SUPPLEMENTARY INFORMATION

Table S1. Carbon cost range

Author	Year	CO2	Carbon	Method	Model/Notes
Stern	2006	$85 per tonne of CO2	$312 per tonne of carbon	SCC	IAM
	2015	$250 a metric ton for coal	nd	nd	
Nordhaus	2014	$18.6/ tCO2 (in 2005 US dollars)	nd	SCC	IAM DICE
	2017	$31.25/ tCO2 (in 2010 US dollars)	nd	SCC	IAM DICE
Pindyck	2016/2017 2018	$80 to $300: most experts range	nd	SCC	Average SCC
	"	$153 to $203: economists mean SCC	nd	SCC	Average SCC
	"	$291 to $326: climate scientists	nd	SCC	Average SCC
Wang et al	2019	minus 13.36 to 2386.91$/tCO2: range	minus $50 to 8752$/tC: range	SCC	Meta-analysis IAMs
	"	54.70$/tCO2: mean value	200.57$/tC: mean value	SCC	Meta-analysis IAMs
Tian et al	2018/2019	44.93 €/tCO2: mean	nd	SCC	
Ricke et al	2018/2019	$417/tCO2: median	nd	SCC	Modular framework
	"	$177–805 per tCO2: 66% confidence intervals	nd	SCC	Modular framework
Tol	2019	nd	$6.48/tC to $21889.04/tC: range	SCC	National climate change impact functions
Kaufman et al	2020	$34 to $64 in 2025; $77 to 124 in 2030	nd	NT2NZ	MAC
Stern & Siglitz	2021	$100	nd	SCC	SCC

(Non-exhaustive selection; mainly focused after 2015; authors calculations with different assumptions)

Box S2. Carbon pricing initiative of Boulder, USA

Carbon pricing initiative of Boulder, USA

Between 2006 and 2007, the city of Boulder published its Climate Action Plan Tax (CAP) as a roadmap for its decarbonization targets. In this context it was approved, by ballot, an energy tax (CAP tax) to fund the plan and put it into force. The city of Boulder, with 100,000 inhabitants, was the first city in the US to adopt a CAP and a tax (Brouillard and Van Pelt, 2007). Boulder CAP tax focus only electricity consumption and considers a set of rates depending on the electricity consumer category and is collected by the single local electric utility and then delivered to the local government. The initial tax was \$0.0022/kWh for residential consumers, \$0.0004/kWh for commerce and \$0.0002/kWh for industry (Sumner, Bird and Dobos, 2011). In the current period (2015-2023), rates are \$0.0049/kWh for domestic consumers, \$0.0009/kWh for commercial and \$0.0003/kWh for industrial (Boulder, 2021). The estimated rate charged for monthly electricity consumption in 2019 is \$9.5/tCO2 (domestic), \$1.75 (commerce) and \$0.58 (industry). No public information was found on the method used to determine the value of this energy tax.

As energy tax, Boulder CAP tax has the effect of a very limited carbon tax, as it only applies to each unit of electricity consumed (kWh) not to each unit of carbon content (CO2). Yet, when the tax was decided, all of Boulder's electricity came from coal.

Xcel is the single utility supplying electricity to the city, having an historically high carbon intensity of its electricity mix. This dependence makes it difficult for Boulder to accelerate decarbonization. For a decade, the population of Boulder tried to buy the utility and make it “cleaner”, but the plan ended in truce in 2020, with Xcel continuing to provide this public service. During the dispute period, Xcel increased its share of renewable production from 13% in 2010 to 28% in 2019 and forecasts 60% in 2030 due to state (Colorado's Renewable Energy Standard; Clean Air Clean Jobs Act10) and federal (House Bill 1261) laws that oblige the energy sector to cut emissions and invest in renewables. For this reason, it is difficult to measure the impact of local climate policy, as the evolution of GHG emissions also has the joint influence of state and federal policy measures (Figure S2).

Municipal revenues from the CAP tax, of ~\$1.8 million per year, have several purposes: financing the city's climate action plan on households’ energy efficiency and buildings, renewable energy and reducing the distance traveled in vehicles (Sumner et al. 2011) with cost-effectiveness concerns (revenue invested for each ton of GHG reduced). As the CAP tax expires in 2023 and it has a limited impact on the other fossil fuels consumption (transports and buildings), the city of Boulder wants to keep this funding source for its Climate Action Plan and therefore is exploring the possibility of adopting a more ample tax, with more sectors, closer to a carbon tax. Known for being environmentally progressive, the city of Boulder started by setting decarbonization targets guided by the Kyoto Protocol, meanwhile aligned with the Paris Agreement: reduction of GHG emissions by 15% in 2020 and at least 80% in 2050 compared to 2005, with 100% renewable electricity objective in that year. Although it registered 21% less GHG in 2019 (*Boulder*, 2019) and therefore complies the 2020 target, it remains one of the cities with higher GHG emission levels in Boulder County, where families (~320.000 inhabitants) have the largest carbon footprint in the USA (Goldstein, Gounaridis and Newell, 2020).

Figure S2. Boulder emissions breakout over time by end use
(Source: City of Boulder 2019 GHG Emissions Inventory)

Box S3. Carbon pricing initiative of New York City, USA

Carbon pricing initiative of New York City, USA

New York City is currently designing a local carbon market as a policy tool to reduce emissions in buildings, the source of 70% of the city's emissions, in order to contribute to the city 2050 carbon neutral target (NYC, 2019a). In 2019, it approved the Climate Mobilization Act (Local Law 97) (NYC, 2019b), which includes the target of reducing emissions from buildings by 40% by 2030 and 80% by 2050, comparing to 2005, for all buildings with 25,000 sp.ft. or more. The target is more demanding for municipal buildings, with 40% less emissions by 2025 and 50% less by 2030. The law covers 50000 buildings which are only five percent of NYC's one million buildings but represent close to 60% of the built area of the city. Owners must submit an expert-validated annual emissions report. For cases not financially feasible to meet the targets, such as affordable housing, alternatives are given.

