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Tax or Trade? An agent-based model of CO2 certificate trading versus taxing.

Bachelor's Project Thesis

Tim Chandler, s3173593, t.chandler@student.rug.nl
Supervisors: Dr B.R.M. Gattinger

Abstract: It is widely accepted that a reduction in global Carbon Dioxide emissions is necessary for combating Climate Change. There are two main economic approaches that governments take to incentivise these reductions; Carbon Taxes and Cap-and-trade systems. In this paper the impact of both emission reduction approaches on the CO2 emissions of the electricity production industry are compared. These comparisons are carried out using an agent-based model, comparing both of the approaches in a variety of settings. This research aims to show the value of each approach, as well as the ideal manner of implementation and serves as a stepping stone to deeper research into the topic.

Keywords: carbon pricing, carbon tax, cap and trade, emissions, agent based model

1 Introduction

It is well established that anthropogenic emissions of carbon dioxide (CO2) are leading to changes in the global climate (Cox, Betts, Jones, Spall, and Totterdell, 2000). Carbon dioxide emissions are produced by a wide range of industries. For many of these industries a decrease in emissions could lead to an increase in costs, or decrease in profits. As such, externally applied measures (carbon pricing) are required to incentivise the reduction of emissions.

Carbon pricing measures have been adopted by governments at state, national or even international levels. These measures have been adopted at an increasing rate over the last 20 years, with the percentage of global emissions covered going from only 1% in 2001 to a projected 23% in 2021 (Ramstein, Dominioni, Ettehad, Lam, Quant, Zhang, Mark, Nierop, Berg, Leuschner, et al., 2019). Within these implementations there are two main approaches to carbon pricing.

Firstly, Carbon Tax - in which entities are either directly taxed on their emissions, or on the carbon content of the fuels that they use. This way, the amount of tax paid scales with the amount of CO2 produced but there is no upper limit on the total amount of emissions.

Secondly, there is Cap-and-trade, also known as Emissions Trading Systems or ETS. In these systems a predefined cap is set on the amount of CO2 emissions. Credits are then typically assigned or auctioned to eligible entities as defined by the schemes' governing authority. Each credit allows the entity holding it to emit a certain amount of CO2, typically one metric tonne. Any emissions by an entity in excess of the credits held are penalised. Entities may also trade the credits amongst themselves, covering higher emission rates from penalties or profitting from lower emission rates.

Both Carbon Tax and Cap-and-trade have been widely implemented (Ramstein et al., 2019). These implementations vary on a case by case basis.

1.1 Tax or Trade?

There are advantages and disadvantages to each carbon pricing approach. The arguments for, or against can largely be split into two categories.

Firstly, the impact on total CO2 emissions. Here, there is an advantage for the Cap-and-trade approach. By setting an overall cap, which can be reduced over time the government has direct control over the total emissions within the given time period (Boyce, 2018). Provided the system is well enforced, and there are meaningful penalties for going outside of the allotted emissions allowance this approach allows for only a very small amount of excess emissions. Conversely, carbon tax holds a greater potential for performing above expectations. Due to the consistent cost of emitting there is a constant incentive to prevent or reduce the emissions.

Secondly, the impact on the economy. Evidence has shown that the negative economic effects of carbon pricing tend not to be statistically significant, with the outlying, significant effects being of low magnitude (Venmans, Ellis, and Nachtigall, 2020).

Both carbon pricing approaches are not equal in their economic impact however. Cap-and-trade has been shown to lead to a greater market volatility than Carbon Tax (Venmans et al., 2020). This is due to the price fluctuations for Carbon credits. Carbon Tax provides greater stability, allowing for more predictable costs and more accurate planning.

Considering the pros and cons of each approach leads to the following question: Does a Carbon Tax lead to a greater Reduction in CO2 emissions than that of a Cap-and-trade System?

This paper aims to provide an answer to the question through the use of an agent based model. The model will simulate electricity companies, each with a series of power plants. The companies will use different combinations of power plants in response to the current carbon pricing and energy demand, dynamically altering their approach as the situation changes in order to maximise profits.

Electricity generation accounted for 25% of CO2 emissions in the Annex I United Nations countries in the year 2000, dropping to 20% in 2018 (United Nations, 2021) as such the electricity sector is an interesting focal point for examining the effects of emission reduction measures.

2 Method

This research makes use of an agent based model that has been developed in Java, using Maven for the dependency management. The visualisation of the model has been developed in Python 3 using the Seaborn library.

The repository for the model and the instructions for running it may be found in appendix A.

The model follows a heirarchical structure with three main components: a world, the agents which operate within the world, and the power plants held by the agents.

2.1 World

The world class represents the economy in which the model is operating. It stores the current setup of the model and holds all other classes within the model. The world initialises the model with the parameters shown in table 2.1. This initialisation involves creating the agents and power plants. The power plants are set up with a ratio of types as defined by the *split* parameter. These power plants are then randomly distributed amongst the agents.

2.2 Agents

The agent class represents power companies within the economy. Due to the manner in which power plants are created and assigned to agents, different agents can represent very different sizes of companies. In addition to this, the types of the plants held by the companies are not specific to the agents. This means that differing types of power plants will be modeled, with the potential for agents to hold only one type of plant, an even spread of all types or anything in between.

