that after the storm, the value of damaged properties fell significantly (17–22%), followed by a partial rebound that probably reflected their slow rehabilitation. The slow appearance of a price penalty among houses in flood zones that weren't destroyed by Sandy, which reached 8% in 2017 and showed no indications of recovery, is however a remarkable outcome.

Addoum et al.(2021) concentrate on the commercial real estate market in the United States to investigate how savvy investors adjust property values in response to a sudden change in the relevance of flood risk. Their empirical analysis required commercial property transactions from the rich Costar data provider, as well as data on flood risk exposure, captured by coastal proximity and elevation and also damages from storm strikes. The study involves three relevant commercial markets, namely New York, Boston and Chicago and considers waterfront properties only. New York was directly impacted by Hurricane Sandy's landfall with conspicuous physical and economic damage, while Boston is included to capture the effect further up North along the East Coast. Chicago lies on the banks of Lake Michigan and therefore is a waterfront location, largely unaffected by the cyclones due to different climate conditions. The inclusion in the empirical analysis serves as a placebo test[32] to support the assumption according to which changing investors' beliefs on risk exposure are the sole driver for the change in the hedonic price associated to proximity to the coast. In other words, this is necessary when considering other preferences affecting the value of coastal locations such as amenity which would lead to statistically irrelevant results. Through their OLS regression model they were able to analyze transaction trends prior and after Hurricane Sandy separately and then apply the same model to the residual price difference, which varies with coastal proximity. They find that," all

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[32] Placebo test: A placebo test checks for an association that should be absent if the research design is sound but not otherwise. Placebo tests can thus be seen as a strategy for checking the soundness of a research finding and, more broadly, improving causal inference.
[https://statmodeling.stat.columbia.edu/2018/09/26/potential-big-problem-placebo-tests-econometrics-theyre-subject-difference-significant-non-significant-not-statistically-significant-issue/]

else equal, a one-mile increase in proximity to the coast is associated with 21.6% slower price appreciation among New York transactions completed after Hurricane Sandy relative to those completed before the hurricane" (Addoum et al. 2021). As for Boston, the results suggest that "a one-mile increase in proximity to the coast is associated with 9.5% slower price appreciation after Hurricane Sandy". Consistent with expectations, price penalties in New York are larger than those for Boston. This finding suggests that, even before a local hurricane strikes Boston, proximity to the shore has a major impact on the appreciation of commercial property prices. They explain this portion of the effect to heightened salience and perception of flood risks, given the lack of tangible damages in Boston.

Cohen et al. (2021) on the other hand applies a difference-in differences approach to quantify the negative shocks induced by hurricanes on residential single-family real estate property values in non-flooded areas, extending beyond the FEMA designated flood zones in New York City[33]. Owing to this only four boroughs in New York are considered. Specifically, their difference-in-differences approach examines how prices of non- flooded properties are influenced by the distance between the storm surge and the flood zone, following the storm. They stress the fact that, hurricanes can provide housing market participants with new information about possible flood risks and in turn, this information is capitalized. They restrict the analysis to the observations lying between 0,03 miles and one mile of the storm surge originating from the hurricane.

They use the differential between the shock's occurrence and the FEMA border, subject to exposure as their primary method of identification. Therefore, separating overall neighborhood damage and damage to single housing unit is not immediate

This leads to introducing two control variables, one referring to the short term surprise, and the other pointing to long run exposure. The coefficient estimate for the short-run negative shock is statistically significant and positive, suggesting that

[33] 100-year floodplain maps are FEMA-designated regions that have a 1% chance of being flooded each year [https://www.usgs.gov/special-topics/water-science-school/science/100-year-flood]

a negative surprise causes prices to decline. The decline in prices fades away with time elapse, indicating that the surprise effect is somehow brief while a sustained depression may be caused by a change in the exposure.

Final conclusions lead to similar results to those of Ortega & Taspinar (2018), despite Cohen's 20 % average discount, much greater than the 6% decrease for a one mile negative shock. A point which is necessary to highlight though is the former's focus on flooded properties rather than un-flooded ones.

Kim & Peiser (2020) explicit the link between storm frequency and intensity and housing prices in Miami Dade County over a thirty-year period (1987-2017). Data regarding sales transactions for single family housing were extracted from the Miami-Dade County's Open Data Hub and Florida Department of Revenue. The dataset was then pruned to account for outliers, "such as homes with more than 10 bedrooms, lot sizes greater than 5 acres, no bedroom unit, zero transaction price, and price less than $10,000 or more than $10 million"(Kim & Peiser, 2020). Detailed information about hurricanes occurring over that period were collected from NOAA. A classification of homes into three flood hazard zones (100-year, 500-year, non floodplains)

The analysis also encapsulates variables related to amenity such as road proximity and points of interests as well as oceanfront view. Through the assessment of price changes due to hurricane frequency on different risk exposures, a hedonic single panel data pricing model accounting for d geospatial data was employed. Two major considerations emerge from the analysis. The first one refers to vacational occupants, having a different risk attitude in contrast to permanent occupants. The other being related to the combined effect of market cycles associated to housing transactions which may lead to biases. To correct for this anomaly, a measure of the elapsed time of sales from each storm strike, is provided and captured by a market factor.

Results finally substantiate that "the effect of stronger hurricane frequency and intensity is negatively capitalized into home sales price" (Kim & Peiser, 2020). According to the study, each extra hurricane is associated with a 1.3% decline in housing prices, and the negative correlation is stronger for higher risk zones.

Gibson and Mullins (2020) report that “Hurricane Sandy flooding decreased house prices by 5 to 7 percent for minimally inundated properties, and 8 to 13 percent for properties that experienced average inundation”. Furthermore they analyze the effect of inglobating more properties inside new, updated, post-Sandy FEMA maps resulting in a 7-8 percent sales price decrease. They stress, however, how the effect of new flood plain maps on properties flooded by Sandy was virtually negligible, while the effect on properties not flooded by Sandy, but now in the floodplain, was estimated to be between 12-23%. This suggests that while updated maps don't offer any new information for properties affected by Sandy's flooding, they did lead to a reassessment of risk for houses that were previously outside the floodplain.

2.6 Sea level rise

Since 1880, the average sea level has increased by around 8 to 9 inches (21 to 24 centimeters). The melting of glaciers and ice sheets and the thermal expansion of warm seawater are the main causes of the rising water level. Global mean sea level reached its highest yearly average in the satellite record in 2021, rising 97 millimeters (3.8 inches) above 1993 levels (1993-present).

Even if greenhouse gas emissions remain on a relatively modest trajectory in the following decades, the global mean sea level is anticipated to rise by at least one foot (0.3 meters) above 2000 levels by the end of the century. Humans have always been drawn to coastal areas because of their abundance of rich and sustainable resources, easy access to marine trade and transportation, and natural interface between land and water for recreational or cultural activities. Global coastal urbanization has increased dramatically in recent decades, and this trend is expected to continue, resulting in significantly higher population density in coastal areas than in non-coastal areas. According to Xie & Tang (2021), around 10% of the world’s populations (more than 600 million people) live in coastal regions with just 10 m elevation of current sea level.

Nearly 30% of Americans reside in coastal areas with large population densities, where floods, shoreline erosion, and storm-related risks are all influenced by sea level. At present, almost 50 million people in Europe live in the low elevation coastal zone (LECZ) and more than 200 million people live within 50 km from the coastline. The majority of the people (70%) living in the LECZ are located in the Netherlands, Germany, UK, Italy, Spain, and Russia.

According to the U.N. Atlas of the Oceans, eight of the top ten largest cities worldwide are located close to a shore. Global mean sea level is rising as a result of global warming in two different ways. First, ice sheets and glaciers around the planet are melting and replenishing the ocean with water. Second, as the water gets warmer, the ocean's volume grows. Aquifers, lakes, reservoirs, rivers, and soil moisture all contain liquid water; their loss is a third, much less significant cause of sea level rise. Groundwater pumping[34] is largely to blame for this movement of liquid water from the land to the ocean.

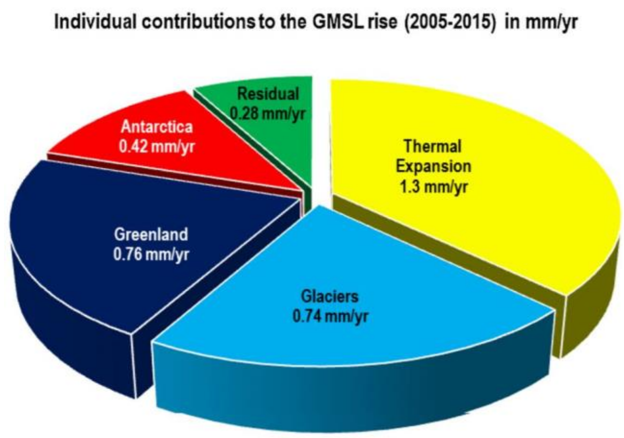

Figure 16-Individual contributions to GMSL rise in mm/yr from 2005 to 2015[Cazenave et al 2018]

2.6.1 The impact of sea level rise on the residential market

Most papers tackling the sea level rise effect on housing market are based on empirical analysis considering the value and price impacts which are nowadays observable in communities living along coastlines. Prior studies, though of a more

[34] Groundwater pumping consists in extracting water from water-bearing sand strata in the ground. Water pumps are used to provide high irrigation efficiency by supplying proper amount of water to every area of the field to gain speed in cultivation [https://www.usgs.gov/special-topics/water-science-school/science/groundwater-decline-and-depletion].

theoretical nature, failed to predict how properties were being affected, since they pooled different data related to degree of inundation, timing of sea level rise manifestation as well as varying estimates on costs and mitigation measures. Another factor which may lead to divergent results and an overall lack of consensus amongst studies is the degree of perceptions and beliefs about climate change. It is paramount to mention that Sea level rise is a future risk, whereas other considered are actually experienced, and thus more tangible.