Monitoring the reduction of energy consumption in buildings (or equivalently, their gain in energy efficiency) is divided into two periods: 2024-2029 and 2030-2034. In each of these periods, the categories of buildings (housing, commerce, health services, among others) have different emission ceilings (kg CO2 eq/sf/year) and are more demanding in the second period. For those who break the limits, the penalty is $268/year/metric ton, considered a *de facto* carbon ceiling. In the first period the 20% of the most polluting buildings in New York City will be covered, in the second it will be 75%.

The study on the feasibility of a citywide trading scheme for greenhouse gas emissions from buildings determined by Local Law 97 produced initial guidance on the approach to a compliance trade mechanism, in terms of pricing mechanisms, credit verification, and mechanisms for regular improvement of the scheme and that it always considers an equitable investment in environmental justice communities. The local carbon trading market plays a complementary role in achieving the goals, allowing building owners the possibility to trade emission offsets, but with restrictions on those who buy them or buy renewable energy credits as they are limited to the energy generated by the system that provides New York City. The Urban Green Council, mandated to carry out the study (Figure S3), emitted as first guidelines in 2020, in relation to the determination of a price, that the market should be allowed to act, though having some degree of control over the price. Five main points suggested: to avoid controls and let the marketplace set prices; set to price floor; set a price ceiling; create market stability reserves and provide a purchase guarantee (UGC, 2020). In its complex and innovative architecture, the NYC climate action model is still under construction. The emission limits should take effect in 2024.

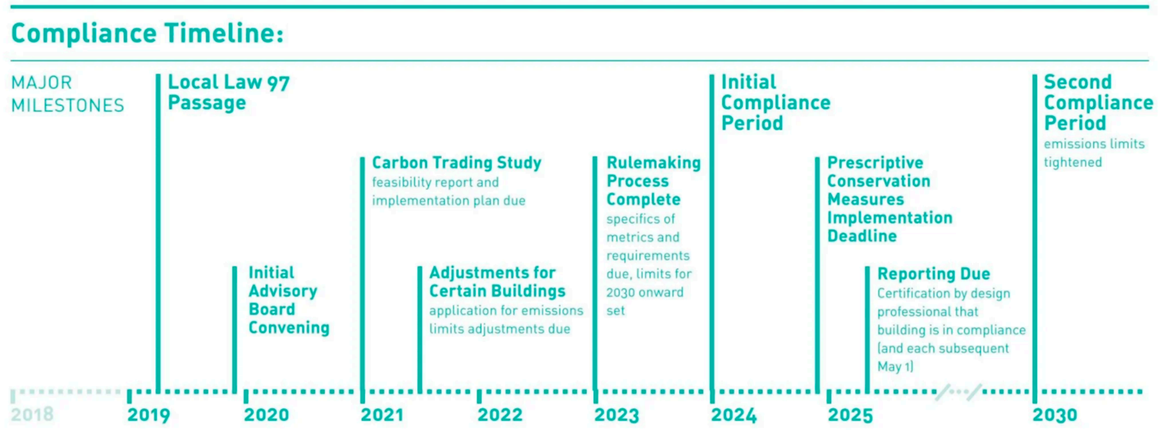

Figure S3. NYC carbon market timeline (Source: NYC Mayor's Office)

Box S4. Carbon pricing initiative of Anne Arbour, USA

Carbon pricing initiative of Anne Arbour, USA

The American City of Ann Harbor asked the University of Michigan to explore the impact and design of a carbon fee program, specifically an internal carbon fee, to find out what the result would be in terms of consumption, cost, and emissions. The program aimed to put a price on Ann Arbor's municipal carbon emissions with the prospect of starting in fiscal year 2021. The simulation[1] was for a \$5 metric ton scenario, with estimated impact of increases in energy and fuel costs of 1.5 to 4.4 percent in 2020. In the first program year, the internal carbon fee would result in a 0.1 percent emission reduction, \$173,200 in revenue. The annual fee increase of \$5 per metric ton would allow the city a 7.4 percent reduction in emissions and gross revenues of \$1.2 million.

In 2021, the mayor of Ann Arbor proposed the city to introduce a 20-year 1-mill property tax to help fund the city meet carbon neutral (A2Zero) target by 2030, with 100 percent renewable energy, electrification of consumption, a "significant" increase in the energy efficiency of buildings and 50% reduction in distances traveled by car (Fleming, 2021). To take effect, Ann Arbor voters have to approve the tax as the city of Boulder did. It is estimated that during the 20 years-life of the fee, \$130 to \$150 million revenue will be collected. Support measures for low-income families are being planned.

[1] Freed, A., Jones, L., Lo, Y. T., and Ren, R. An Internal Carbon Price for the City of Ann Arbor. Master Thesis, University of Michigan, USA, 2020.

Oslo, Norway

Carbon pricing initiative of Oslo, Norway

Oslo wants to halve its emissions by 2023 and be carbon neutral by 2030, 95% less than in 2009, the baseline year because of being the first with detailed emissions data at the local level (Oslo, 2016). Instead of a market-based policy instrument for GHG mitigation, the city chose to base its climate governance on a Carbon Budget (since 2016), supported by a city funding scheme, combining it with government grants and subsidies, to fund its GHG emissions mitigation action.

It was the first city in the world to have this type of model. The local fund is financed by an electricity fee, the interest on its liquidity and other municipal revenues, and subsidizes climate and energy measures, for emissions reduction and increasing energy efficiency, through contributions from citizens and businesses. Families pay one cent fee on the electricity bill to the fund.

Annually, the Carbon Budget establishes the city's GHG emission ceiling and calculates the effect of the measures to reach the goal, in the contribution of not only local measures, but also national and regional ones. The local Carbon Budget effort is integrated into the local fiscal budget as well. The city has 42 mitigation measures initially identified at the national government level and reaching the target depends heavily on a Carbon and Capture and Sequestration (CCS) installation at the Klemestrud waste and energy incineration plant (15% of the reduction). The municipality hopes to be able to export the technology that it is currently developing.