2.3 Power Plants

There exist a large number of different types of power production facilities, however, the differences between some of these categories in terms of emissions, power production and running costs are negligible. For the purposes of this model the types have been categorised as follows:

- Coal represents both coal and lignite power plants.
- Gas represents both natural and derived gas power plants.
- Wind represents wind turbines, solar plants, hydro electric plants and the other most common renewables as a whole.
- Nuclear represents only nuclear power plants.

The grouping of the different types of power production into these four categories both streamlines the model and makes it more widely applicable. Renewables such as solar, or tidal are not suitable for all environments, but share similar production, upkeep and emission costs. Therefore, with this categorisation the model does not need to consider whether the region being modelled has a coast, or has consistent sunlight.

The power plants are each assigned a type. Each type holds arechetypal values, as shown in table 2.2 for the electricity production rate, levelised cost of electicity (LCOE) (IEA, 2020) and CO2 emissions (IPCC, 2015).

To allow for variation in the power plants each new power plant is assigned values from a normal curve, using the archetypes as the mean values μ and using a standard deviation $\sigma = \frac{1}{10} \cdot \mu$.

The power plants keep track of the amount of time for which they are idle. The longer the plants are idle, the lower the idle cost of the plant.

2.4 Assumptions

Some assumptions have been made in order to prevent fragmentation within the model. These can broadly be categorised as follows:

2.4.1 Applicability

It is assumed that the reaction of the energy sector, as modelled here, is broadly extendable to the

Parameter	Purpose	Value, set or range
Split	The proportion of each type of power plant	US 2007
Agent count	The number of agents (Power Companies)	20
Total ticks	The number of ticks to run the model for	780 (15 years)
Tax rate	The initial tax rate in 1000 euros per tonne	{15, 30, 60}
Tax limit	The maximum tax rate in 1000 euros per tonne	{30, 60, 120}
Cap	The initial emissions cap in tonnes	
Cap change	The per year reduction in the emissions cap	{1, 2.5, 5}
Required electricity	The initial yearly amount of electricity needed in GWh	5300
Electricity price	The price of electricity in 1000 euros per GWh	94.71
Electricity increment	The yearly increase in electricity requirement	3%
New build chance	The per tick probability of a new power plant being built	0.3

Table 2.1: Parameters stored in the world and its associated classes

Parameter	Production (GWh/week)	LCOE (1000 euros/GWh)	CO2 Emissions (tonnes/GWh)
Coal	67	40.2	820
Gas	50	25.3	490
Nuclear	150	28.7	12
Wind	25	21.7	12

Table 2.2: Parameters per power type

reaction of the wider economy. This assumption is founded on the roughly 20% of emissions that can be directly linked to energy production (United Nations, 2021).

2.4.2 Other Measures

Additionally, no direct government intervention beyond the implementation of tax and/or cap and trade measures exists within the model. This draws from the assumption that additional measures would, on balance, increase the reductions presented by the model regardless of the approach being modeled.

2.4.3 Demand

The global trend for energy usage has been a year on year increase with a mean of 3% and a standard deviation of 1.5% annually from 1980 to 2017 (U.S. Energy Information Administration, 2021). This is assumed to be a constant rate of increase for the model.

2.4.4 Compliance

The companies do not break the law with regards to the tax or trade systems. As such the model assumes that the penalties for evading the measures are strong enough to fully disincentivise law breaking.

2.4.5 Stability

The model does not account for market instability such as that caused by the 2008 financial crash or COVID-19. Whilst such events do have an impact on energy markets general trends such as the aforementioned demand tend to normalise over time.

Stability also accounts for the assumption that the prices of electricity and the costs of running the power plants will remain constant throughout the models run. Whilst this is not true to life, it is assumed that inflation would have a minimal impact on the model.

State name	Coal	Gas	Nuclear	Wind
90% Fossil fuel	50%	40%	10%	0%
70% Fossil fuel	50%	20%	20%	10%
50% Fossil fuel	30%	20%	30%	20%

Table 2.3: Initial power plant distributions

2.5 Process

The model will be run with three different initial states, as shown in table 2.3. These represent the distribution of power plants during the initialisation of the model. The initial state of 70% fossil fuel is an approximation of the state of the United States power plant distribution in 2007, at the peak of US CO2 emissions (EPA, 2021). This distribution was gathered from the U.S. Energy Information Administrations data browser, querying the annual net generation by energy source (EIA, 2021b). The 90% and 50% fossil fuel distributions provide a basis from which to view how a higher or lower initial rate of C02 emissions is impacted by each applied reduction measure.

For each of these initial settings the model will be run with a high, medium and low carbon tax of 120, 60 and 30 euros per tonne of CO2 respectively (OECD, 2021). The model will also be run at a high, medium and low carbon cap reduction, with the medium rate based off the current EU cap reduction rate, giving 5%, 2.5% and 1% reduction rates respectively.

The models will be run for 780 ticks, representing 15 years. For the first 520 ticks the measures will grow stronger. For Carbon Tax this entails starting from an initial tax rate of half the goal tax, increasing at a steady rate for 520 ticks and then remaining constant. For Cap-and-trade this entails a yearly decrease in the cap equal to the specified amount for the first 520 ticks, then a constant cap.

The general process per run is shown in figure 2.1. The symbols used in the equations in this section can be found in table 2.4 This can be broken down into two main operations, the initialisation and the tick.