Bin et al. (2011) consider four counties in North Carolina, a State which is deemed vulnerable to sea level rise, over a fifty years timespan- considering possible observations occurring in 2030 and comparing those to 2080- and three different scenarios of SLR for each year observed (low, medium, high). They argue that northern counties are significantly more exposed to potential losses, estimated to reach 9.45% of the overall property's value in Dare County, whereas losses of less than 1% of total value would be recorded in southern counties such as Bertie and New Hanover. In broader terms, total losses affecting properties located in the four counties would amount to 179 million $ in 2030 only, considering the medium scenario, neglecting the discounting effect. They also found a three times larger value loss in 2080, keeping other factors unchanged. This loss in value is mainly attributable to inundation and shoreline erosion and reflects the lack of mitigation and adaptation policies. By employing Rosen's hedonic price model, they were able to regress the natural logarithm of property value against a spatial weighted matrix based on Euclidean distance between the properties and the shoreline and environmental amenities, such as waterfront location which generally lead to price premia. This study, characterized by a predictive nature, tends to neglect important aspects, such as public infrastructure and adapting behaviors within coastal communities. Although they did not prove that SLR risk is currently priced, they could however highlight the potential losses it may drive to without mitigation actions such as beach nourishment and seawalls and adaptation actions such, namely retreat.

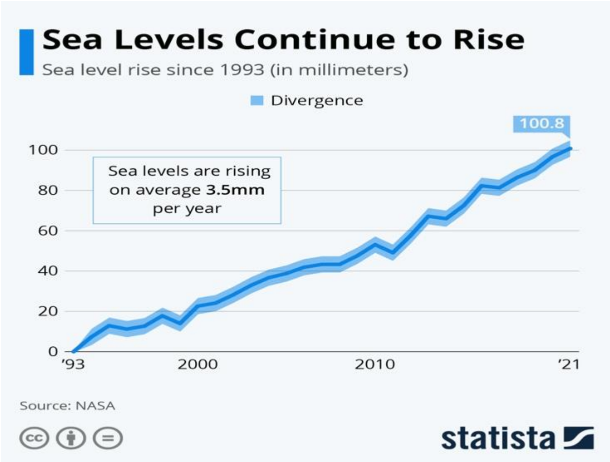

Figure 17-Sea level rise since 1993 [https://www.statista.com/chart/27581/rate-of-rising-sea-levels/-Sea level rise since 1993]

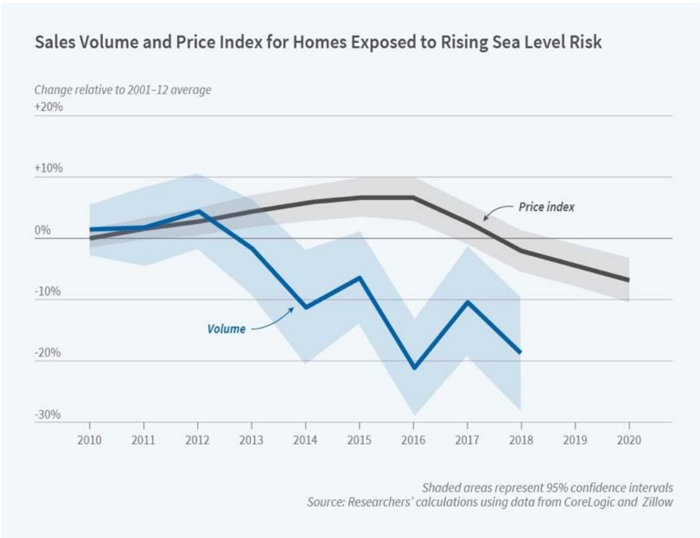

Figure 18-Sales volume and price index for homes exposed to sea level rise[es volume and price index for homes exposed to sea level rise]

Almås & Hygen (2012) extends the study to public infrastructure and estimates that the overall costs for Norway to address sea level rises in the construction of buildings could reach 725 million euros without factoring in government expenses. The study demonstrated how complicated uncertainties make it difficult to predict any changes in the value of SLR, similarly to Bin et al. (2011).

In their Florida study, Fu et al. (2016) go a step further and argue that a pure economic cost analysis does not take into account broader socio-economic consequences, such as loss of amenity and loss of wetlands, with the resulting impacts on biodiversity. They stress how their special hedonic model may be helpful to local coastal planners and managers in determining the possible financial impact of sea level rise and supporting decision-making for adaptation. Following the line of similar research, Keenan et al.(2018) detect “patterns of settlement and investment which point to Climate Gentrification”. They identify a significant redistribution of capital and population residing within Miami Dade county from lower elevation areas to higher elevation area, less prone to tidal flood risk due to sea level rise. This retreat is consistent with an adaptation measure and is able to produce remarkable shifts in residential market demand, notwithstanding the wealth that most households tie up to the purchase of real estate, which counterbalances this phenomenon. Higher elevation in flood prone areas is helping homes appreciate at a faster rate. Despite this finding, the authors remind that other locational desire factors might add and that investors should be fully aware. This paper is doubtlessly revealing the importance of the role played by municipality when dealing with adaptation, much in line with Fu et al. (2016). McAlpine & Porter (2018) [51] make use of historical transactions in Miami Dade county, covering 2005-2016 timespan to estimate the actual lost dollar per square foot and controlling for macroeconomic variables, house features and amenities. As expected, they find a negative impact from forecasted inundation levels on properties’ value, especially if compared to similar unaffected properties, which likewise underwent value changes. This translates into almost 500 million US dollars market value loss in Miami Dade county over the period considered. By combining recent trends and future forecasts, they find that homes predicted to experience tidal flooding in 2032 have lost $3.08 annually on every square foot of living space, while properties close to roadways predicted to experience tidal flooding in 2032 have lost $3.71 annually on every square foot of living space. This study is important because it encompasses a focus on nearby roads which may be directly be flooded and therefore adjacent properties. Xie et al. (2021) investigate over parcel-property sea level rise impact in a specific urban context, that of Tampa, Florida and they seek to predict future locations, exposed to flood and the related damage costs, resorting to property maps and high resolution digital elevation data. Through the comparison with satellite altimeter data, they obtain a thorough sea level prediction, and they are, therefore able to pin down the most to-be vulnerable commercial as well as residential areas, within the Floridian coastal city. By applying three different sea level rise acceleration scenarios, they estimate the number of flooded properties as well as the total land area in million square feet for the years 2030, 2050, 2070, 2100 and 2150. Both direct costs and indirect costs, including housing pricing surge due to higher demand, contractor's company bankruptcy and financial constraints that would impede reconstruction due to unavailability of land, are all accounted for. Results for 2030 seem all but encouraging, with almost 16,000 million square feet of land being inundated and 8,400 million dollars worth of damages, thus prompting the local government to take action.

In another recent study, Taylor and Aalbers (2022) highlight how Climate Gentrification is sparking urban changes and uneven development in Greater Miami through financialized climate risk management practices, which further accelerate this phenomenon. Historically, wealthier populations have owned highly desirable waterfront properties and lower income populations have lived on the "less desirable" land inland and at higher elevation from the coast. Waterfront properties are now experiencing an increased risk of flooding due to sea level rise, storm surge, heavier precipitation, and stronger hurricane force winds during landfall. In response, some coastal property owners invest in higher seawalls; others rely on flood insurance with higher premiums to be able to stay in place. Others choose to move to higher elevation properties further inland to minimize their risk of flooding. Increased demand for higher elevation properties directly impacts the property values in these areas, which were historically occupied by low-income residents. As wealthier residents move in, existing residents are priced out and cannot afford to live in their communities any longer. "The impacted communities are dealing with housing affordability and also experiencing loss of community identity and cultural disruption".

Taylor & Aalbers (2022) start from the rent gap theory, developed by Smith and according to which, "the rent gap refers to the difference between the current value of land and the future value if that land is brought to its so-called highest and best use through improvements (e.g., by upgrading the asset on it)". This concept helps capture the changing nature of gentrification across time and space. They extend this theory to better explain the dynamics underlying gentrification by introducing two concepts, those of *risk rent and risk at rent.* Both are strategies played by real estate and financial institutions to extract rents from buildings and properties to the detriment of third parties and with the purpose of extracting above average rents. The creation and capture of new increments of economic value in relation to climate risk is referred to as *risk rent*. The most obvious example is property insurance underwriting, which markets real estate climate risk via annual policyholder premium payments. Rent at risk refers to existing or anticipated rent increases that may be lost due to climate risks or their management and includes the above said industry concerns about the prospects of higher capital and operating expenditures, direct losses incurred by damages to property, and declining potential markets for assets in risky property markets.

An interesting contribution also stems from Heberger & Cooley (2011) who stress the socio-economic and demographic impact of sea level rise on residents along the California coastline, an area subject to considerable urban development and population density. This study assesses the potential threats posed by anticipated sea level rise to the existing people, infrastructure, and property if no measures are taken to safeguard the coastline. The Intergovernmental Panel on Climate Change's (IPCC) medium-to-high greenhouse gas emissions scenarios were employed to generate the sea level rise scenario, which does not, however, represent the worst-case scenario for sea level rise. They interestingly found that a correlation between risk exposure and households' income and racial ethnicity with lower-income African Americans being more affected by the phenomenon in the Counties of San Mateo and Orange. They also argue that "$100 billion (in year 2000 dollars) worth of property is threatened by increased probability of coastal flooding". Their paper, however does not discuss in detail which adaptation and mitigation measures ought to be taken to address SLR. It must be emphasized that, despite the detailed cost analysis, no impacts on market value are mentioned in this study.

Moreover Beck & Lin (2020) adopt a similar hedonic price model to study the effect of sea level rise on properties located in Savannah, Georgia. They restrict their analysis to comprise homes with age of two years or greater, selling for at least 50,000 $, in order to clean their dataset. A sample of almost 35,000 homes is considered for this purpose as well as physical features for the standard property, time of sale characteristics and factors controlling SLR risk.
By using MLS home transaction data from 2007 until 2016, they find a 3.1 percent price discount for homes at risk, which becomes more statistically relevant for later sample periods (2012-2016 instead of 2007-2012), thus reflecting raising climate risk awareness amongst homeowners. Tyndall (2020) performs a similar analysis on a dataset of repeated home sales from 2000 until 2017 in Long Island, New York, to assess how future sea level rise projections are causing a slower price appreciation to properties considered at risk, in comparison with risk-free properties. According to their model:" Properties within three meters of current sea level were found to have annual price appreciation that was 1.2 percentage points per year lower than unexposed homes" (Tyndall, 2020). This paper provides insight on a much debated topic, that of risk information held by real estate investors on climate risk. He surmises that, in a context of perfect information, the appreciation penalty would be more significant, since investors and stakeholders would internalize the purported risk in their evaluations. The study concludes by stressing how the information gap can be overcome with the intervention of governments during the purchase process.