For annual monitoring, Oslo uses a climate barometer with 14 indicators updated three times a year, allowing it to identify flaws in metrics and track all changes, for example, in traffic flows, fuel consumption, travel or public transportation. The city found that it missed the 2017 target and in 2020 a new methodology for GHG inventories from the Norwegian Environment Agency (Oslo, 2021) which disaggregates data by municipalities, significantly increased distance to targets for buildings and construction (Figure S5). In Oslo, 88% of the city's GHG emissions come from road transport, buildings/construction, and waste. Between 2009 and 2024, the predicted reduction in historical emissions is 402700 tCO2e.
The municipality combines different non market-based climate and energy instruments for its public policy, from command-and-control instruments (requirements for recycling materials and zero emissions for the construction sector), to active green technology support (CCS plant), subsidies (encouraging increased demand for public transport), tariffs (charging of electric cars and differentiated tolls for electric and combustion vehicles) and fees (electricity fee).

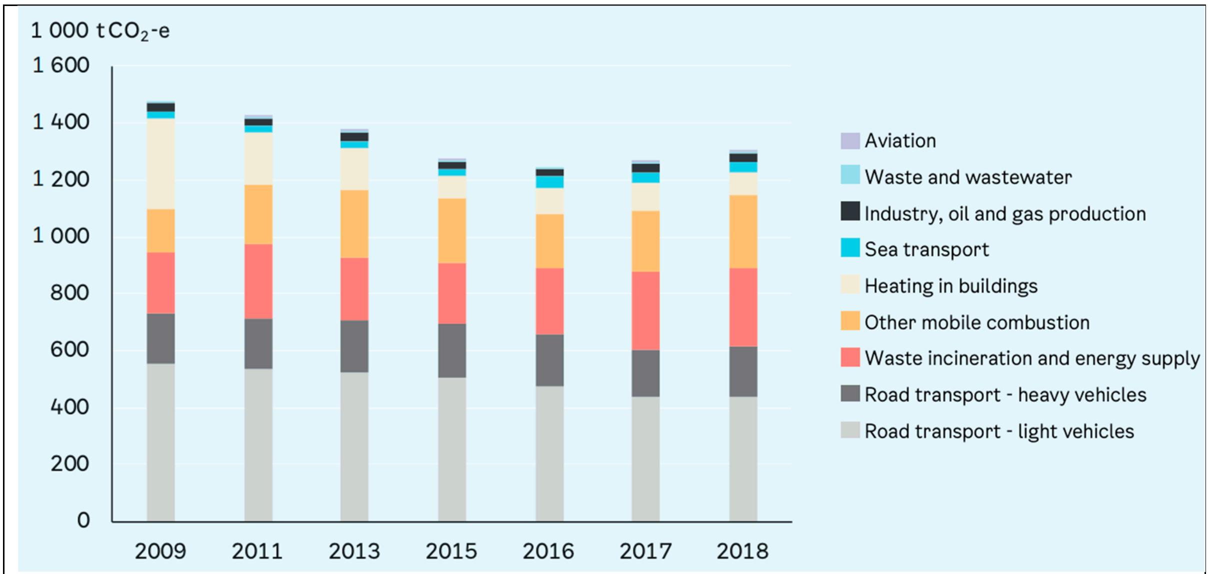

Figure S5. GHG-emissions in Oslo, 2009–2018.
(Source: The Norwegian Environment Agency/Climate Budget 2021 Oslo)

Lahti, Finland

Carbon pricing initiative of Lahti, Finland

The city of Lahti, in partnership with local academic (e.g. Lappeenranta University of Technology and Lahti University of Applied Sciences) and private organizations (e.g. Mattersoft Ltd and MOPRIM Ltd), developed a the CitiCAP project aimed to promote sustainable and low-carbon urban mobility in the city by experiment a Personal Carbon Trading (PCT) scheme. The PCT aim to promote and reward behavioural changes and was co-designed in the framework of the Sustainable Urban Mobility Plan and through a participatory and user-led process (CitiCAP, 2018). The scheme considers an allocation of a certain carbon allowance to each individual from within an overall national or local cap on the quantity of carbon emission produced by individuals under the same boundaries. In other words: *People surrender their credits as they make certain purchases that result in emissions. Those who need or want to emit more than their allowance have to 'buy' allowances from those who can emit less than their allowance. Alternatively, those who emit less can be rewarded for doing so. The market effect encourages people to pursue energy efficiency and to reduce their carbon emissions*. (CitiCAP, 2018). The CitiCAP project was the first pilot to test PCT to reduce city transport emission and was tested during 2020 and covering 1300 users.

The project considered different CO2 prices and based on literature or adopting prices of national/supranational carbon trade schemes (e.g. EU-ETS). Therefore, € 1 000 tCO2eq− 1 was chosen as the first carbon price for the high price scenario. The second price chosen was € 100 tCO2eq− 1, and the third € 27 tCO2eq− 1, referring to the present EU ETS carbon price (Kuokkanen et al., 2020; Uusitalo et al., 2021). Lahti study show benefits of competition between citizens in terms of co2 emissions allowance using a proxy of higher income and lower income status. The citizen specific share allocates the same amount of allowance to each user but grants extra allowances based on the number of children under 15 years of age and the distance between the user's home and services. The age of 15 was chosen because a 15- year-old person may get a moped driving license in Finland which provides more independent mobility.

Lahti also add additional criteria to conditionate the allowance amount:
-Number of children: extra allowances depending on the number of children
-Living location: if 20km city centre receive more allowances because services are located further from where they live.

The Lahti case study tested the capacity a of using economic incentives to influence individual's mobility habits with a CO2 price and under a PCT scheme, and effective and engaging way to encourage people to register and reduce transport emissions (CitiCAP, 2021).