2.5.1 Initialisation

Before the model is run the model must be set up in accordance with the following operations:

1. Create agents equal to the number defined in table 2.1.
2. Create power plants such that the number n_p of power plants of each type $x \in \tau$ corresponds to equation 2.1 where the sum of electricity production for power plants of a given type is equal to the global electricity requirement weighted by two times the predefined portion of power plants of that type.

$$\sum_{i=0}^{n_p} e_{x_i} = R_g \cdot 2\rho_x \tag{2.1}$$

3. Distribute the power plants amongst the agents randomly.
4. Set the emissions cap C using equation 2.2. This calculates half of the total carbon emissions from all existing power plants. This is the amount of carbon produced for the required electricity generation using the exact predefined split of power plant types.

$$C = \frac{1}{2}\sum_{x\in\tau}\sum_{i=0}^{n_x} \alpha_{x_i} \tag{2.2}$$

5. Set the individual electricity requirement R_a per agent. This is determined by equation 2.3 where the maximum electricity production of a given agent is weighted by the maximum global electricity production.

$$R_a = \frac{e_a^{'}}{e_g^{'}} \tag{2.3}$$

2.5.2 Tick: Tax

For each tick in a tax simulation the following steps take place:

1. Each agent sorts their respective power plants in descending order of profitability normalised for electricity production $\bar{P}_p$, determined by equation 2.4.

$$\bar{P}_p = v - \frac{\alpha \cdot T + r_p}{e_p} \tag{2.4}$$

2. Each agent iterates through their power plants generating electricity until the total generated exceeds the agents alloted electricity requirement.

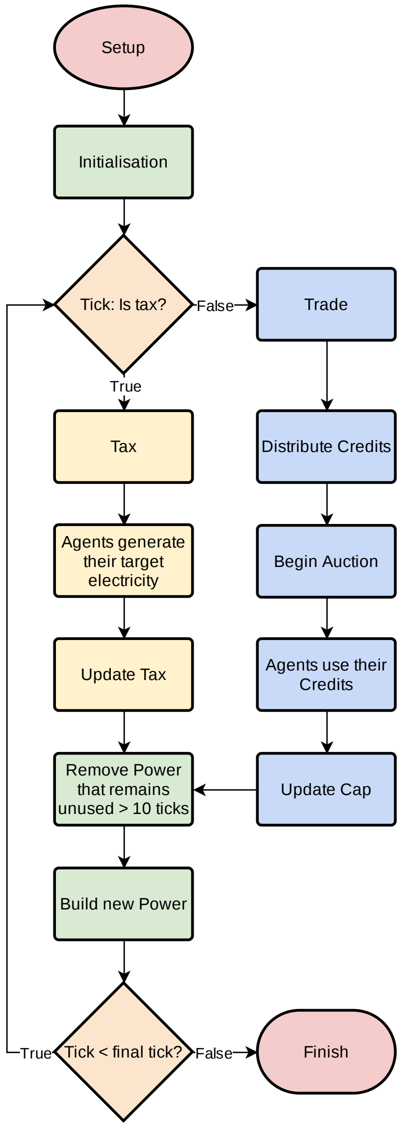


Figure 2.1: Conceptual design of the model process

3. Unused power plants have their inactivity recorded, and are removed from the model after 10 ticks without use.

4. The tax rate is updated. This is done per tick rather than per year (52 ticks) as it is in most real world systems to allow the agents to simulate the planning that real world companies may do in preparation for an upcoming increase in tax. If the simulation has reached 10 years (520 ticks) the tax rate is no longer updated. This allows any after effects of the measure to be observed.

5. The generic tick operations are completed.

2.5.3 Tick: Trade

For each tick in a trade simulation the following steps take place:

1. Each agent sorts their power plants in descending order profitability normalised for CO2 emission $\hat{P}_p$, determined by equation 2.5.

$$\hat{P}_p = \frac{v \cdot e}{\alpha} \tag{2.5}$$

2. Credits are distributed to each agent relative to their power generation capacity with the amount of credits c_a determined by equation 2.6.

$$c_a = c_g \cdot \frac{e_a^{'}}{e_g^{'}} \tag{2.6}$$

3. A decreasing price auction is initiated with an initial bid equal to b_{base} equal to the sum of the profit of the most profitable power plants, up to the individual power cap. This is then weighted by the electricity that the agent has generated in the current tick e_{a_tick} relative to the agents required production and the global proportion of credits that remain unused c_{tick} as shown in equation 2.7.

$$b_a = b_{base} \cdot max\left(1, 1 - \frac{c_{tick}^{'}}{c_{tick}} + \frac{e_a^{'}}{e_{a_{tick}}}\right) \tag{2.7}$$

4. Agents accept or reject a given price from the auction, accepting when their personally calculated bid, determined based on whether their most profitable unused power plant equals or exceeds the bid proposed by the auction, accepting the bid if it does and rejecting otherwise. When accepting a bid the agent states how many credits it would like to buy. If the agent already possesses that many credits no money or credits change hands, otherwise the credits are bought. The agent then immediately uses the credits.

5. The auction ends when either the global electricity requirement is reached or the carbon credits run out.

6. The cap is updated. As with tax, this is done per tick rather than per year to allow the agents to continuously adapt to changes. In the same manner as with tax, from 10 years the cap remains constant.