Walsh et al. (2019) show that, despite the depressing nature of SRL impact on housing prices, when no adaptation measures are taken, the construction of physical barriers can lead to significant premia. Based on geo-spatial analysis of adaptation measures location, as well as real estate transactions and mean sea level rise projections in a Maryland State County, they could assess whether four types of adaptation structures, namely breakwaters, groinfields, riprap revetments, and bulkheads had any impact on residences located along the shore. An average 20% decrease in home prices is recorded for unprotected homes, while positive interactions between SRL level zone scenarios and structure variables are found. More specifically, more realistic scenarios are related with statistically significant price premia, when structures are adopted, while coefficients are close to zero when the SLR scenario is too far-fetched. This means that, no matter the measures adopted, their benefits are not yet internalized by real estate investors. Price premia are of the magnitude of 9% to 12% for 0-2 foot SRL zones according to the proposed breakdown zone classification. This paper highlights how mitigation can lead to value enhancement and how resilience in property prices may in turn help local municipalities.

Exiting the American real estate market, there is also salient literature regarding the Australian real estate market. As of September 2022, the total value of residential dwellings in Australia amounts to $9,674.4 billion - or about one-third of Australia's GDP- with a mean price of $889,800 [Australian Bureau of Statistic, 2022]. The most relevant paper to be analyzed is that pertaining to Myers et al.(2018). The paper concludes, based on predictions of various SLR scenarios that are likely to impact Melbourne, that substantial value loss will be incurred, not only directly due to total inundation loss, but also indirectly due to repair costs, overall drop in demand, demand-supply mismatches, civilian casualties, and environmental degradation. It acknowledges that, despite the obvious repercussions for real estate, private property stakeholders have provided little thought, interaction, or action. As a result, the risks have not yet been priced in. Results show that, in a flat water and 1 meter sea level rise scenario only 0.3% of total properties would be affected, however the effect may be more intense when also including tides, wind, heavy precipitation storm surge. The clear articulation of the costs, that will result, which collectively are likely to lead to expensive insurance or even unavailable, and raise taxes to cover mitigation and adaptation work, could prove useful to investors. Cooper and Lemckert (2012) paper focuses on planned adaptation measures, compared to ad-hoc measures, to be implemented in the coastal city of Goald Coast, Queensland, Australia, following three SLR scenarios, 1 meter, 2 meters, 5 meters. This popular tourist destination is known for its sandy beaches and kind weather and offers many recreational activities to vacationers throughout the year. They conclude that, for the lowest scenario a carefully planned and advanced strategy may be adopted, inducing a positive externality on very demanding residents and holidaymakers, without compromising the local real estate market in terms of affordability. They stress the centrality of the waterfront location to the existence of the resort city and highlight how there may be some constraints when trying to build defence mechanisms, not to spoil the attractiveness of the environment. They also mention how resort cities, are of marginal relevance when compared to major business centres, which are the number one priority for policy makers.

2.7 Wildfires: an overview

Climate change, including increased heat, prolonged drought, and a thirsty atmosphere, has been a major contributor to the risk and extent of wildfires in the western United States over the last two decades. Several factors, including temperature, humidity, and the lack of moisture in fuels such as trees, shrubs, grasses, and forest debris, must be in sync for wildfires to occur. All of these variables have strong direct or indirect links to climate variability and change.

Drought and persistent heat set the stage for extraordinary wildfire seasons from 2020 to 2022 across many western states, with all three years far surpassing the average of 1.2 million acres burned since 2016[35].

According to Zhouang et al. (2021), the increase of vapor pressure deficit (VPD[36]) would be the main cause of increase wildfire activity. However, the extent to which an increase of VPD is due to natural variability or anthropogenic warming has been unclear. Their estimates based on observation indicate that roughly one-third of the VPD trend is attributable to natural variability of atmospheric circulation, whereas two-thirds is explained by anthropogenic warming.

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[35] NOAA.GOV-Wildfires https://www.noaa.gov/noaa-wildfire/wildfire-climate-connection: NOAA stands for National Oceanic and Atmospheric Administration.

[36] VPD Vapor pressure deficit (VPD) measures how much water is in the air versus the maximum amount of water vapor that can exist in that air, what's known as the saturation vapor pressure (SVP). As air warms, its capacity to hold water increases.

In addition, climate models attribute 90% of the VPD trend to anthropogenic warming.

Despite lying outside the scope of this dissertation, there exists a relatively broad range of literature that has examined the relationship between wildfire behavior and factors, including climate and weather, topography, land use and land cover, socioeconomics and demographics. Damages from wildfires include direct losses such as deaths, injuries, and structure damage along with indirect damage such as business interruption, utility loss, and ecosystem impacts.

Thomas et al. (2017) discuss the losses and costs associated to wildfires, mainly focusing on US data drawn by the National Interagency Fire Center (NIFC), which provides data on the annual annual estimates of the number of acres that were burned in wildfires. Runoff from a wildfire-cleared area may eventually wind up in a waterway in many cases. This has the potential to harm the aquatic ecosystem as well as water treatment facilities and other communities exploiting the watershed. As of 2021, there is no comprehensive database tracking the number of structures burned and the value of property damaged. For the year 2016, an estimated 617 million $ was lost due to wildfires. Wildfire can have a variety of effects on soil properties. Consuming the surface organic layer, exposing mineral soils, transforming nutrients, accumulating ash, soil particles lacking binding organics, and water repellency are some of these effects. Human health consequences, such as smoke inhalation, post-traumatic stress and anxiety as well as severe burns are also accounted for with varying precision and assumptions. A large catastrophic event can cause significant damage to the region's infrastructure. While direct damage is classified as a direct loss, there are secondary effects that result from infrastructure failure. One example is business interruption; however, lost infrastructure can also cripple transportation, power, water, public safety and health safety, and telecommunications. For example, in August of 2015 fires in Oregon and California left thousands without power. Impact on housing market will be analyzed in the next section.

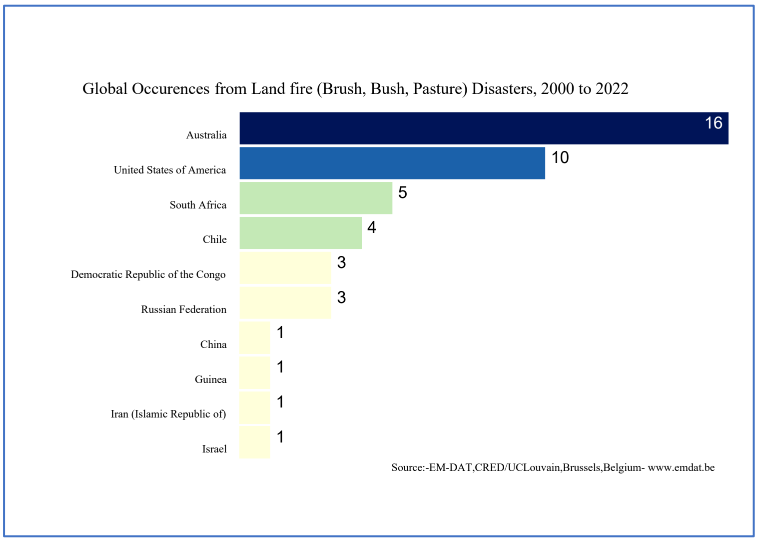

Figure 19-Global occurrence from land fire from 2000-2022[www.emdat.be]

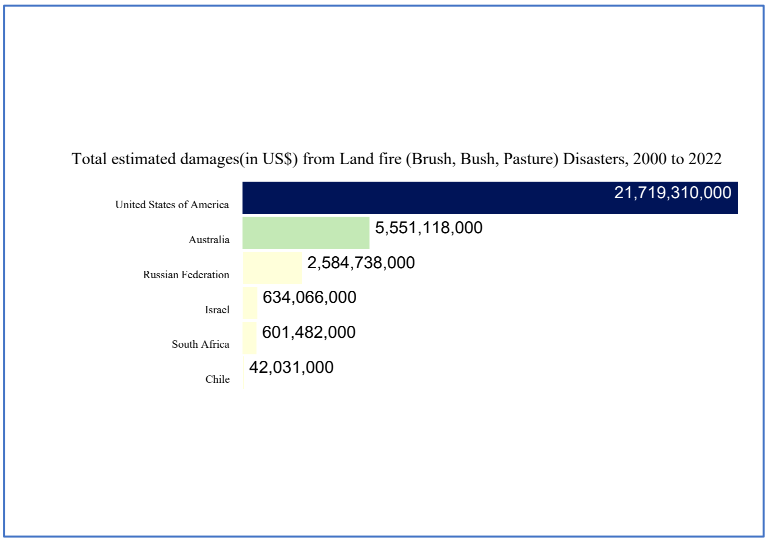

Figure 20-Total estimated damages fromladn fire from 2000 to 2022[www.emdat.com]

2.7.1 Literature review for wildfires

Several studies have attempted to illustrate whether the risk of wildfires, also known as bushfires, is relevant in the context of real estate evaluations. Most of these papers either focus on Australian or American case studies since these areas have suffered severe consequences due to recent urbanization in hot dry areas[the Bureau of Meteorology (BOM)]. However little information is available as to homebuyers factor in wildfire risk when purchasing homes in fire-prone areas and the existing literature is still limited compared to other types of extreme climate events. The impact of wildfire risk is sometimes offset by the additional value homebuyers would enjoy by living in the proximity of green spaces. Buyers tend to pay premia for dwellings which lie in the vicinity of forested areas, confirming an increase in perceived value due recreational activity and therapeutic action. Moreover these places are synonym with slower pace of life and provide an opportunity to live close to nature, therefore allowing a significant improvement of overall quality of life for residents. Pooling from 20 years old papers, Tyrvainen and Miettinen (2000) show that the market value of a home decreases by an average of 5.9 percent for every additional kilometer that separates it from the closest forested area. On average, homes with a view of a forest cost 4.9 percent more than homes with other similar characteristics. Crompton (2001) concludes that homes that are close to parks and other open spaces often have appraised property values that are 8 to 20% greater than those of nearby properties that are comparable. Commercial office building rental rates were around 7% higher in locations with a high-quality landscape filled with trees. Some other studies explore the benefits of wildfires to local flora and fauna, since its aftermath allows some species to thrive and how this is essential for the ecosystem, but they will be left out of the analysis, since they fall outside of real estate context. Donovan et al. (2007) studied how the change in home prices as soon as more information is available is able to shape buyers' purchasing behaviours. They acknowledge that the public is not very reactive towards wildfire risk unless the latter materializes and property owners believe that the insurance company will cover for losses incurred, downgrading potential additional risk. Raising awareness through public education efforts has often proven ineffective. In particular, theyNCREIF focus on the area of Colorado Springs, where, in 2000, a major intervention by the Colorado Springs Fire Department allowed homebuyers to assess and potentially reassess wildlife risks associated to properties. Based on an algorithm, they were able to extract wildlife risk ratings of about 35000 parcels in the wildland-urban in- terrace and make the information available on a web site. They were then able to split wildfire risk ratings into 25 variables with varying weights, studiyng the effect of each one separately. Some of these variables make up for the most impact and can also be a source of mitigation action which would lead to a reassessment of the risk rating previously attributed.