Box S7. Carbon pricing initiative of Aradippou, Cyprus

Carbon pricing initiative of Aradippou, Cyprus

Aradippou city climate action plan (established in 2015) considers incentives for investment by households in energy efficiency and solar photovoltaic (PV) to accelerate energy transition. The experimental project, supported by the European platform City Finance Lab (CFL), rewards citizens who invest in PV panels and generate credits for avoiding CO2 emissions (CFL, 2015). The initial stage of this process includes the sale of these credits in small local auctions, with verification by energy auditors. The credits become aggregated at city level, with a second level of verification by local auditors, and verified emissions are placed on the international carbon market. The credits are then traded as carbon offsets for actors on compliance or in the voluntary carbon markets (Figure S7). Revenues are channeled to a municipal fund and the payments to citizens associated with the sale of these credits are made by credit card linked to the municipality, called the Oxygen Rewards Club. The Cypriot municipality announces that it wants to transform it into a permanent municipal service through its One-Stop-Shop (OSS) project ((Boza-Kiss, 2020).

In 2016, the city adopted a climate mitigation pilot program aiming for a 28% reduction of GHG emissions by 2020. It included loans on favorable terms (soft loan scheme) for the installation of photovoltaic panels in homes, in partnership with Cypriot financial institutions and support from European institutions (Aradippou, 2018). Aradippou, with 20,000 inhabitants, is a member of the Covenant of Mayors and Energy Cities. The city had the technical assistance of City Finance Lab, Climate-KIC and South Pole, European entities devoted to developing innovative financial solutions for sustainability and climate action, and co-funding by the European Union. No information is available about transactions carried out and the price.

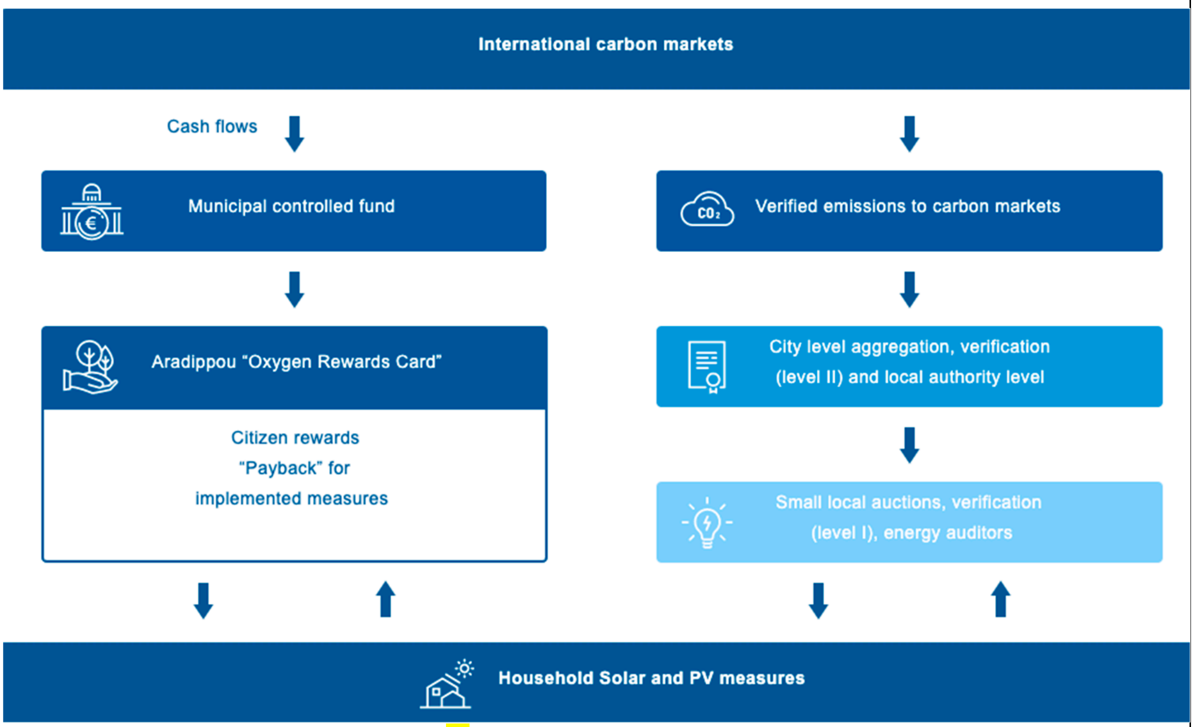

Figure S7. Aradippou carbon market model
(Source: European City Finance Lab)

Bologna, Italy

Carbon pricing initiative of Bologna, Italy

Between 2015 and 2018, the city of Bologna developed a concept of a local voluntary carbon market (see Figure S8), based on the positive effects of the municipality's investment in bicycle lanes and on the generation of CO2 credits from the emissions avoided by this sustainable active mobility option(Bologna, 2018b, 2018c, 2018a). The capacity of a local carbon market to finance climate mitigation initiatives of the local government was tested using the revenues generated by the sale of avoided emissions credits to companies. The credits are certified by a third-party. For the local public administration, it can act as a mechanism to encourage investment in sustainable projects in the city. For business actors, it can also stimulate their real engagement in the climate action in the city where they operate, with partial compensation of their activity GHG emissions. The city bike path network was expanded and renewed in this period since it was the core infrastructure used by the citizens to generate carbon credits. The period between 2003 to 2008 was established as the baseline of CO2 emitted in car trips in the city and used to quantify the emissions saved in the subsequent period, from 2009 to 2018. The generation of voluntary credits by bicycle users was estimated through a manual and digital monitoring system, with 11 stations located on the main roads of the city center and surroundings. External certification bodies verify these credits for compensation purposes, which also serve to define their economic value. Through credit purchase agreements by companies, they undertake to protect the environment and containing CO2 emissions. Credits are traded using eco2care.org platform.

