Section 1: Introduction

Climate change from greenhouse gas (GHG) emissions represents the biggest market failure the world has seen, *(Stern, 2008)*. The urgent nature of the climate problem has strengthened pledges made by the UK government; one such target being full decarbonization of Great Britain's electricity system by 2035. Large changes in the structure of UK electricity production are needed to achieve this. Wind energy is widely recognized as one of the most viable methods of renewable electricity generation and presents a sustainable platform for the future of power production, *(Galparsoro et al, pp. 1)*.

The levelized cost of energy (LCOE) for wind has fallen considerably since 2000, depicted in Figure 1.1. Figure 1.2 displays elements contributing to the LCOE for multiple forms of energy in 2010. Both wind sources are among the cheapest renewables, with less than half the full cost of solar supplies. The figures illustrate the increasing competitiveness of wind energy with traditional fossil fuels, providing just incentives to increase installed capacity.

With wind energy becoming a cornerstone of electricity production in the UK, potential trade-offs may appear, requiring complete assessment to synergize policy objectives. This report shall give an overview of the importance of wind electricity production in Great Britain, outlining the potential economic and climate impacts that a greater share of wind energy could have.

Figure 1.1:

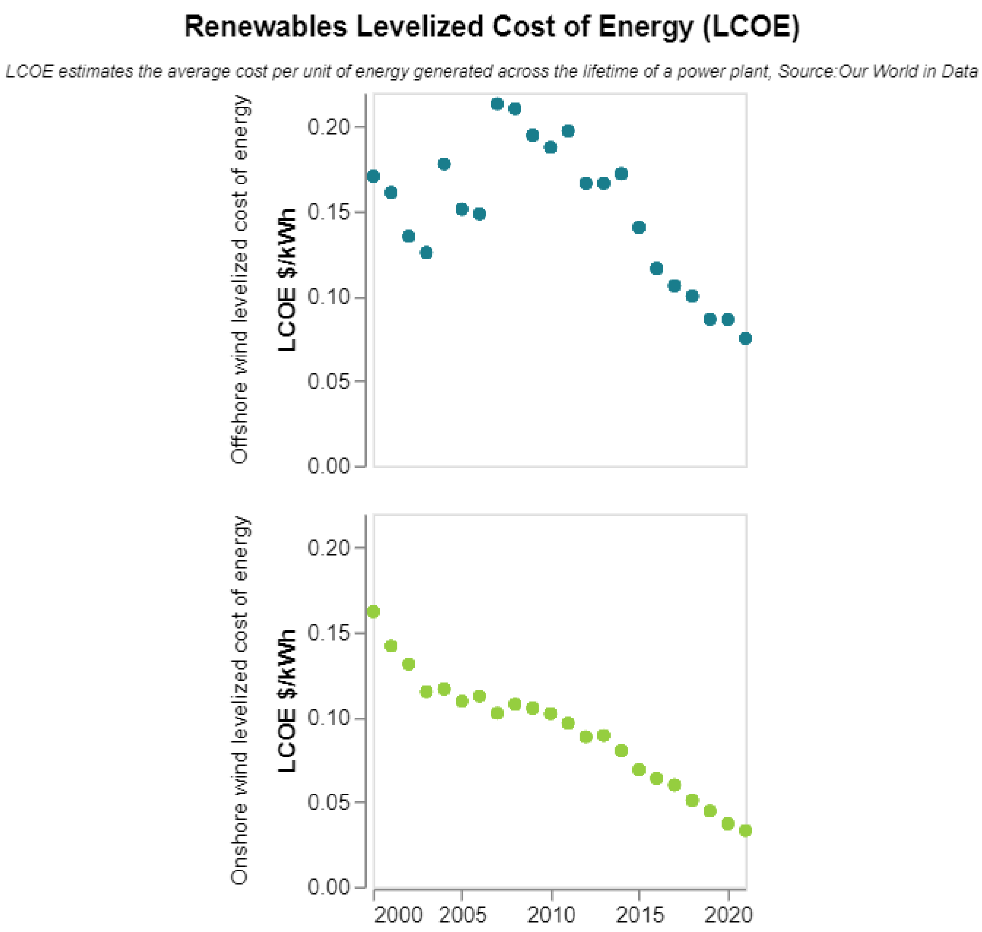
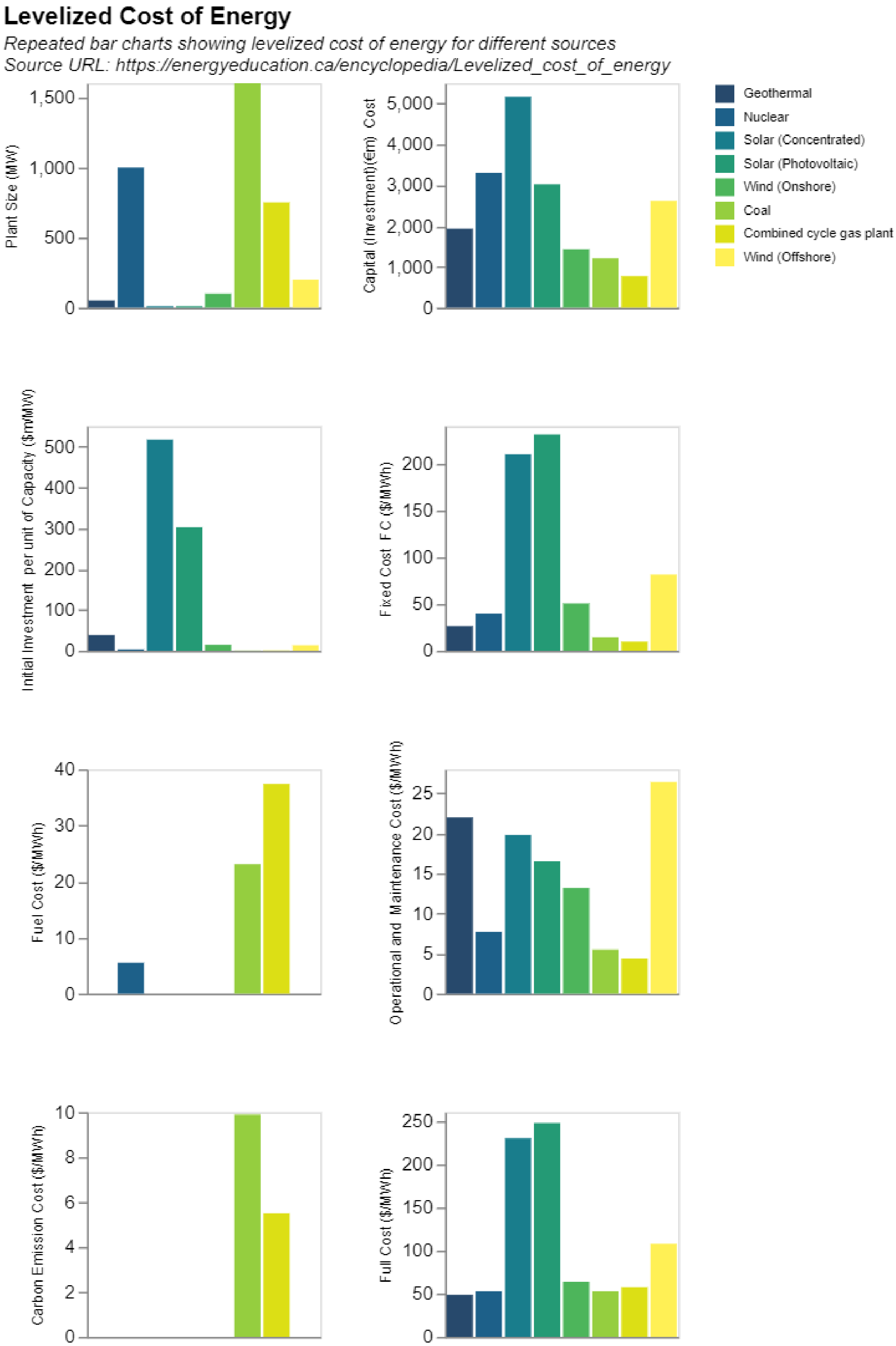


Figure 1.2:


Levelized Cost of Energy
Repeated bar charts showing levelized cost of energy for different sources
Source URL: https://energyeducation.ca/encyclopedia/Levelized_cost_of_energy
Geothermal
Nuclear
Solar (Concentrated)
Solar (Photovoltaic)
Wind (Onshore)
Coal
Combined cycle gas plant
Wind (Offshore)
Plant Size (MW)
0
500
1,000
1,500
Capital (Investment)(€m) Cost
0
1,000
2,000
3,000
4,000
5,000
Initial Investment per unit of Capacity ($m/MW)
0
100
200
300
400
500
Fixed Cost F C ($/MWh)
0
50
100
150
200
Fuel Cost ($/MWh)
0
10
20
30
40
Operational and Maintenance Cost ($/MWh)
0
5
10
15
20
25
Carbon Emission Cost ($/MWh)
0
2
4
6
8
10
Full Cost ($/MWh)
0
50
100
150
200
250