Donovan mentions the replacement of inflammable construction material with non-inflammable one as a mitigation measure. By comparing the pre-website situation to the post-website one, they find that wildfire risk ratings positively affect housing price prior to any information being available online, since the amenity value would outweigh that of loss in utility due to wildfire risk. On the other hand no relevant effect is found in the post-website model since the amenity value is completely offset by the newly acquired information. Furthermore they find a price decline immediately after the web results. Champ et al (2009) complement results from the previous study by Donovan et al. by conducting a survey and verifying how well informed are homebuyers about wildfire risk and their level of knowledge during the purchasing process. In addition they discover a price reduction in wildfire-prone locations for homes made of more flammable materials, but not for those with a lot of nearby vegetation. They also seek to ascertain how much of the increased perception of risk stems from past experiences. Almost 900 participants from Colorado Springs took part in the survey with gaussian-distributed risk ratings. Findings show that many home buyers move into fire-prone areas without understanding the risk. In most cases, almost 60 %, risk from wildfire is underestimated. Though the ratings had been available for some years, buyers would still overlook them and, when asked about potential sources, they expressed the wish to know about wildfire risks from realtors. Nevertheless, since Colorado does not have a disclosure law requiring that wildfire risk be disclosed to the homebuyer, realtors have little incentive to discuss wildfire risk with prospective buyers. This paper highlights the importance of due diligence and disclosure through the purchasing process. Another study which revolves around the amenity value is that of Athurokala et al. (2019) who investigate whether homeowners are willing to pay a premium for suburban properties in bushfire prone areas. They consider four suburbs within Brisbane City Council, Queensland, Australia and show how all variables within the regression are significant. The distance to bushfire area, which coincides with the distance to green space has a negative sign and is statistically significant, meaning that its increase leads to a price discount. These results imply that residents rely on mitigation action by authorities or they simply overlook risk. Prior to the that study, Athukorala et al. (2016) finds an interesting connection between unaffected suburbs and affected ones lying nearby. They analyze house price dynamics before and after the separate impacts of wildfire and a severe flood between 2009 and 2013, each of them hitting two different suburbs, lying nearby a completely unscathed third suburb, in the area of Rockhampton, Queensland. They observe a decline in market price for properties lying in the two affected areas, while a gain in properties lying in the adjacent unaffected area is also observed. This gain tends to decrease as the frequency of natural disasters increase again in the largely affected areas, suggesting a rising stigma for newcomers. By using HP models with dummy variables to reflect year in year change in prices, they are able to find an overall 6% decrease in prices immediately after a wildfire, but their study also remains consistent with other ones and shows changing coefficients as to reflect the expected impacts from other variables, such as number of bathrooms, presence of swimming pool and so forth, with different level of confidence 5%, 10%, 20%. In addition, the amenity effect is also present, since newcomers are willing to pay more to be near a green space, relying on insurance and institutions' intervention in case of hazard. Another aspect for policy implication is that disclosure from authorities and real estate companies can solve for the market failure due to asymmetric information and match the true costs of living in a risk prone area with the purchasing price prospective buyers are willing to pay. Stetler et al.(2010) also acknowledge the potential attractiveness of amenities in North-Western Montana, near Kalispell, drawing large numbers of new residents in WUI communities (wildland-urban interface). The paper starts from and confirms the assumption according to which residents associate the view and the proximity to a wildfire burned area with increased risk perception. It also suggests a more efficient allocation of resources regarding wildfire management intervention strategies since wildfire suppression[37] leads to escalating costs and

[37] https://en.wikipedia.org/wiki/Wildfire_suppression

induces a negative externality that is not internalized by residents. The study highlights how society at large bear the costs of wildfire suppression for residents living in fire-prone areas, by transfering part of their wealth through taxes. Increased interventions will lead to an increase in moral hazard- i.e. people feeling safe that someone else will protect them from hazard- and an incentive to further build in WUI due to amenity value and asymmetric information. In order to reduce wildfire suppression expenditures, more funds must be directed to better regulate residential growth patterns, educate residents about the risk of wildfire, available mitigation options, and long-term ecological effects. McCoy and Walsh (2018) develop a model which combines the underlying changes in location-specific risk beliefs to residential market dynamics in WUI areas of the Colorado Front Range, by analyzing transactions for the said market between 2000 and 2012. The underlying idea is that price and quantity effects associated to extreme weather events lead to inferences about underlying changes in risk perceptions, previously excluded from most analysis. Their empirical work stresses the *saliency effect* of bushfire and considers *proximity* to wildfire and *view* of wildfire burn scars as treatment variables which well define the dis-amenity effect of such hazard. Results from sale rates show that households living in the vicinity of a wildfire high risk area experience a ramp-up in their risk saliency, however brief (one or two years). House prices in affected areas fell by 6-13% the year after a fire, and the effects persisted in subsequent years. Prices in unaffected but high-risk areas fell by 9-12%, but quickly recovered in 2-3 years. According to their findings, households update their risk beliefs and market behavior in reaction to disaster-related information shocks. Mueller & Loomis (2014) which similarly analyzes long term price effects suggest these depend on the market value of homes, with homes originally selling for heftier prices, suffering the greatest losses to amenity. Mueller et al. (2009) indicate that repeated exposure to fires, rather than an isolated event mostly affects prices and this leads to an increase in the risk perceived and to an overall loss of utility from the property. Their research is centered around Northern California residential market. Issler et al. (2020) discuss impact of wildfire on lenders and insurers as well as mortgage effects and is a central paper since it mentions wildfire related market outcomes. This paper finds a better collocation in section 3.4. Finally another key paper discussing deeply and with innovative frameworks the amenity value and fire risk perception belongs to Gill et al. (2015). In essence the latter's aim is to obtain information on feasible fire management strategies as a way future to mitigate future risks based on interviewees' landscape preferences.

2.8 Adaptation and mitigation strategies: an overview of existing literature

This paragraph is devoted to understanding the importance of adaptation strategies and their future pay offs. In chapter three, analysis of discount rates related to climate abatement investments will be carried out, to frame the market willingness to pay for real estate as an income-providing asset.

Recent literature defines climate adaptation as efforts to alleviate or prevent harm, caused by expected or unexpected climate change, from adversely affecting human and natural systems by human intervention (Field et al., 2014). Throughout the last century, human intervention to alleviate or prevent climate disasters has primarily taken the form of policies, infrastructure investments, and technological development. In recent decades, much attention has been paid to the systematic adaptation characteristics that influence a community's ability to adapt and priority for adaptation measures. These characteristics have been dubbed "adaptation determinants[38]" because they influence, promote, and stimulate the nature of adaptations (IPCC, 2007) and these are vulnerability[39], sensitivity, resilience, flexibility[40]. Furthermore, adaptive capacity combines human capital and non-monetary factors such as technological, socio-economic, institutional and represents the ability of a system to adjust to disturbance and cope with

[38] Another aspect one should take into account is that of "Salience". Salience is "the phenomenon that when one's attention is differentially directed to one portion of the environment rather than others, the information contained in that portion will receive disproportionate weighting in subsequent judgments." (see Taylor and Thompson, 1982)

[39] Vulnerability is the predisposition of people, wealth, and landscape to be adversely affected (Pachauri et al., 2014).

[40] Flexibility refers to "the degree of maneuverability which exists within systems or activities" (Smithers & Smit, 1997).

consequences of possible disruptions (IPCC, 2007). Sensitivity[41], resilience[42], exposure, and adaptive capacity lead to vulnerability which directly feeds risk. Hay and Mimura (2006) classified the fundamental concepts of adaptation into four categories. First, "avoidance and reduction": taking precautions against potential consequences. Second, "damage mitigation": relieving the negative effects of a disaster and assisting in the recovery from those damages. This is the model's reactive adaptation category. Third, "risk dispersion": spreading the costs of damage over a wider population or over a longer time period. Insurance is a notable example of this category. Finally, "acceptance of risk and doing nothing": accepting the risk of negative consequences.

To better clarify “avoidance and reduction”, the Intergovernmental Panel on Climate Change (IPCC) specified adaptive measures for coastal zones: planned retreat, accommodation, and protection (IPCC, 1990). IPCC’s adaptation strategies may be further categorized into anticipatory and reactive. Anticipatory adaptation (ex-ante strategies) refers to measures taken before the effects of climate change become visible, whereas reactive adaptation (ex-post strategies) is used after the initial effects of climate change are observed. Accommodation strategies allow on-site operations to continue while allowing some flooding to take place by safeguarding facilities and properties from damage. Natural stormwater management and green building techniques are examples of this category, but land use changes and regulatory enforcement are also required to achieve this goal (Mills-Knapp et al., 2011; Mimura, 2010). Protection encompasses a wide range of design and policy interventions to mitigate damage, such as various hard and green infrastructure measures for disaster prevention, water resource management, and coastal ecosystem conservation (Mills-Knapp et al., 2011). Decision making for promoting adaptation necessitates cost and benefit optimization, as well as the timing of adaptation financing, to avoid costs

[41] Sensitivity defines as the degree to which a system is affected, either adversely or beneficially, by climate variability (Gallopín, 2006).