The municipality indicates that between 2009 and 2018 around 10593 tones of CO2 were saved, corresponding to 18000 credits, with a unit value of €10, which represents ~€17/tCO2. Lamborghini encouraged the development of this experimental project and was the first company to join, having acquired 4000 credits. The development of Bologna Carbon Market (BoCaM) was financed by European Union support programs for experimental projects in the field of local climate governance. The municipality of Bologna, with 380,000 inhabitants, is a co-founder of the Covenant of Mayors, a member of ICLEI and other international local government initiatives for climate governance.

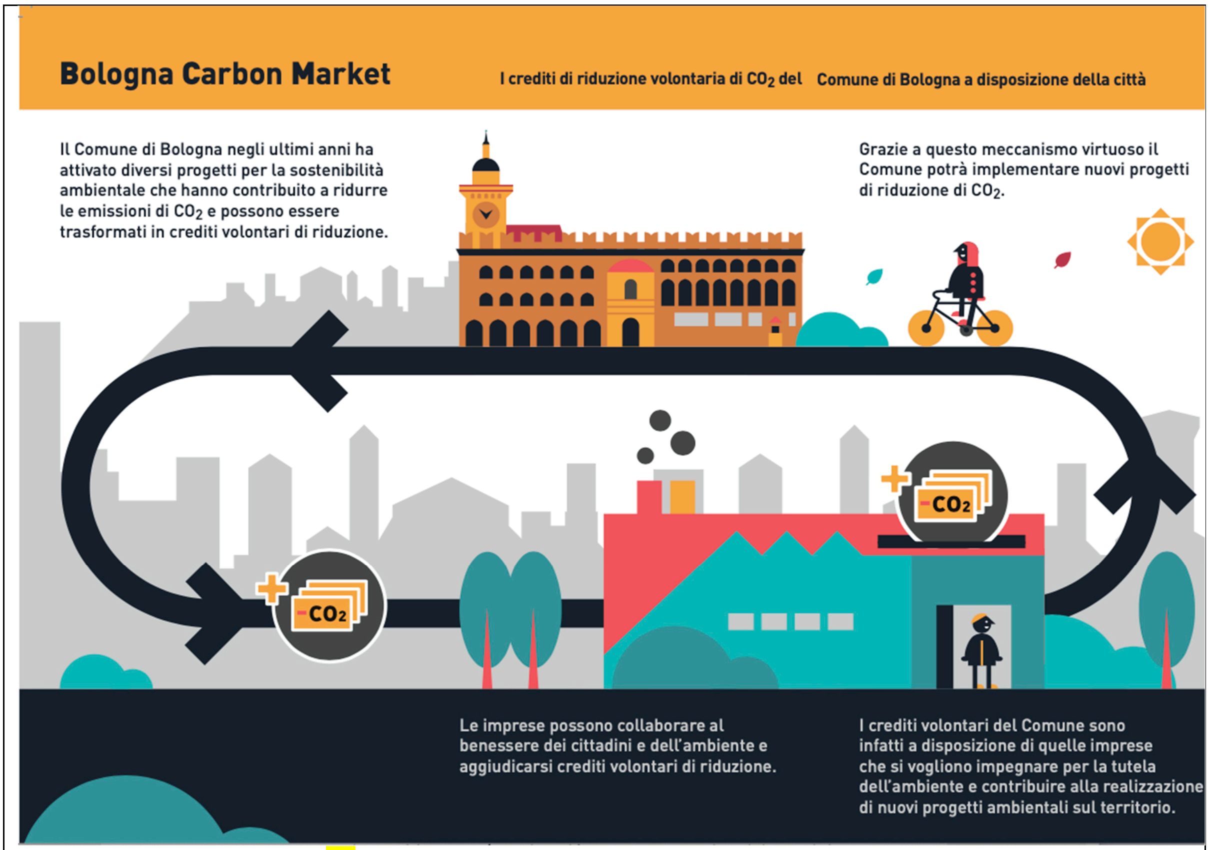

Figure S8. Bologna Carbon Market model (Source: Comune di Bologna)

Carbon pricing initiative of regional pilots in China: Beijing, Tianjin, Shanghai, Shenzhen, Chongqing

China has long faced the challenges of rapid urban expansion and economic growth, high GHG emissions and serious environmental pollution. At the highest political level, China has decided to pursue a green development strategy with a commitment to reach carbon emission peak by 2030 (mid-term) and carbon neutrality by 2060 (long-term). The near-term goal for 2025 is to reduce 13.5% energy intensity and 18% CO2 emissions intensity from 2020 levels. The Chinese government considers that market-based policy tools such as ETS can help the country achieve these ambitious goals and has been experimenting these tools via eight subnational voluntary ETS pilots in the last nine years: Beijing, Tianjin, Shanghai, Shenzhen, Chongqing (city level), Fujian, Guangdong, and Hubei (provincial level). In parallel, a national ETS scheme has also been in preparation based on the rich body of experiences of regional ETS pilots for more than four years. In this mechanism, the central government first sets the total emission limits for each province and city, and then the provincial and city governments allocate emission permits to designated industries and enterprises. Currently, the enterprises participating in carbon emissions trading are mainly enterprises with extensive carbon emission records. Enterprises can only discharge within the given emission allowances. Enterprises that need larger emission quotas than those given must acquire more quota, while those who have emission quota surpluses can profit from selling them. Enterprises adjust their production needs and goals by trading carbon emission quotas and completing their obligations of quota supervision, reporting and verification independently within each compliance period. The Chinese government considers this the most direct and effective market incentive for enterprises to manage their GHG emissions. In January 2021, the Ministry of Ecology and Environment officially announced the start of operations of the national ETS along with the promulgation of the regulation document Management Measures for Carbon Emission Trading (in Chinese: 全国碳排放权交易管理办法; pronounced as quánguó tàn páifàng quán jiāoyì guǎnlǐ bànfǎ). This document stipulates the details of the actors and methods of trading. The national ETS platform is planned to be launched in June 2021, marking 2021 as the first compliance cycle of China's national ETS.[1]