Section 2: Assessing impacts on climate change

To fully comprehend policy intentions, first sustainability must be understood. *Goodland (1995)* defines environmental sustainability as "maintenance of natural capital". From an economic perspective, sustainability requires current economic activity to not have a detrimental effect on the living standards of future generations, *(Foy, 1990).* Combining these concepts, economic sustainability within the context of this report will be defined as the level of economic activity that *1) does not reduce the welfare of future generations and 2) maintains natural capital at levels that does not compromise the health of ecosystems*. Due to the nature of climate change, negative impacts from current GHG emissions will be persistent for long time periods (*Stern, 2007, pp. 35)*, requiring a dynamic approach to evaluation of welfare effects and policy implementation.

Consequently, evaluation techniques must involve large time horizons and consider uncertainty in the "size, type and timing of impacts" and "the costs of combating climate change" *(Stern, 2007, pp. 28)*. Designing policies that meet these requirements needs an approach which unites economic instruments with natural sciences *(Nordhaus, 1992)*. The economist's role is to construct an appropriate dynamic model of the economy, which is built upon environmental science, integrates the goals of sustainability, equity and efficiency and is attentive to uncertainty. One methodology frequently used is an integrated assessment model (IAM). These provide a framework for incorporating findings from multiple fields of study, allowing analysis to extend past the conclusions made from individual disciplinary perspectives *(Weyant et al, pp. 371).*

Weyant et al (1996) define two broad categories of IAMs: policy optimization models, which investigates optimal policy design *(such as Nordhaus' (1992) DICE model, see Box 2.1)* and policy evaluation models, used to appraise policies *(Tol and Fankhauser, 1997).* IAMs which aim to cover the full scope of climate issues are "full-scale" IAMs. At the core of full-scale IAMs lie four areas: human activities, atmospheric composition, climate and sea level and ecosystems *(Weyant et al, pp. 377).* Figure 2.1 recreated from *Weyant et al (Figure 10.1, pp. 377)* shows one possible interaction between these components.

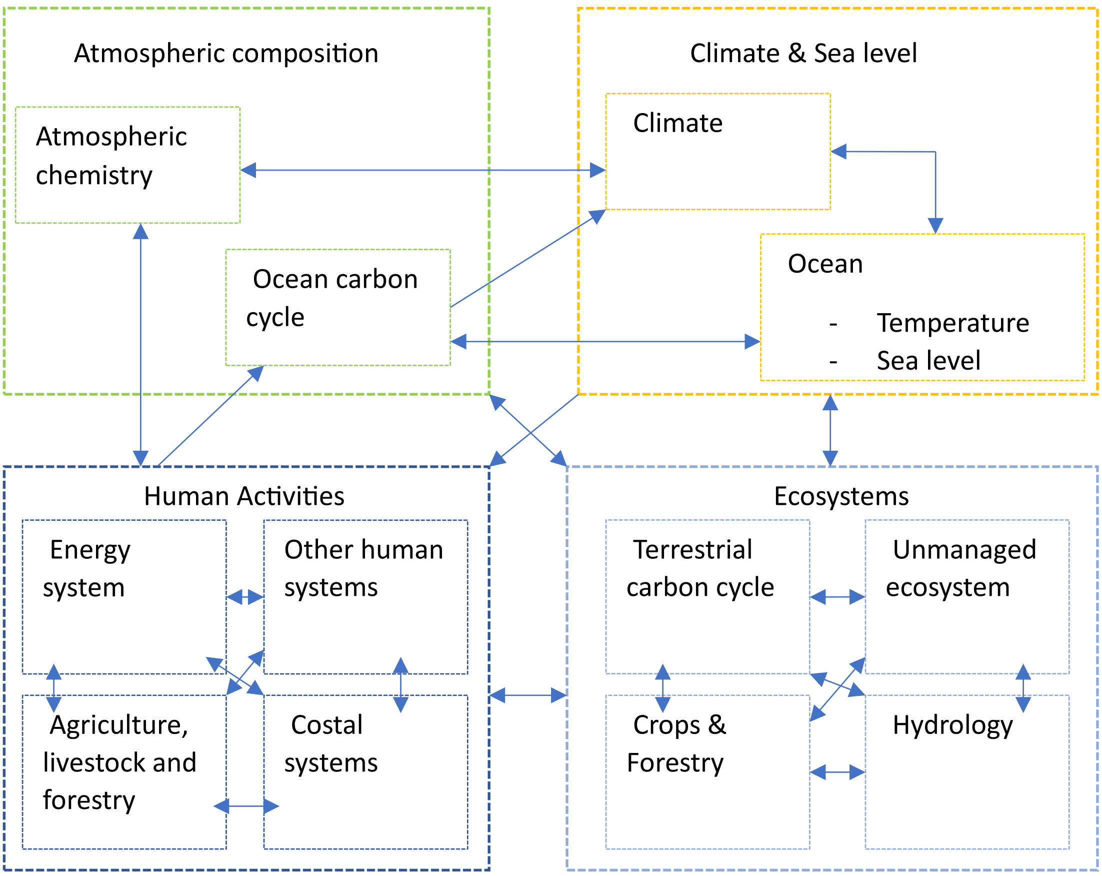
IAMs have been used to assess the dynamics of GHG emissions and the economic impacts of policies to reduce emissions to desired levels *(Nordhaus, pp. 1315).* IAMs give different "optimal" pathways for controlling GHGs, understood as the most efficient direction for abating climate change given specified inputs and technologies *(Nordhaus, pp. 1315)*. This includes estimates of both capital accumulation and GHG reductions needed to sustain the resulting trajectory. Energy systems are the "single most critical component determining emissions in IAMs" *(Weyant et al, pp. 378)*, with clearly defined relationships between the production of energy and the release of GHGs. Given the electricity sector is highly flexible – *changes in the structure of the electricity mix are more easily achieved* - different mixes of technologies can have sizable impacts on carbon emissions *(Wilkerson et al, pp. 27).* This produces clear-cut differences in IAM results from different inputs, such as higher shares of renewables in the mix, allowing economists to assess the relative impacts of changing energy composition on climate change and guides how to best leverage cleaner technologies to achieve sustainability.