[42] Resilience is often expressed as “the capacity of a system to be able to prevent, withstand, absorb, adapt to, or bounce-back from shock” (Jonker, Miller, & Brechwald, 2011).

exceeding future benefits. Adaptation can also be either private and public, with the former being implemented by individuals for their own benefit, while public adaptation, which likely depends upon government action, is implemented for many beneficiaries. Individuals alone, however, will rarely provide the desired level of adaptation due to costs, disincentives, technical limitations, and resource requirements (Chambwera et al., 2014). As a result, government intervention is required to maximize the net benefits of adaptation efforts while minimizing market failures such as externalities and distributional issues. Furthermore, according to Bunten & Kahn (2014), real estate reflects the present discounted value of climate risks—climate risk capitalization in low-risk regions is underestimated, whereas household valuation in high-risk regions is overestimated. As a result, it is reasonable to assume that those who have already suffered significant losses as a result of extreme weather events are more actively investing in adaptation measures, and the use of homogeneous study areas to measure risk capitalization is logically reliable. Among the aforementioned coastal adaptive classifications, planned retreat and relocation options have received a lot of attention from planners and policymakers, particularly in Western developed countries (Alexander, Ryan, & Measham, 2012). However, because of the financial burden, legal conflicts, and numerous socio-cultural issues, these coping strategies are highly unfavorable (Hino, Field, & Mach, 2017). As a result, coastal developers seek the most dependable adaptation strategies in the categories of "protection" and "accommodation" to mitigate the potential asset value degradation caused by climate change. To address the latent risks, some property owners are purchasing costly insurance and raising foundations. Coastal cities and municipalities are allocating significant funds to climate change adaptation measures such as seawall and dike construction, pump station installation, and shoreline erosion control (Azevedo de Almeida & Mostafavi, 2016).

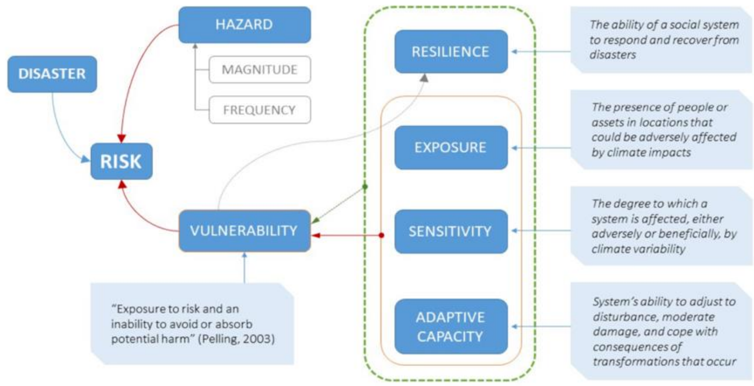

Figure 21-Conceptual frameworks of risk and vulnerability. Sources: Gallopín, 2006; Pelling, 2003

2.8.1 Existing adaptation measures

Hard infrastructure includes sea walls, dikes, local protective barriers, groins[43], breakwaters, jetties[44], bulkheads[45], and piers. These structures allow to preserve waterfront proximity as a feature for amenity effects while in general they also reduce risks. On the other hand, they require significant up-front expenses and maintenance costs. Fell and Kousky (2015) discovered that commercial properties with levee protection sell for approximately 8% more than comparable properties in 100-year floodplains without such protection. According to Jin et al. (2015), single-family homes located behind a seawall have a 10% price increase due to anticipated risk reduction effects from inundation. However, the beneficial effect of seawall protection was limited to properties within 164 feet (50 meters) of bodies of water. Green infrastructure is a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services (European Commission). Wetland restoration, riparian buffer zones, sand dunes, beach nourishment, freshwater ponds are worth to mention. Green infrastructure also helps to increase insurance value by lowering vulnerability and the costs of hard infrastructure adaptation to climate change (Green et al., 2016). The main benefit of green infrastructure is

[43] Groins are shore perpendicular structures, used to maintain updrift beaches or to restrict longshore sediment transport [https://www.nps.gov/articles/groins-and-jetties.htm]

[44] Jetties are another type of shore perpendicular structure and are placed adjacent to tidal inlets and harbors to control inlet migration and minimize sediment deposition within the inlet. Similar to groins, jetties may significantly destabilize the coastal system and disrupt natural sediment regimes[https://www.nps.gov/articles/groins-and-jetties.htm]

[45] a retaining wall along a waterfront

that it requires lower maintaining costs and hosts other ecosystem services. The drawback is that it takes longer to provide a full functioning service (e.g., trees take time to grow). Furthermore, adaptive capacity involves local shelters, evacuation plans and facilities, emergency preparedness, planning, education programs, organizational training. Adaptation capacity stimulates flexibility and readiness in decision-making, and it emphasize problem solving. It also allows deeper cooperation between public intervention and private initiatives. Lastly, having capacity does not entail that adaptation occurs (a good evacuation plan may not be implemented). Literature also points towards individually engineered solutions, which involve interventions such as raising foundation, private drainage improvement. It can directly address site-specific issues but, as pointed out by Mendelsohn (2000), individual adaptation tends to shrink whenever joint public adaptations such as green and hard infrastructure are significant, because individuals are unwilling to pay more than the actual risk exposures already provided by public authorities to maximize their economic benefits. The housing value on the other hand, remains unchanged and still strong due to shared benefits in risk reduction given by joint adaptations, and this is immediately captured by market price. As for wildfires, the most popular adaptation technique is that of prescribed burning, which entails intentional applying fire to vegetation. Prescribed fires are conducted under desired conditions to meet specific objectives, such as to restore fire regimes in adapted ecosystems or to limit the amount of dry brush in an area prone to wildfires (Kane, 2020). Dedicated managers usually compose a detailed prescribed burn plan that clearly defines the suitable weather and fuel conditions, the desired fire behavior, and the effects needed to meet predetermined objectives. It contributes to the preservation of land and ecosystems as well as lowering the risk of wildfires. Wildfire suppression can also be considered part of adaptive capacity and can be split into direct attacks, indirect attacks, aerial attacks, or combination of the above. Direct attack is where personnel and resources work at, or very close to, the burning edge of the fire. During direct attack, firefighters attack the fire aggressively by using hand tools and beaters and/or by applying water and/or retardants and it is recommendable for lower intensities since it involves directly approaching to the fire. Indirect attack is where personnel and resources complete suppression activities some distance away from the fire front. This type of attack can be used on flames of any length, but it is often used for high and extreme intensity fires where it is not safe to implement direct attack methods[15] .

To maximize climate adaptation efforts, cities and local governments must consider both infrastructure adaptation and adaptive capacity, as well as factors like equality and inclusive participation (de Coninck et al., 2018), to avoid excluding certain social groups from enjoying the benefit of these strategies.

The evidence presented above indicates that real estate has significant exposure to climate risk, and also shows how housing discount rates can be employed to learn about how to value investments in climate change mitigation.

CHAPTER 3

Market factors contribution to asset value and market assessment though financial metrics

3.1 The role of beliefs and perceptions

There is substantial evidence pointing to perceptions and beliefs about climate risk which adversely price impacts within US residential market. Rational individuals hold some beliefs which are the result of experience, and they heavily influence decision making processes. These beliefs can be further backed up by reliable data, the reassurance in both governments' mitigating action and the insurers to cover for possible losses. Bhattacharya et al. (2015) acknowledges that homeowners who previously experienced major flooding events, tend to be more tolerant of certain risks, but also have deeper knowledge and confidence in mitigation activities by authorities. Not only frequency but also severity of climate hazards (e.g. Hurricane Sandy hitting New York), as already mentioned by Ortega et & Taspinar (2018) has the power to produce more intense and prolonged changes in perceptions, rather than incremental attitude changes due to recurring minor flood events.

In order to conduct a large-scale quantitative analysis on respondents' perceptions of the hazards that climate change poses to their way of life, Baldauf et al. (2020) [47] use Gallup poll results. They then seek to determine whether these beliefs are consistent with the transaction prices of properties at high risk of future climate impacts (i.e., potential SLR flooding), as opposed to those whose values has changed as a result of prior occurrences, such as storm surge, wildfire, or flood. The research indicates a difference of more than 7% between residences in "believer" and "denier" neighborhoods, but it does not say whether doubters downplay the hazards or "believers" overestimate them. Murfin and Spiegel (2020) take a more rational stance and conclude that non-believers will not fully internalize sea level rise risk when purchasing property and as a consequence the effect on prices is not manifest. Furthermore they simply acknowledge that believers will simply “exit the game” and retreat to safer areas, with lower risk exposure.

According to Bernstein et al (2019), investors discount values more than owner-occupiers did in order to account for the risk posed by SLR. This finding supports their conclusion that investors are more informed about risk than owner-occupiers. They also assert that people tend to believe in SLR more when they are better informed.

The properties at risk of coastal flooding were overvalued, according to Bakkensen and Barrage (2021), who used a combination of hedonic analysis and door-to-door surveys in Rhode Island. However, the degree of overvaluation was sensitive to both buyers' perceptions of potential policy measures to mitigate any effects as well as their beliefs about climate change. This may indicate a lack of confidence in governmental action, and the perceived importance of the risk may also be influenced by future insurability. Fuerst et al.(2019) discusses how information asymmetry can influence consumers’ decision making processes, leading to a market failure when rational consumers lack adequate information to make well informed decisions. Humans are highly sensitive to the risk they perceive regarding exposure to future losses and thus their willingness to pay is also affected. As a continuation of the earlier hedonic model by Myers et al. (2018), Fuerst et al.(2019) combine geospatial data from GIS, transactions from 2011 to 2016, flood information data extracted from LiDAR, authority rating systems to establish whether sea level rise and flooding lead to significant discounting in the city of Melbourne, Victoria. Capital values for properties show a clear negative effect due to mandatory reporting of the properties in a flood risk area. This is consistent with Beltran et al. (2018) who claim that floodplain identification explains significant discounting to housing values. The same cannot be stated for future sea level rise which shows no effect on house discounting, therefore suggesting that it is definitely not capitalized in decision making processes or rather market participants seem unaware of it or unprepared for it. The paper thus stresses how information disclosure by local authorities, the timely processing of information and the response planning, play an essential role for short-term and long-term effect on market values and urges the need for policy implementation.

This may indicate confidence in government intervention, and future insurability may also affects the perceived relevance of the risk. The lack of an adequate response may accelerate discounting even further and determine negative consequences for other stakeholders involved. The study mentions insurance companies raising premiums in response, or being among the first to demonstrate the risk of sea level rise and increased flooding by declaring properties uninsurable. This could lead to banks being unwilling to lend on uninsurable properties, further depressing property values. Now it is worth mentioning several studies which examine a link between perceptions about wildfire risk and other socio-economic factors. According to Beringer (2000), wildfire risk is better perceived by long-time residents and by male gender households, with respect to female and newcomers. Anderson-Berry (2003) argues that people holding a higher education better assess risks deriving from wildfires, since they have the instruments to comprehend the scientific implications behind hazards and are more sensitive to information regarding the topic. Moreover Mcgee & Russell (2003) link risk assessment and overall perception to past experience and collaboration with fire managements institutions. Fothergill & Peek (2004) identify higher risk perception in lower social classes since they have lower confidence in fire managements institutions, while Fisek et al. (2002) suggests that socio-economic status does not influence perceptions.