In general, climate mitigation actions at the city level in China are mainly conducted in three ways. One is the through designation, in which the central government assigns or designates a certain city or province to conduct pilot projects and provides technical, financial, political support. Often these pilot projects are the most innovative and highly experimental. The second way is through public bidding, in which the central government opens a call and cities submit their application to test or build a pilot program. Those who are selected to implement a pilot program often get technical, financial, and political support from the central government. The third type is local voluntary action to meet the initiatives of the central government. These local voluntary actions could be along the direction of national initiatives or innovative proposals from the local level. Usually, the central government does not provide financial support for these local voluntary actions but could provide technical and political support through honorary titles and political influences. The latter often also brings private sector investment opportunities and economic growth potentials. These three types of urban governance follow the same trajectory: once they are learned and proven successful, they would be promoted by the central government to scale up nationwide.

These Chinese ETS pilots share the same governance structure. The Provincial/Municipal Development and Reform Commissions are the leading authority responsible for the ETS pilot management and supervision. The Provincial/Municipal Market Supervision Bureaus are responsible for the qualification and management of emission verification agencies and professionals. The Provincial/Municipal Bureaus of Statistics are responsible for the verification of the industry-specific GDP data.

Shenzhen (city) and Hubei (province), for example, are among the most active Chinese subnational ETS pilots. The industries included in the emission base quota distribution in Shenzhen are electricity, water, gas, manufacturing, public transport, airports, and ports. While in Hubei, the industries involved in its ETS pilot are somewhat different: power, glass, aluminum, calcium carbide, pulp and paper, automobile manufacturing, iron and steel, ferroalloys, ammonia, cement, and petroleum processing. Both ETS pilots are participated by enterprises whose annual emission is equivalent to or above 3000 ton of CO2e. Given the infancy status at which the subnational ETS schemes were, the central government had granted the local governments the autonomy to adjust the number of candidate enterprises in the emission quota distribution. Candidate enterprises are those whose emissions are between 1000-3000 tons, which, at the time of the pilot scheme, only had reporting obligations but need not obey the limit of base quotas. The Chinese subnational ETS pilots drew on the experience of European practices to allocate base quota and adjust market dynamics with surplus quota, with the base quotas always allocated free of charge.

In terms of pricing and trading models, different subnational ETS pilots have also developed their own models based on local emission scenarios and actual needs (such as mitigating excessive price fluctuations). For example, in addition to online trading, the Beijing ETS pilot has also introduced an over-the-counter trading model: entities selling more than 10,000 tons CO2e are required to use the over-the-counter trading method. Participants negotiate offline and reach an agreement before registering the transaction at the local ETS platform. The Beijing ETS pilot does not set nor suggest an initial price; rather, enterprises placing buy and sell orders on their own in the trading system, which generate and influence the market price. The average transaction price of Beijing's ETS pilot on the first day of opening in 2013 was 51.25 yuan (~6 euro). Shanghai's ETS pilot has taken the lead in issuing carbon emission accounting guidelines, adopting the historical emission method and the baseline method to measure emission allowances. While Shenzhen has given full play to its fine tradition of being the special pilot zone of China's Economic Reform and Opening-up, opting to allow individual and corporate financial investors to participate in carbon trading. Guangdong, on the other hand, has taken the lead in setting up a pilot program for the paid allocation of surplus quotas/allowances through auctions and bidding. In the issuance of paid allowances, the Guangdong ETS platform sets a final bid price based on market demand and emission reduction targets (for example, the price for per ton of CO2e of surplus quota in 2013 was 60 yuan per ton or roughly 7.5 euro), and then sells the surplus allowances to the specified bidders who offer higher quotations within a given time. In the Hubei ETS pilot, 8% of the total cap is reserved by the local government for market stabilization after consultation with an advisory committee consisting of government institutions and other stakeholders.

The Chinese subnational ETS pilots have a unique MRV process: the carbon emission and GDP data of enterprises are verified by third-party carbon verification agencies and municipal statistical agencies. Third-party verifiers may be involved in verifying emission data or verifying the verification reports done by other third-party verifiers. In addition, further validation is carried out by government-assigned experts to enhance the accuracy further; alias, the "fourth-party verification". These ETS pilots register and manage emission quotas similarly to the stock exchange practices, with the provincial/municipal government authorities managing the emission quota information system. The provincial/municipal governments also supervise the data, verification institutions, trading institutions and the trading behavior of market participants. Trading institutions refer to trading rules, trading methods, publication of trading information, handling of market anomalies, and trading fees. These pilots are open to diversified market participants, including enterprises that are qualified for base quota or those that have reporting obligations and institutional and individual (domestic and foreign) investors.[1] It is notable to mention that Wuhan, the capital city of Hubei Province, is hosting one of the largest public bike-sharing schemes in the world at the city level promoted through an innovative bottom-up carbon credit scheme, with more than 80,000 bicycles and more than 3,000 service points invested and put to service. The carbon emission avoided by individual bicycle users is converted into carbon credits for purchasing local goods and services or for deducting their carbon emission from other activities[2]. Although it is not in the plan yet to integrate this individual carbon credit scheme into the Hubei subnational ETS pilot.