7. The generic tick operations are completed.

Symbol	Meaning	Units or values	Subscripted
P	Profit	1000 euros	always
e	Electricity production	GWh per tick	always
v	Electricity price	1000 euros per GWh	never
R	Electricity requirement	GWh per tick	always
α	CO2 production	tonnes per GWh	always
T	Carbon tax rate	1000 euros per tonne	never
C	Carbon cap	GWh per tick	never
c	Carbon credits		always
r	Running cost	1000 euros	always
b	Auction bid	1000 euros	always
n	Number of subscripted		always
ρ	The portion of power plants of a given type		always
τ	The set of power types	{coal, gas, nuclear, wind}	
A	The set of all agents		
Subscripts			
g	Global		
a	Agent		
p	Power plant		
Superscripts			
$'$	Maximum possible, for example $P_a^{'}$ represents the maximum possible profit for agent a		
$\bar{}$	Normalised for electricity production		
$\hat{}$	Normalised for CO2 production		

Table 2.4: Symbols and their associated meanings

2.5.4 Tick: Generic

For each tick in either a tax or trade model the following operations are carried out after the model specific operations are completed:

1. The global electricity requirement is updated.

2. New power stations are added with a probability of either 0.2 (low probability) or 0.4 (high probability). The probability of a specific type of power plant being added $Pr(x)$, where $x \in \tau$, is based on equation 2.8.

$$Pr(x) = \left(\frac{P_x}{e_x}\right) \cdot \left(\sum_{i \in \tau} \left(\frac{P_x}{e_x}\right)\right)^{-1} \tag{2.8}$$

3. Agents have the idle costs of any unused power plants deducted from their total money.

4. The electricity production and CO2 emissions are logged.

3 Results

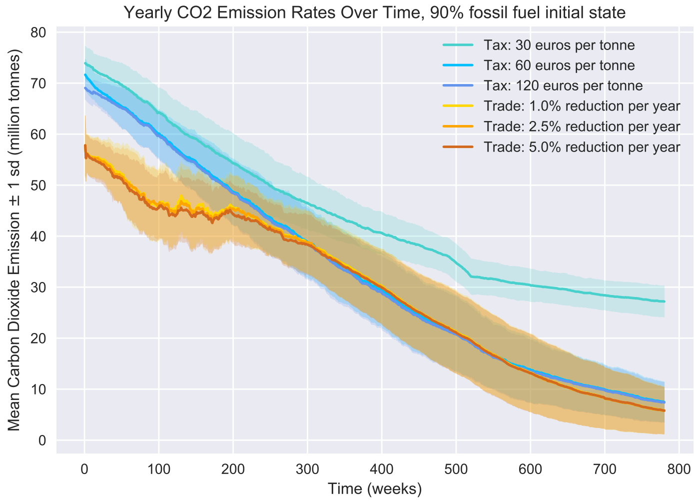
The model was run using the following CO2 reduction measures:

- Tax rates of 30, 60 and 120 euros per tonne of CO2

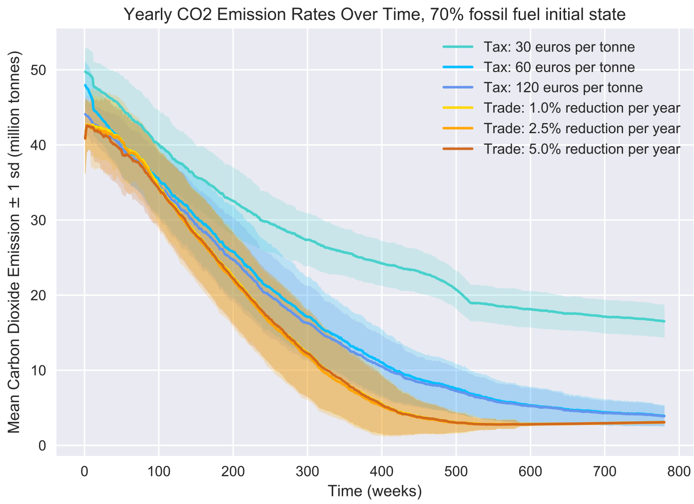
- Carbon cap reduction rates of 1%, 2.5% and 5% per year

Power plant distributions of 90%, 70% and 50% fossil fuel state, as shown in table 2.3 were used as the starting states.

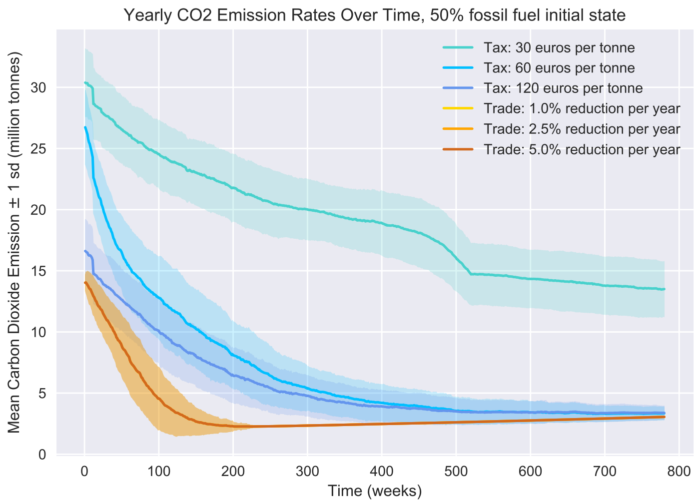
Each combination of CO2 emission measure and plant distribution was run 100 times using seeds



(a) Initial state 50% Coal, 40% Gas, 10% Nuclear, 0% Wind



(b) Initial state 50% Coal, 20% Gas, 20% Nuclear, 10% Wind



(c) Initial state 30% Coal, 20% Gas, 30% Nuclear, 20% Wind

Figure 3.1: The projected CO2 emissions when run at 30, 60 and 120 euros per tonne Tax and at a 1%, 2.5% and 5% yearly cap reduction.