3.2 The role of landscape amenity

The hedonic price model is based on the separation of attributes of the marketed good, namely the housing unit and also allows to consider the price premia due to amenity effect. In the literature so far analyzed, that translated to waterfront locations and residential forests. The latter provide many amenities to communities, including aesthetics, air quality improvement, recreational opportunities and higher property values. Nevertheless, there may be differing value drivers within a location, as evidenced by the literature reviewed here in the framework of physical climate - related risks. Namely, the properties most vulnerable to climate risks are frequently those with the greatest 'amenity adjacency' value. Cooper & Lemckert (2012) prioritize the importance of the tourism industry in Goald Coast and thus suggest that adaptive measures should be directed towards maintaining the amenity value for the hospitality industry.

Despite the risk of wildfire, Athukorala et al. (2019) shows that proximity to bushland has a beneficial impact on house prices in Brisbane, Australia's suburbs. Donovan et al. (2007) however argues that increased information availability on (wildfire) risks can also mitigate amenity effects.

Gill et al. (2015) applies landscape evaluation frameworks, thus a qualitative approach from the literature to assess households' preferences in terms of landscape outline as well as bushfire risk perceptions as a way to conceive consistent vegetation techniques aimed at reducing fire hazard. With the help of photo-elicitation and narrative interviews drawing from a pretty diverse sample of people living near national parks or green spaces- the so called WUI- across New South Wales, Australia, they were able to extract preferences based on aesthetic, recreational value as well as bushfire risk mitigation preferences. The photo-elicitation consists in showing different pictures and having the interviewee express a ranking as well as explaining the rationale behind their decisions. According to interviewees, the most preferred landscape is open landscape with little understory and low vegetation density both from a safety standpoint as well as aesthetically.

This result also highlights that, contrary to US literature on landscape preference, the "bush blindness", defined as the inability of residents to perceive bushfire risk does not occur with frequency within their sample. The paper is paramount for fire managers to intervene with strategies such as vegetation clearing, thinning or removal through either mechanical means, grazing or prescribed burning, in a way to preserve both residents' amenity and fire risk mitigation needs.

Existing literature on commercial properties is very limited, but the value driver is not landscape amenity in this case, rather it is distance to central business district (CBD). Lamond et al. (2019) discover that the business indispensable criterion for proximity may exceed the known flooding risks, but they come to the conclusion that other factors, such as the governance context, are relevant to any value discounting.

3.3 The role of Governance

In this section, an analysis of the state or government policy implementation and investments in resilience is provided. The matters include land use, taxation, infrastructure provision and loss prevention, all which can be severely impacted by climate risk. Some countries and have a marked tendency towards state-funded preventive measures to preserve human activity. As already mentioned by Cooper and Lemckert, some areas within the same country may be prioritized due to strategic importance, to the detriment of more marginal areas. Literature suggests a link between good governance practices and value, despite limited evidence pointing to a direct relationship between value and physical climate change measures. McEvoy et al. (2021) interview a sample of 150 respondents, with sizable expertise with regard to SRL in 32 European countries about their countries' coping with SRL planning. In their survey they analyze different climate change scenarios regarding a 1 meter sea level rise by the year 2100. This method is thought to be effective since national policy documents lack precise information on how countries prepare for SLR, but provide limited general information about SLR. Results suggest that only 23 of 32 European countries drafted a SRL planning scheme at the national level, with some having a federal level plan, with Germany, Belgium and the UK placing at the top of the ranking. Some countries with sizable population inhabiting the LECZ[46] lack a SLR planning, with Italy being one of these. Moreover the study points to the need of a combination dedicated and mainstreaming approaches which could raise awareness among population and ensure coordinated responses. Besides, national and regional efforts focusing on addressing SLR are defined within individual projects, such as Venice's MOSE system, the UK's Thames Estuary, the Netherlands' Delta Programme.

[46] LECZ is commonly defined as the contiguous and hydrologically connected zone of land along the coast and below 10 m of elevation [https://sedac.ciesin.columbia.edu/data/collection/lecz].

Furthermore they find that countries are planning for an amount of SRL which occurs in all projections, irrespective of climate emission scenarios (RCP 2,6; RCP 4,5 and RCP 8,5) derived from IPCC information. Lastly, they argue that "experts working on SLR are not always aware of existing policies and plans in their country" due to a science-policy gap occurring at government level. Australia's and the United States of America's efforts are locally managed due to their Federalist systems. Some States place local benchmarks and SRL planning horizons such as South Australia, while others have more generalized approaches, i.e New South Wales. While American papers provide detailed characterization, Europe lacks such highly grained policy determination and description.

Rasmussen et al. (2021) delivers an interesting point of view on how Governments favor or undermine the implementation of coastal flood reduction megaprojects in the US. They acknowledge an inert behavior from local authorities when addressing floods and that multiple floods are needed to elicit an ad-hoc reaction. They conclude that developing a feasible risk reduction strategy requires more than just scientific knowledge and skilled engineering. Technical experts can answer the prescriptive question of what may be built, but not what should be built. This explains why strong political leadership and stakeholders' active involvement during design stage are crucial to this end. Furthermore they recognize a certain degree of opposition from environmental protection advocates and all the legal issues related to project implementation. Social conflicts, inefficient and complex governance structures therefore pose a relevant obstacle to flood mitigation measures.

According to Lamond et al. (2019) following amendments to the Federal Water Act 2009, property owners in Germany are expected to implement private precautionary measures in accordance with their capabilities and resources, despite significant governmental contribution in case of flood occurrence. The authors record substantial incentives for owners to put in place mitigation measures drawing from their resources since this might lead to "higher take-up of insurance policies and premia". They also contend that, in the absence of repeated events, people tend to overlook flood risk, even if a property is located in a floodplain. Eventually, they suggest that "commercial property values may even rise in response to a severe flood if there is a high likelihood of increased government mitigation spending”. Bakkensen and Barrage (2021) draw similar conclusions and they further add that ad-hoc government intervention may also contribute to a brake in the rapid collapsing of residential prices, whereas the lack of it, as with Hurricane Katrina will lead to severe and longer lasting price discounts.

3.4 Mortgage lender reaction, liquidity, and insurability

Homes, and real estate in general are considered financial as well as physical assets since they require upkeep to maintain value or even to increase it. Similarly to stocks and other financial products, they may as well lose value according to demands in the market. Real estate may generate an income, as well as expenses such as management fees, maintenance costs, a mortgage. Furthermore homeowners may owe taxes on gains each year and possibly upon the sale of the property.

Even though no academic studies of the commercial real estate debt markets were found, there has been an increase in research and analytical activity among investor, rating agency, and mortgage analytics organizations, which implies that more people are becoming aware of how significant the climate risk is. Property transactions require considerable debt financing. Moreover, credit or debt markets are the largest component of the global financial system, therefore prompting lenders, regulators and credit rating agencies to take a more conscientious stance towards climate risk. Recently rating agencies and regulators have been attributing importance to the market of mortgage-backed securities which is a sign of the power of Government-sponsored enterprises (GSE[47]) over

[47] Fannie Mae, Freddie Mac, and the Federal Home Loan Banks (FHLBs) are government-sponsored enterprises (GSEs) that help bring capital to the housing markets. Their regulator is the Federal Housing Finance Agency (FHFA) [https://www.fhfa.gov/AboutUs]

lending institutions, such as banks, reflecting changing perceptions of risk in lending after hurricanes.

To this end, Ouazad & Kahn (2020) provide evidence about the tendency of lenders to transfer climate risk, by approving mortgages that are prone to being securitized. Their intent was to explore whether risk of mortgage defaults due to climate hazards is borne by lenders or securitizers, the latter being the GSE's mentioned above, and also to understand whether the insurance activity and lenders' underwriting strategy is pushing borrowers to relocate to flood areas. The identification method used in this article depends on calculating how natural disasters affect discontinuities in approval, origination, and securitization rates as well as bunching in a window around the conforming loan limit. The findings imply that lenders are much more likely to raise the fraction of mortgages created and securitized right below the conforming loan limit following a catastrophic event. This paper also shows how GSE's bear most of the increasing climate risks due to mispricing in the market and market incompleteness. To summarize, GSE's support liquidity in the loan market to allow homeownership but they also incentivize lenders to distribute their climate risk. Keenan and Bradt (2020) take a slightly different approach in the sense that they acknowledge a transfering risk action by local lenders through mortgage securitization relative to future events. This signals a recently increased awareness of the potential impact of climate risk on defaults in high risk-areas of the United States. These two papers refer to residential property only, as results for commercial property owners are nonexistent.

Extreme weather events and/or increased awareness of climate risk may have an impact on which properties are available for sale, the group of interested buyers, and, as a result, sale times and volumes. The cost and availability of creditor financing and re-financing, as well as insurance, are expected to be significant determinants of future investor behavior and liquidity. However, there have been instances of buyer demand declines in high-risk areas that cannot be traced back to changes in lender and insurance provider practices. Private real estate markets are characterized by low liquidity in comparison to other financial assets[48]. Higher transaction costs, longer and more uncertain transaction times, and less frequent trading are all indicators of this. Private real estate liquidity varies over time and across locations, and prices do not always adjust sufficiently to equalize liquidity across locations or market states. This implies a different number of buyers versus sellers, as well as different pricing responses by buyers and sellers in response to economic circumstances or other factors such as climate risk exposure. If the occurrence or risk of a climate event reduces the number of buyers relative to the number of existing owners, prices and selling times should be affected. In addition, if buyer valuations of properties in affected areas differ from owner valuations, for example, by a more rapid drop in what buyers are willing to pay this will affect prices and trading times. Because price effects require sales to occur, metrics such as trading volumes or time on market could provide early warning signals of how markets are responding to climate events and risks. To better illustrate how climate risk affects transaction activity in real estate, two relevant papers are taken into consideration. Keys & Mulder (2020) show that between 2013 and 2018 real estate transactions in SRL most exposed coastal Florida communities has shrunk by 16-20% compared to less exposed areas, while home prices remained stable through the years, only declining in the same direction as transactions did after 2016, recording a 5%. This lead and lag phenomenon between home sales volumes and prices is consistent with housing cycles dynamics, namely the housing market bubble effect and is attributable to a decline in demand on the side of homebuyers, while lenders fail to immediately react, keeping prices unvaried. These mainly empirical findings confirm that at the peak of a housing boom, sellers remain optimistic about their home's value because they overestimate demand by inferring from recent price increases. As a result, sellers set prices that are higher than most prospective buyers are willing to pay, causing transaction volumes to fall before prices. Large declines are detected for both cash home purchase and home purchase loan volumes. Moreover, they document

[48] A financial asset is a liquid asset that gets its value from a contractual right or ownership claim. Cash, stocks, bonds, mutual funds, and bank deposits are all are examples of financial assets [https://www.investopedia.com/terms/f/financialasset.asp]

irrelevant changes in the rate of loan denial, securitization, or refinancing volume with respect to SLR exposure, thus revealing that shifts in demand were not driven by changes in lenders or insurers ‘behavior. However, it must be noted that sellers systematically underestimate a price discount, deriving from SLR risk, coming from increasingly risk aware buyers. The papers remains a milestone in highlighting the importance of lower liquidity through lower sales volume as a symptom of increasing purchasers risk awareness, rather than pricing signals. The immediate implication for lenders is that they may face an increased risk of default in the future if a *"tipping point"*[49] of SLR risks is identified, provided they do not readily intervene.