1. Shi Shi and Aoling Shen: 2021. National ETS going live in end of June. (In Chinese: 全国碳交易系统即将启动，6月底开始线上交易) http://www.tanjiaoyi.com/article-33637-2.html

2. Asia Development Bank. 2018. Climate solutions from 50 Chinese cities – best practices in urban climate change actions. (In Chinese: 来自中华人民共和国50座城市的气候解决方案 – 城市应对气候变化的最佳实践). Available at: https://www.adb.org/sites/default/files/publication/482646/50-climate-solutions-prc-cities-cn.pdf

Box S10. Carbon pricing initiative of Tokyo, Japan

1

Carbon pricing initiative of Tokyo, Japan

Some authors consider megapolis Tokyo world's first cap-and-trade program for office buildings as local (Kojima and Asakawa, 2021) others as regional (Arimura and Abe, 2021), given its demographic dimension of 13,3 million inhabitants. Tokyo ETS is Japan's first mandatory ETS (EDF *et al.*, 2015), launched in 2010 by Tokyo Metropolitan Government (TMG), after national government hesitancy to create a national ETS (Figure A.7). Tokyo ETS is linked with Saitama local ETS, both having exchangeable credits. Prior to this program, Tokyo had two others, the Green Building Program in 2002 and the District Plan for Energy Efficiency in 2008, with a common goal to increase the energy efficiency of buildings in the Tokyo metropolitan area. Tokyo wants to achieve a 30% reduction of GHG emissions by 2030 and to be net-zero in 2050. Tokyo ETS covers ~20% of the total GHG emissions, covering buildings that are large consumers of fossil energy (at least 1,500 kl of crude oil per year), such as large commercial and services buildings (1.000 facilities) and factories (200).There have been few transactions in the market (30), mostly bilateral trade, because covered buildings have managed to keep below the ceiling by adopting highly efficient equipment (internal reduction measures), and only emitters are allowed to trade since financial sector is excluded.

Tokyo ETS is currently in the third compliance period (2020-2024) which mandates that buildings must lower their emissions by 25% to 27% compared to the base year. Under the program, 27% of emissions were cut in the first two compliance periods (2010-2014, influenced by the earthquake, and 2015-2019), despite an increase in gross floor space, meaning that overall, facilities did better than expected; 91% of facilities overachieved the emissions reduction target and 9% reached the goal through the acquisition of credits. According to Arimura and Abe (2021), half of the emission reduction in Tokyo was a result of the ETS, while the rest of the reduction was due to the electricity price increase caused by the Great East Japan Earthquake in 2011. And new measures as rolling blackouts and power saving orders, also because of the earthquake, may have contributed for the emissions reduction (Abe and Arimura, 2021).

The average 2020 price was JPY 540 ($5,06), according to TMG, and credits traded in Tokyo ETS come from four offset types (ICAP, 2021): renewable energy credits generated under Tokyo ETS; emissions reduction from large facilities outside Tokyo; emissions reductions from non-covered small and medium-sized facilities in Tokyo; and Saitama credits. TMG own credits are a market stability mechanism as they can be traded for containing large market price variations. Some aspects make Tokyo emissions trading scheme unique: the emission regulation covers universities, commercial and manufacturing sectors, and nonlarge-scale power plant because they are not located in Tokyo. The measurement of emissions is not by fossil fuels combustion (as in the EU ETS), but by carbon intensity, an indirect indicator of emissions through electricity consumption. The certification of emission reductions is based on 200 energy efficiency measures (Abe and Arimura, 2021).

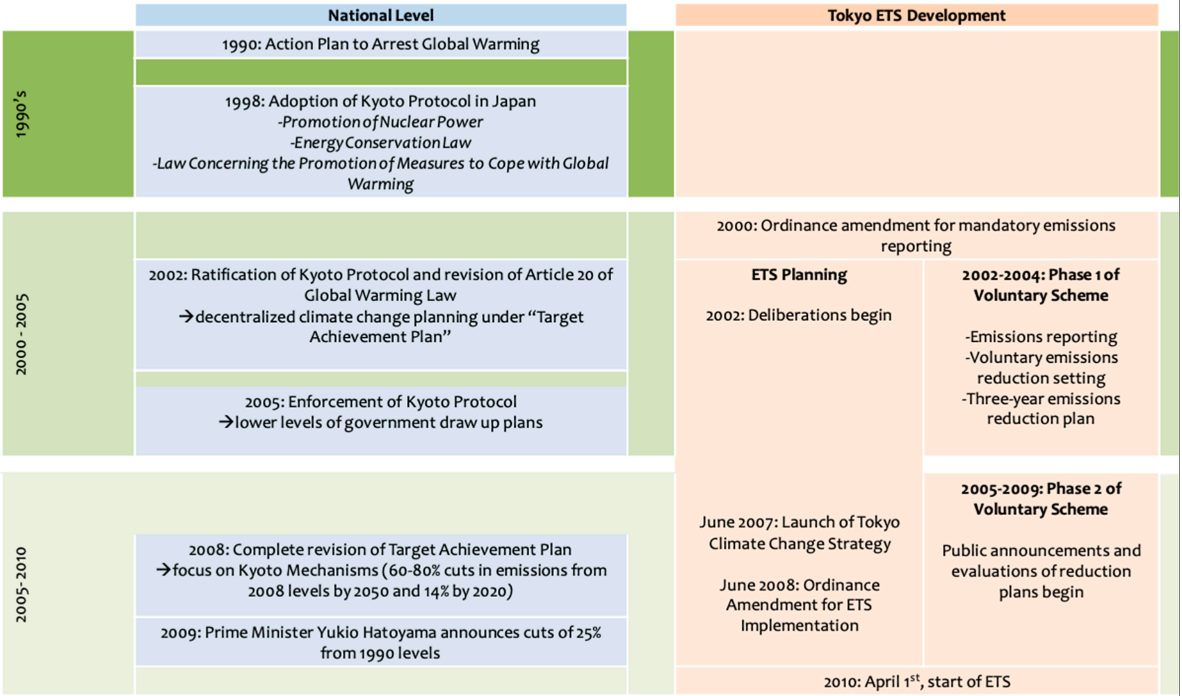

Figure S10. National and city level climate change mitigation in Japan
(Source: World Bank/ openknowledge.worldbank.org)

Singapore

Carbon pricing initiative of Singapore

Singapore's carbon pricing model for its decarbonization is a two-phase plan (see Figure S11) The first with the adoption of a carbon tax, the second with the launch of a global carbon crediting market supported by two carbon exchanges, seeking to respond to specific circumstances of its competitive geography and economy. The city-state is a territory with no space to install utility scale renewable energy, and despite a growing services sector and a competitive global financial hub, it continues to have a strong presence of industrial multinationals and their suppliers, large exporters, and energy consumers, under pressure to reduce its CO_2 emissions (Carbon Dated, 2021). Singapore's government also aims halving GHG emissions between 2030 and 2050 and achieve carbon neutrality “as soon as possible” (Singapore, 2021) . From 2019, it applies a carbon tax of S$5 (€3) until 2023, for the entire industry that emits more than 25 thousand tons of CO_2 per year. In February 2017, the government had announced a carbon tax between S$10 and S$20 per ton of GHG emissions (Li and Su, 2017). The prediction was significantly reduced as in February 2018, the acceptance of the S$5 fee by ExxonMobil and Shell (Bantillo, 2018) was announced. In 2023 the rate will be revised.