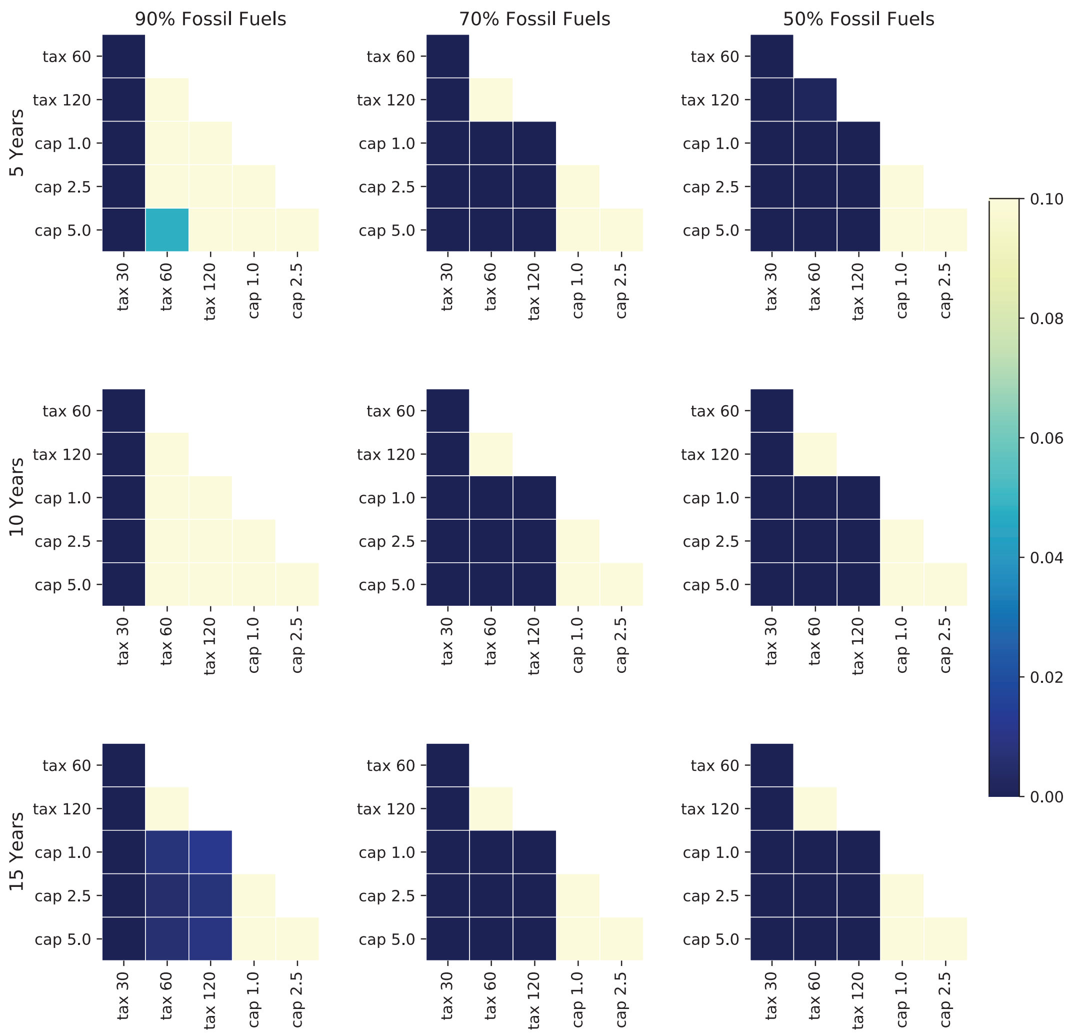


Figure 3.2: Pairwise t-test p values at the 5, 10 and 15 year points for the 90%, 70% and 50% Fossil Fuel starting states

1 through to 100. This ensured identical initialisations for each emission reduction measure at a given power plant distribution.

The resulting CO2 emissions for each of these simulations are shown in figure 3.1. Here we can see that the trade lines remain clustered for the duration of each of the simulations. The tax lines are more spread out for the majority of each run, with the 30 euros per tonne line noticeably deviating from the other lines.

The starting emission rate for the lines also differs, this difference is particularly notable in the 50% fossil fuel setup. Here the trade lines start with roughly half the emissions of the 30 euro tax. All of the lines appear to be coming together over time, with the 30 euro line doing so at a much slower rate.

Conversely, with the 90% fossil fuel starting state, the lines for all but the 30 euro tax seem to come together at around the five year mark. The 30 euro tax seems to deviate from the other lines.

In each plot the 30 euro tax line can be seen to rapidly descend just before the 10 year mark, suggesting that there is a tipping point just below 30 euros per tonne at which the tax rate becomes notably more effective at reducing emissions.

3.1 Analysis

In order to compare the various CO2 emission measures used, pairwise t-tests were carried out on each run of the model at the 5, 10 and 15 year points with $\alpha = .05$.