Investors, other real estate stakeholders and insurers covering for losses will eventually influence the timeline of changes in liquidity.
While there is mounting evidence that insurers suffer losses as a result of the increasing frequency and intensity of extreme weather, as well as the relatively high value of assets exposed to hazards, there is little evidence that insurance availability or pricing affect asset values. Regulations concerning insurance are a complicate matter since it varies across countries and even within the same country, therefore research is also sparse. The possibility to obtain affordable insurance certainly impacts pricing and liquidity of an asset. If the probability or extent of losses is deemed to be extremely high, insurance may become unavailable. It could also lead to changes in policy terms, such as more exclusions and higher surpluses, as well as changes in insurance premiums.
As for flooding, the most relevant study belongs to Lamond et al. (2019), who illustrate different approaches adopted in Australia, China, Germany, the UK, the U.S. These countries differ in terms of public versus private provision of flood insurance, the cost and coverage of such insurance, and whether regulations require insurance to be held by owners or occupiers. Whenever insurance is

[49] The Intergovernmental Panel on Climate Change (IPCC) defines tipping points as "critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system, often with an understanding that the change is irreversible." [https://earth.org/tipping-points-of-climate-change/]

unobtainable or costly, other solutions are preferred; namely self-insurance[50] and under-insurance[51]. The latter implies the enrollee being liable for a large financial expense if a serious event occurs and sometimes the insurance payout may not be enough to cover repairs or replacement. These considerations lead to significant implications for the value of properties, in terms of property investment decisions and outcomes. National and State-level policies are available In the U.S., the NFIP (National Flood Insurance Program) has favored flood risk coverage in vulnerable areas and subsidized premiums for properties in such areas. Bin & Landry (2013) conclude that, as a rule of thumb, homebuyers are unaware of flood risks and insurance requirements when bidding on properties, but also ascertain that recent experience with floods also urge buyers to better exploit these policies. Insurance payouts mitigating home value may contribute to explaining the reason behind short-lived price discounts after major storms according to Miller et al. (2019). Issler et al. (2020) argue that after wildfire events, mortgage delinquencies and foreclosures[52] recorded a sharp increase- 0,40% and 0,30% respectively- though the effect is not no clear after larger fires. This may be attributable to co-coordinated rebuilding and renewal which brings value benefits. They find that coordination externalities as well as insurance frictions lead to a rebuilding in fire struck areas of Southern California, which is characterized by increase in home sizes, house prices (housing market dynamics) income, and wealth (gentrification). Moreover, they highlight how regulatory distortions question the ability of insurance companies and mortgage lenders to price climate-related losses and assess mortgage risk. The study adopts a difference-in-difference approach and also sheds light on household decisions after major wildfire events within a context of frictions associated to negotiation settlements, rebuilding and state level insurance term and policies and so forth. Conclusions point to incentives to

[50] Self-insurance involves setting aside your own money to pay for a possible loss instead of purchasing insurance and expecting an insurance company to reimburse you [https://www.investopedia.com/terms/s/selfinsurance.asp]

[51] Under-insurance refers to the retention of substantial exposure to losses despite having some insurance cover [https://www.investopedia.com/terms/u/underinsurance.asp]

[52] Foreclosure is the legal process by which a lender attempts to recover the amount owed on a defaulted loan by taking ownership of the mortgaged property and selling it. Typically, default is triggered when a borrower misses a specific number of monthly payments, but it can also happen when the borrower fails to meet other terms in the mortgage document. [https://www.investopedia.com/terms/f/foreclosure.asp]

rebuilding following wildfires, and to policies favoring larger, and more modernized dwellings. These incentives are augmented by the fact that everyone, in affected areas would start rebuilding around the same time. Furthermore, Nyce et al. (2015) discovered that every 10% increase in insurance premiums results in a 1% decrease in housing prices. According to Epley (2017), higher insurance rates are associated with lower housing values.

3.5 Price decline duration

The impact of significant weather events on property values in affected areas has been immediate and sometimes lasting, although the scholarly research consistently finds that prices eventually return to trend. This finding particularly holds true for water- related hazards such as flooding and hurricanes. Evidence suggests that frequent exposure to natural hazards affects risk appraisal, albeit temporarily and with a varying impact for different types of events, does impact risk assessment. Higher frequencies produce longer lasting effects. According to findings from recent studies, lenders, investors in commercial real estate, and homebuyers are all paying more attention to climate risk. This attention is believed to be causing property values to decline, as shown by decreased liquidity and mortgage lender behavior, and is believed to be a cause of the erosion of home values. According to research by Miller et al. (2019) and Below et al. (2017), single-family home prices quickly return to historical trends following significant storms with limited long-lasting detrimental impact on value.

In the NCREIF[53] Property Index (NPI), Fisher and Rutledge (2021) demonstrate a similar tendency for institutionally owned commercial buildings, with prices dropping for up to three years following hurricanes before reverting to trend. The temporary nature of price changes in regions known to be at risk suggests that the threat is real and that, as a result, the risks are partially capitalized into the prices of these properties. Once again, a recurrent finding points to the frequency with

[53] NCREIF is a non-profit, membership organization of the institutional investment managers that invest in U.S. commercial real estate on behalf of their clients, including high net worth individuals, pension funds, and endowments. [https://corporatefinanceinstitute.com/resources/commercial-real-estate/ncreif/]

which these events occur, as evidenced by Graham et al. (2007) with hurricanes and Mueller et al. (2009) for wildfires (see section 2.4) since, similar to the hurricane dynamic, recovery in real house prices is prolonged but does ultimately take place without repeated events. A smart conclusion from Lamond et al (2019). suggest that, following a flood, commercial property values may even rise in response of a clear additional mitigation action by the Government. Most studies highlight how the effects pertaining to these catastrophic hazards will eventually reach previously unaffected areas as in Ortega and Taspinar (2018) and Addoum et al (2021). Similar results will be drawn from wildfires as well. What can be inferred is that, if the sustained rise in the frequency and severity of extreme weather events and SLR occurs as scientists predict, then awareness and recognition should increase, leading to a permanent reflection of climate change event-related risks in property prices in high-risk areas.

3.6 Valuing investments in climate change mitigation

This paragraph serves as a wrap-up to show the existence of a relationship between climate change risk, term structure of discount rates for real estate, and consumption. Giglio et al. (2021) set up a quantitative equilibrium asset pricing model, based on Lucas (1978) to extrapolate discount rates for climate-change abatement investments at any horizon from evaluations on term structure for the real estate, by exploiting the endogenous relationship between consumption and climate risk[54].

[54] A financial asset market is a location where a contractual right to a certain form of wealth is bought and sold. This is usually characterized by the liquid nature of the asset, or how quickly it can be converted to cash, and includes such financial assets as savings and checking accounts, stocks and bonds, and mortgages [https://www.smartcapitalmind.com/what-is-a-financial-asset-market.htm]

Below is the setup of the model for aggregate consumption.

$\Delta c_{t+1} = \mu + x_t - J_{t+1}$ (1)

$x_{t+1} = \mu_x + \rho x_t + \varphi J_{t+1}$ (2)

c_t represent the aggregate output at equilibrium and is subject to economic shock J_t which embodies climate risk and is a jump stochastic process which takes value $\xi \in (0,1)$ with climate calamity probability λ_t in each period, and 0 otherwise. The model assumes complete markets, which entails perfect risk sharing among households and excludes all risks that are not be related to climate risk.
Finally, the process x_t captures enduring variations in consumption growth rates and is vital in determining the term structure of discount rates.

A separate cash flow process model representing the rents for real estate is discussed below:

$\Delta d_{t+1} = \mu_d + y_t - \eta J_{t+1}$ (3)

$y_{t+1} = \mu_y + \omega x_t + \psi J_{t+1}$ (4)

Rents are more sensitive to economic shocks, and this is reflected by $\eta > 1$ since property per se is more is characterized by higher exposure to risk, due to land being immovable. Similarly to x_t, the stochastic process y_t captures persistent changes in growth rate of rents. While ρ and ω indicate the increase of growth of economy over time, while ψ and ϕ represent the growth rate of economy in absolute terms. After disaster shocks, these values are positive. The rationale behind these models strongly resembles that of CAPM[55] (Capital Asset Pricing

[55] The Capital Asset Pricing Model (CAPM) describes the relationship between systematic risk, or the general perils of investing, and expected return for assets, particularly stocks.
It is a finance model that establishes a linear relationship between the required return on an investment and risk. The model is based on the relationship between an asset's beta, the risk-free rate (typically the Treasury bill rate), and the …[47] equity risk premium, or the expected return on the market minus the risk-free rate.[https://www.investopedia.com/terms/c/capm.asp]

Model), which calculates the value of a security based on the expected return relative to the risk investors incur by investing in that security. The main difference is that these models are dynamic rather than stationary, but the goals are alike.