Aircarbon was launched in June 2020 and securitizes carbon credits that are placed on the market for airlines. It presented itself as the first platform to use blockchain technology, in which credits are tradable tokens and each token is equivalent to a ton of carbon credits.

In May 2021, Climate Impact X (CIX) was launched, a marketplace for nature-based projects with monitoring of their integrity, generating carbon credits for multinationals and institutional investors. The difference that CIX intends to make in relation to the existing exchanges is in the transaction of credits that come primarily from Southeast Asia's reforestation, ecosystem conservation and wetlands and grassland recovery projects, with the use of satellites, artificial intelligence and blockchain to ensure the credibility of the projects, so-called high quality carbon credits.

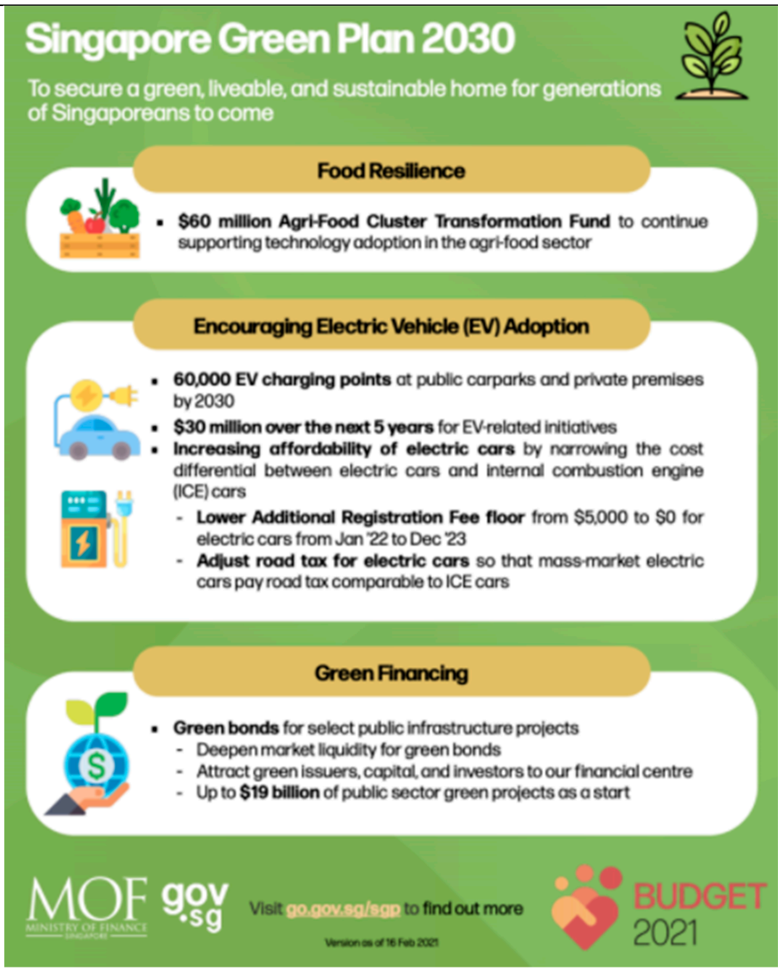

Figure S11. Singapore Green Plan 2030
(Source: MOF Singapore)

Table S12. Total energy system cost and GHG emission in the modeled scenarios

Table S12. Total energy system cost and GHG emission in the modeled scenarios

Scenario	Total system cost in 2030 M€2018	GHG emission ktCO2e

With 2050 Carbon neutrality objectives		
Reference	44064	28 576
PT_17.5%	43399	28 576
PT_20.6%	42974	28 576
PT_23.7%	42569	28 576
PT_26.8%	42137	28 576
PT_30%	41754	28 576
AM_7%	42591	28 576
AM_8.3%	42393	28 576
AM_13%	41457	28 576
AM_18%	40481	28 576
AM_25%	39159	28 576
SM_3.5%	43852	28 576
SM_5.1%	43725	28 576
SM_6.8%	43568	28 576
SM_8.4%	43421	28 576
SM_10%	43437	28 576
IM_PTAM	40593	28 576
With 2050 Carbon neutrality objectives		
Reference (no2050NZ)	43660	32 218
PT_17.5% (no2050NZ)	43090	31 769
PT_20.6% (no2050NZ)	42709	31 469
PT_23.7% (no2050NZ)	42315	31 906
PT_26.8% (no2050NZ)	41922	31 795
PT_30% (no2050NZ)	41542	31 778
AM_7% (no2050NZ)	42331	31 225
AM_8.3% (no2050NZ)	42155	31 097
AM_13% (no2050NZ)	41244	31 343
AM_18% (no2050NZ)	40350	31 241
AM_25% (no2050NZ)	39069	30 618
SM_3.5% (no2050NZ)	43472	32 055
SM_5.1% (no2050NZ)	43373	31 966
SM_6.8% (no2050NZ)	43236	31 845
SM_8.4% (no2050NZ)	43098	31 723
SM_10% (no2050NZ)	43112	31 728
IM_PTAM (no2050NZ)	40539	29 895