The p-values of these t-tests may be observed in as a heatmap in figure 3.2 the darker areas show significant comparisons and the light areas show comparisons that are not significant.

The exhaustive list of outputs from the pairwise t-tests may be found in Appendix B.

The following key take away points may be determined from the t-tests:

- At 15 years $p < \alpha$ for all direct tax/trade comparisons. This means that the null hypothesis of no difference in mean CO2 emissions may be rejected. From the plots it can be seen that the difference refers to a higher CO2 emission for tax than for trade.
- At the 70% and 50% Fossil Fuel presets $p < \alpha$ for all direct tax/trade comparisons. The null hypothesis of no difference may again be rejected for these comparisons. This difference refers to a higher CO2 emission rate for tax compared to trade.
- In all settings, for the tax rate of 30 euros per tonne against all over measures $p < \alpha$. The null hypothesis of no difference between these measures may again be rejected. This difference is a higher CO2 rate for the 30 euro tax over all other measures.
- For all trade/trade comparisons in each setting $p > \alpha$. As such the null hypothesis of no difference between CO2 emission rates for these comparisons may not be rejected, suggesting no significant difference between the trade levels.
- In the 90% Fossil Fuel setting at 5 and 10 years $p > \alpha$ for the 60 and 120 tax rates against all CO2 caps showing no significant difference between the emission. The sole exception to this is in 5 years for the tax 60 / cap 5.0 comparison where $p = 0.0478$, showing a significant difference with the 60 euro tax relating to a higher CO2 emission than the 5% cap reduction.

4 Discussion

This paper aims to answer the following question: Does a Carbon Tax lead to a greater reduction in CO2 emissions than that of a Cap-and-trade system? This question has been approached using three different levels of Carbon tax and three different levels of Carbon cap each taking place with one of three initial distributions of power plants.

The results show a marginally better performance of carbon cap measures over the carbon tax. The model also suggested that each version of either measure did promote a substantial reduction in CO2 over time, with stricter taxes coming close to the effects of the Cap-and-trade systems.

In their review of tax vs trade measures Goulder and Schein (2013) suggest that both measures can behave comparatively well, if implemented in an effective manner. Whilst the plots in this paper do show general trends of similarity between the types, the statistics suggest that Cap-and-trade outperforms Carbon Tax when it comes to reducing CO2 emissions.

4.1 Limitations

The agent based model used in this research is an approximation of the electricity production industry and its reaction to CO2 emission reduction measures. As such, there are some ways in which the data derived from the model could be considered inaccurate or misleading when compared to real world data.

4.1.1 Agents

The manner in which the agents used their constituent power plants was modelled as a binary choice for each plant; either the plant operated at full capacity or remained unused. This differs from real world situations in which power plants may be operated at partial capacity.

There is a difference in the mean running capacity per plant type EIA (2021a). This was partially taken into account, with the production rates per plant within the model relating to the mean output of each type, rather than mean maximum capacity. However, the relatively low number of plants per agent combined with the binary choice of on at mean production rate or entirely off could have caused some inaccuracies within the data.

4.1.2 Cap-and-trade

The Cap-and-trade data remained consistent between the 1%, 2.5% and 5% yearly cap reduction rates. This is due to the manner in which the trade system was implemented. The trade incentivises the use of the globally most profitable power plants, rather than the per agent most profitable power plants. This results in the model finding the ideal combination of power plants immediately. This ideal state is then updated in line with new power plants, leading to a reduction in CO2 emissions that remains generally constant regardless of the actual cap.

This data is still believed to be relevant however, as it simulates the less profitable agents selling their credits rather than using them directly.

4.1.3 Tax vs. Trade

As touched upon in section 4.1.2 the implementation of the Cap-and-trade system leads to the per tick usage of the globally most profitable power plants, whilst the Carbon Tax system leads to the per-agent most profitable power plants being used. This difference in approach can explain the very close, but significantly different results observed in 3.2 for the 15 year results.

The general trends of the Carbon Tax and Cap-and-trade data can still be considered relevant however, as this difference in approach should only have the potential to cause inaccuracies when the results are very close to one another.

4.1.4 Applicability

Whilst electricity production accounts for a large portion of global CO2 emissions, the difference between the least and most polluting production methods is exceedingly large. Within the range of power plants modelled, this is a difference between 820 tonnes per GWh for Coal plants and 12 tonnes per GWh for Wind or Nuclear plants - allowing for almost 64 times lower emissions when switching from the most to the least polluting. As such, there is great potential for the industry to reduce its emissions through only changes in production method.

Conversely, in industries such as steel production, which itself accounts for around 9% of global CO2 emissions as of 2021 (Wang, Ryberg, Yang, Feng, Kara, Hauschild, and Chen, 2021) the current potential for lower emission production methods would only account for around a 50% reduction in emissions (Holappa, 2020).

Therefore, whilst we can assume that emission reduction measures will incentivise CO2 emission reductions in all industries, excessively aggressive measures could lead to certain industries becoming untenable and being lost far quicker than the electricity production sector would.

4.1.5 Carbon Capture

Changes in production method are not the only approach that can reduce net CO2 emissions. It is also possible to reduce net emissions through Carbon capture.