The last component of our model is an endogenous climate disaster probability λ_t

$$\lambda_{t+1} = \mu_{\lambda} + \alpha\lambda_t + \nu x_t + \chi J_{t+1}$$

This equation clearly shows the dependency of disaster probability to consumption growth, it therefore endogenous to growth rate of the economy. The rationale behind this is that the probability of a disaster increases over time when the economy grows at a faster rate, since the latter leads to more environmental damages which empirically and scientifically transform into adverse weather events. Figure 22 (source: Giglio et al. 2021) clearly shows a path in which the economy grows faster than expected, beginning in year 10 (exactly as before), but with a climate disaster occurring after year 25. This disaster causes a significant drop in consumption and rents. The dynamics of climate risks are especially intriguing. As previously stated, the likelihood of a disaster increases as the economy accelerates. Once a disaster occurs, the likelihood of another disaster increases. It takes nearly 40 years (in a sample path chosen to have no further disasters) for the probability of a disaster to revert to its long run mean after the initial growth spurt shock. The bottom panel of Figure also depicts mean reversion in the economy's growth rate. Following a natural disaster, the rate of growth of the economy increases ($\psi > 0$) and this increase is persistent ($\omega > 0$).

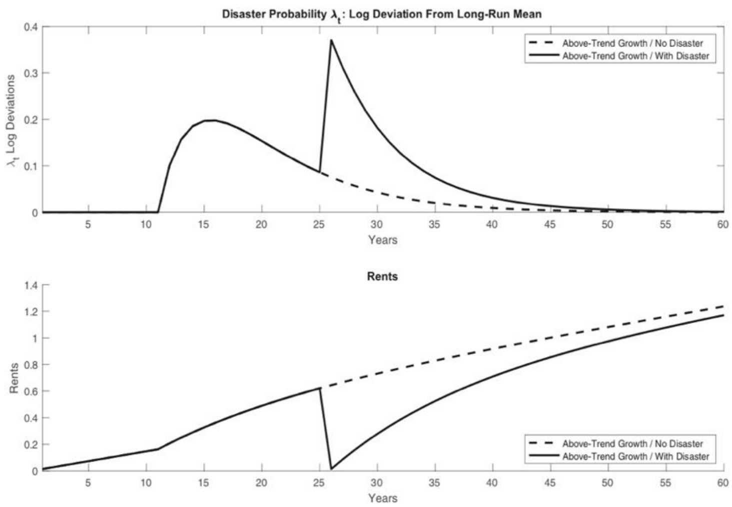

Figure 22-economy growth and climate disaster probability and rents-[Giglio et al. 2021]

The next passage, about which only some insights will be provided is the determination of the term structure of discount rates for risky assets and the drivers of its marked downward slope. It all starts from the periodical utility function drawn from Lucas (1978), which assumes that the existence of a representative agent who maximizes lifetime utility and faces a complete set of financial instruments. What the model seeks to find is the periodic discount rate that equates the price of a single cash flow with its present discounted value. This is consistent with arbitrage pricing theory and risk neutral probabilities. The purpose is to derive the variables affecting the shape and the level of the yield curve by analytical solving for recursive equations.

The paper proceeds to calibrate the model, that is matching the data with evidence found both for risk free rates and for the yield curve for risky assets (housing as previously mentioned). "In our calibration, a house with a 1% higher exposure to climate change (i.e., higher η), responds to a one percentage point increase in the probability of a climate disaster (λ_t) with a price decline that is 0.4 percentage points larger relative to a house with lower exposure"(Giglio et. al, 2021).

3.6.1 Investments as hedges[56]

So far, a thoroughly analysis considers consumption and discount rates but how do really climate change investments enter the equation? They are modeled as "assets that compensate investors for future damages to production and rents due to climate change, akin to insurance policies on climate change." (Giglio et al., 2021). These investments are treated as infinitesimal since they are not large enough to influence equilibrium. By setting up a process for damages to rents due to climate change by Q_t and taking its logarithmic dynamics as:

$\Delta q_{t+1} = \mu_q - y_t + \eta J_{t+1}$

Intuitively J represents the economic shocks and y is the growth rate of damages which is immediately high after a disaster but is counterbalanced by the adaptive nature of the economy. These investments act as a hedge and provide a payoff which partially offsets damages. They pay back a fixed portion θ, indicated by of growth rate in damages $\theta\Delta q_{t+1}$.

Discount rates are lower for higher pay- backs, which translate to lower risks since the insurance is "covering more". Discount rates increase in lower incentives for investors to insure their assets (homes). Some rates may even become negative for shorter horizons because of investors unwillingness to pay for a price which is below the expected payoff of the project.

Some important conclusions to the use of hedge as covering form risks are that investing in climate change abatement leads to discount rate which always lie below the risk-free rate, which works as a tight upper bound for shot horizons and a looser upper bound for higher horizons. Moreover Appropriate discount rates for investments in climate change abatement increase with the horizon, which disproportionally tightens our upper bound as the horizon increases. Term structure is therefore upward sloping. Other studies, (Arrow et al, 2013) identified

[56] To hedge, in finance, is to take an offsetting position in an asset or investment that reduces the price risk of an existing position. A hedge is therefore a trade that is made with the purpose of reducing the risk of adverse price movements in another asset [https://www.investopedia.com/terms/h/hedge.asp]

downward sloping term structures of discount rates, for evaluating long-run investments, leading to policy changes in France and the United Kingdom. For long term investments, discount rates under both term structures remain low. As for short-run investments, lower discounting is implied immediately after a catastrophic event, since hedging the immediate cost is more valuable. Therefore, discount rates are below 2%, which is the risk-free rate, for the upward sloping term structure, while they grow to a 4% in the downward sloping term structure within 30 year of a project's cash flows.

3.7 "Tax View" against the "Disaster View" of Climate Change

Modeling climate change risk and its economic effects is a tough challenge, both because the physical processes lying beneath climate change are not fully grasped and because historical data to predict how climate change will affect the economy is scarce. The effects of climate change on the economy rely on two major school of thought: that pioneered by Nordhaus (2008) which views climate change as a tax on output (see 1.2 and following). When output is high, pollution and the costs of climate change are also high. The path of the economy serves as the main uncertainty source in this view and pollution is positively increasing in good states of the economy, whereas in periods subject to deterioration of welfare and economic conditions, damages from climate change are expected to be lower. Investments in climate change mitigation are thus risky because they pay off in states where the economy is expanding. The alternative view stems from rich research conducted by Weitzman (2012), who posits that "climate change is a disaster-type risk that, if it materializes, causes output to drop" (Barro, 2015). In these cases, climate change per se is the main source of uncertainty, and it inducing risk on the economy. Investments in climate change abatement are then hedges that reduce aggregate risk, because they pay off when consumption is low (after a climate disaster materializes) (Giglio et al., 2021). Giglio proceeds to adapt the calibrated model derived from Lucas (1978) to both economic views and draw the due conclusions. They acknowledge that for their model to be closer to that of Weitzman, two hypothesis have to be relaxed; no mean reversion of the economy and climate risk that does not endogenously depends on the growth rate of the economy and manifestation of climate disaster, i.e: a constant probability of climate shocks. The results of *Weitzman* imply low discount rates as in the original setup model by *Giglio*, but invariancy across horizons, which clearly conflicts. By re-introducing the previously relaxed hypothesis, it is possible to obtain the empirically-observed horizon-dependent term structure of discount rates. Investments pay off as soon as weather-related disaster occur and continue to pay off at a declining rate to reflect the influence of adaptation. The “tax” posits that a constant climate tax on revenues should be applied and affect pay offs. Investments are risky and payoffs increase with consumption: damages are more resonant when the economy is growing. The main implication is higher (above risk free rate and time invariant discount rates. By relaxing the assumption about the tax rate to be constant and have it increase with the economic production, the outcome is not only higher discount rates but discount rates that increase in time. Rationally, when the economy slows, the expected climate damages remain low, making long-term investments in climate-change mitigation riskier than short-term investments.

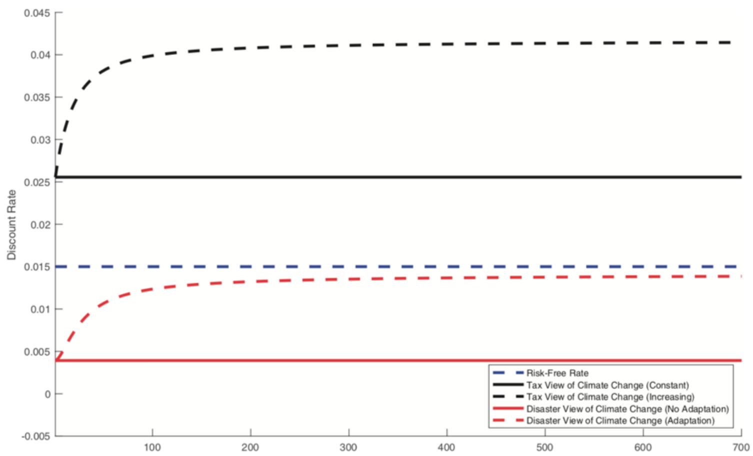

Figure 23-Giglio model of term structure of discount rates [Giglio et al.2021]

Conclusions and takeaways

Different theories were developed to match the behaviour of climate change, real estate and including the notion of consumption. This model has helped to infer discount rates from real estate, which is a rather consolidated market segment whose dynamics are easier to interpret compared to the mostly unexplored behaviour of climate change. This was possible by leveraging on the mean reversion in cash flows as the economy adapts to climate catastrophe. The consequence of this mean reversion is that higher-maturity cash flows have lower risk exposures because a climate disaster that occurs today has a greater impact on upfront cash flows than on remote cash flows. These discount rates, which could be used to value climate abatement investments - consistently with Weitzman – are always increasing with the horizon and are bounded by the risk free rate; said upper bound becomes tighter as the horizon lengthens. As for climate risk, the extensive examination of the literature points to a price penalty and consequently into an opportunity cost, or the foregone value which a prospective buyer would enjoy by investing elsewhere, into a property which is not as significantly exposed to climate risk, all else equal. Similar results would be harder to obtain for the Italian real estate market since it “is characterised by both a strong heterogeneity of real estate assets and a reduced number of property sales” (Lisi & Iacobini, 2020). These features are thought to undermine the use of hedonic price model and also account for the influence of weather-related events on house market value. To make the model “more homogeneous”, a subdivision into OMI zones[57], where "OMI zone" refers to a homogeneous sector of the local real estate market (of a specific city) in which economic and socio-environmental conditions are valued consistently. Lisi & Iacobini (2020) suggest the use of dummy variables to account for OMI variables and capture the effect of location of house price.

[57] The acronym OMI refers to the institute that takes care of the data and statistics relating to the Italian real estate market, i.e., the Observatory on the Market of Immovable property (OMI) of the Italian Revenue Agency]

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