Carbon capture prevents CO2 emissions from reaching the atmosphere by storing them in either products or geological formations with a long lifespan. There is evidence that suggests that this could decrease total CO2 emissions by up to 74% across various industrial sectors (Yang, Meerman, and Faaij, 2021). As such, Carbon capture methods could make the higher emission power plants more viable at higher emission reduction measures than suggested by the results presented in this paper.

4.2 Future Research

This research opens the door for a deeper exploration into the differences between Carbon Tax and Cap-and-trade systems.

4.2.1 More Sectors

It would be interesting to extend this research to investigate how the measures differ when applied to other sectors or industries. As mentioned in section 4.1.4, not all industries currently have the same potential for change as the electricity production sector. Expanding this research to such industries could provide interesting insights into upper limits for CO2 emission reduction measures, or measures which apply at different levels per industry.

4.2.2 Hybrid Approaches

Alongside the Cap-and-trade and Carbon Tax systems there are hybrid approaches (Goulder and Schein, 2013). One method is Cap-and-trade with a tax floor, in which each unit of CO2 emitted requires a credit, but is also taxed. Another is Cap-and-trade with a tax ceiling, in which for each unit of CO2 emitted either a credit is required or a tax may be payed.

Whilst we can assume that in the model used for this paper, both approaches would fall in the middle of those already used, in a model taking into account a broader economy, the results could be more varied.

5 Conclusions

Whilst this paper shows a significantly greater reduction in CO2 emissions for Cap-and-trade models compared to Carbon Tax models, it should be noted that the differences are modest. As covered in section 4.1.3 these differences are explainable from the manner in which the model was implemented. With this in mind, the general trends displayed within the model can be taken to be indicative that both measures can lead to a substantial reduction in CO2 emissions within the electricity production sector. Furthermore, either a Cap-and-trade system, or a Carbon Tax of 60 euros per tonne or greater is significantly quicker to influence this reduction.

This paper therefore has relevance in suggesting that the electricity production sector should not be the primary focus when selecting the level of severity of a CO2 reduction measure. Rather it suggests that the electricity production sector will lower its CO2 emissions at a similar rate with any enforced reduction measure of sufficient severity, namely taxes greater than 30 euros per tonne, or any Cap-and-trade system within the 1% to 5% yearly cap reduction range.

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Appendix A

The model used in this paper may be found here: `https://github.com/timjchandler/tax-or-trade`

Running the model

The model may be run from either of the two Jupyter Notebooks located in the analysis directory.

The `run.ipynb` runs a single instance of tax and trade for the given parameters, showing plots of the constituent power plant usage over time as well as the overall CO2 and electricity trends.

The `combine.ipynb` runs the model at a given initial power distribution for three levels of tax and three levels of trade. The CO2 outputs of these are then plotted for comparison.

Both notebooks have the option of rebuilding the model from its source using maven. They also both have the option to clean up all generated `.csv` files upon completion.

Appendix B

Below are the tables for the exhaustive results of the pairwise t-tests that were carried out and discussed in section 3.

90% Fossil fuel initial state

Comparison		5 Years			10 Years			15 Years		
A	**B**	**T**	**dof**	**p**	**T**	**dof**	**p**	**T**	**dof**	**p**
tax 120	cap 1.0	0.765056	200.0	4.451399e-01	-0.425071	200.0	6.712421e-01	2.545965	200.0	1.165094e-02
tax 120	cap 2.5	1.071651	200.0	2.851683e-01	-0.348148	200.0	7.280950e-01	2.676698	200.0	8.052153e-03
tax 120	tax 30	-8.451759	200.0	5.912847e-15	-16.626934	200.0	1.473516e-39	-39.780035	200.0	5.993631e-97
tax 120	cap 5.0	1.557390	200.0	1.209589e-01	-0.355984	200.0	7.222274e-01	2.626529	200.0	9.293917e-03
tax 120	tax 60	-0.404294	200.0	6.864285e-01	-0.328969	200.0	7.425237e-01	-0.143174	200.0	8.862968e-01
cap 1.0	cap 2.5	0.299560	200.0	7.648242e-01	0.074917	200.0	9.403553e-01	0.105255	200.0	9.162787e-01
cap 1.0	tax 30	-9.774132	200.0	1.081484e-18	-14.249019	200.0	2.927166e-32	-38.584026	200.0	1.333580e-94
cap 1.0	cap 5.0	0.807684	200.0	4.202318e-01	0.067718	200.0	9.460781e-01	0.052861	200.0	9.578954e-01
cap 1.0	tax 60	-1.185950	200.0	2.370492e-01	0.117738	200.0	9.063935e-01	-2.682422	200.0	7.920432e-03
cap 2.5	tax 30	-10.443243	200.0	1.179627e-20	-14.508518	200.0	4.633254e-33	-39.024838	200.0	1.792377e-95
cap 2.5	cap 5.0	0.524395	200.0	6.005843e-01	-0.007269	200.0	9.942073e-01	-0.052929	200.0	9.578409e-01
cap 2.5	tax 60	-1.503942	200.0	1.341738e-01	0.038932	200.0	9.689834e-01	-2.814392	200.0	5.375286e-03
tax 30	cap 5.0	11.063121	200.0	1.668165e-22	14.505933	200.0	4.719103e-33	39.077434	200.0	1.412345e-95
tax 30	tax 60	7.980330	200.0	1.114913e-13	16.033430	200.0	9.524309e-38	39.739911	200.0	7.170497e-97
cap 5.0	tax 60	-1.990872	200.0	4.785628e-02	0.046625	200.0	9.628585e-01	-2.764471	200.0	6.234528e-03

70% Fossil fuel initial state

Comparison		5 Years			10 Years			15 Years		
A	**B**	**T**	**dof**	**p**	**T**	**dof**	**p**	**T**	**dof**	**p**
tax 120	cap 1.0	4.217036	200.0	3.748854e-05	12.294915	200.0	3.040861e-26	6.234789	200.0	2.636771e-09
tax 120	cap 2.5	4.771521	200.0	3.522057e-06	12.959395	200.0	2.775016e-28	6.310077	200.0	1.760245e-09
tax 120	tax 30	-15.414466	200.0	7.523153e-36	-33.559445	200.0	4.235486e-84	-50.932803	200.0	1.757377e-116
tax 120	cap 5.0	4.250200	200.0	3.274290e-05	12.797574	200.0	8.728800e-28	6.224066	200.0	2.792289e-09
tax 120	tax 60	-1.292789	200.0	1.975753e-01	-0.483752	200.0	6.290910e-01	-0.268038	200.0	7.889460e-01
cap 1.0	cap 2.5	0.563932	200.0	5.734320e-01	0.734952	200.0	4.632295e-01	0.960753	200.0	3.378363e-01
cap 1.0	tax 30	-18.846098	200.0	3.211070e-46	-60.968508	200.0	3.698503e-131	-63.469826	200.0	1.763992e-134
cap 1.0	cap 5.0	0.011514	200.0	9.908250e-01	0.440675	200.0	6.599241e-01	-0.407835	200.0	6.838309e-01
cap 1.0	tax 60	-5.294813	200.0	3.123828e-07	-12.071345	200.0	1.467112e-25	-6.181969	200.0	3.494655e-09
cap 2.5	tax 30	-19.268974	200.0	1.821315e-47	-63.378186	200.0	2.323182e-134	-63.266781	200.0	3.248422e-134
cap 2.5	cap 5.0	-0.554949	200.0	5.795499e-01	-0.324369	200.0	7.459979e-01	-1.024770	200.0	3.067095e-01
cap 2.5	tax 60	-5.822852	200.0	2.276823e-08	-12.664234	200.0	2.241992e-27	-6.257688	200.0	2.332565e-09
tax 30	cap 5.0	18.982963	200.0	1.265907e-46	63.097286	200.0	5.415292e-134	63.462618	200.0	1.802591e-134
tax 30	tax 60	13.170730	200.0	6.202945e-29	31.436150	200.0	2.531410e-79	49.729749	200.0	1.478840e-114
cap 5.0	tax 60	-5.331299	200.0	2.621070e-07	-12.515420	200.0	6.417381e-27	-6.171982	200.0	3.685202e-09

50% Fossil fuel initial state

Comparison		5 Years			10 Years			15 Years		
A	**B**	**T**	**dof**	**p**	**T**	**dof**	**p**	**T**	**dof**	**p**
tax 120	cap 1.0	15.269683	200.0	2.096011e-35	8.180512	200.0	3.234815e-14	5.807165	200.0	2.466930e-08
tax 120	cap 2.5	15.269683	200.0	2.096011e-35	8.180512	200.0	3.234815e-14	5.807165	200.0	2.466930e-08
tax 120	tax 30	-46.595453	200.0	2.383236e-109	-42.060252	200.0	2.824208e-101	-43.501355	200.0	6.481376e-104
tax 120	cap 5.0	15.269683	200.0	2.096011e-35	8.180512	200.0	3.234815e-14	5.807165	200.0	2.466930e-08
tax 120	tax 60	-3.243184	200.0	1.385121e-03	-0.478149	200.0	6.330663e-01	0.523668	200.0	6.010894e-01
cap 1.0	cap 2.5	0.000000	200.0	1.000000e+00	0.000000	200.0	1.000000e+00	0.000000	200.0	1.000000e+00
cap 1.0	tax 30	-67.286427	200.0	2.513951e-139	-48.278683	200.0	3.509580e-112	-46.316459	200.0	7.157851e-109
cap 1.0	cap 5.0	0.000000	200.0	1.000000e+00	0.000000	200.0	1.000000e+00	0.000000	200.0	1.000000e+00
cap 1.0	tax 60	-17.204869	200.0	2.604392e-41	-8.183429	200.0	3.176662e-14	-5.321413	200.0	2.748924e-07
cap 2.5	tax 30	-67.286427	200.0	2.513951e-139	-48.278683	200.0	3.509580e-112	-46.316459	200.0	7.157851e-109
cap 2.5	cap 5.0	0.000000	200.0	1.000000e+00	0.000000	200.0	1.000000e+00	0.000000	200.0	1.000000e+00
cap 2.5	tax 60	-17.204869	200.0	2.604392e-41	-8.183429	200.0	3.176662e-14	-5.321413	200.0	2.748924e-07
tax 30	cap 5.0	67.286427	200.0	2.513951e-139	48.278683	200.0	3.509580e-112	46.316459	200.0	7.157851e-109
tax 30	tax 60	41.208076	200.0	1.111147e-99	41.324289	200.0	6.710307e-100	43.792258	200.0	1.938594e-104
cap 5.0	tax 60	-17.204869	200.0	2.604392e-41	-8.183429	200.0	3.176662e-14	-5.321413	200.0	2.748924e-07