Policies are designed to align theoretical outcomes to real-world action, coming in multiple forms including carbon taxes, permits and renewable energy subsidies. Importantly, IAM results are not homogenous; the structure and "value-judgements" of models can drastically change conclusions drawn. A notable example is the disagreement between William Nordhaus and Nicholas Stern, two climate economists who aim to calculate the social cost of carbon (SCC) from IAMs. The SCC is the economic cost born from an additional ton of carbon dioxide (or equivalent) emissions *(Nordhaus, 2016)*. *The Stern Review (2007)* places the SCC at $266.5 per ton of CO_2 for emissions in 2020 compared to $37.3 by Nordhaus *(Table 1. Nordhaus, 2017)*.

This stark difference arises largely due to the discount rate used in each respective model. Discounting converts future costs and benefits into present values *(The Green Book, 2022)*. In IAM evaluation, it is considered to be *how much we value the welfare of future generations relative to our own*. When future generations are heavily discounted, their welfare has less weight relative to current generations. A high discount rate favors postponing costs of reducing emissions now, implying a low SCC, and vice versa *(Stern, 2007).*

This brings new dimensions of ethical concern. A policymaker must decide how to value future generations in relation to the current, and provides partial explanation for the different SCC results seen above. This is one example of the forementioned "value-judgements" that those using IAMs must consider and how variation in strategic conclusions can emerge. Therefore, IAMs often are limited to the user in question, as broad alignment in political, economic and ethical beliefs is often unattainable. Finally, the pitfall of taking results at face value is noteworthy. Whilst IAMs give important suggestions of the implications of climate change, they do not offer a complete picture of the issue at hand, and must not be treated as omniscient *(Stern, 2007, pp. 189)*.

Figure 2.1:



Section 3: Fishing

In 2019 offshore wind farms (OWFs) made up 10% of new wind power installations globally, with massive growth needed to achieve climate targets *(Galparsoro et al, 2022)*. The environmental impacts of new OWF projects must be thoroughly considered if production growth is not to divest ecosystems of nurturing conditions. Endorsed plans must exercise "ecosystem-based" methodologies to assure that human activities do not disrupt the healthy workings of oceanic systems *(Galparsoro et al, pp. 1).*

Stenberg et al (2015) report positive impacts of OWFs on fish fauna in the North Sea, with the highest levels of species abundance occurring close to turbines (compared to control area 6km away). This is attributed to OWFs functioning as artificial reefs and prohibited fishing in proximity, granting moderate protection from fishing *(Stenberg et al, pp. 263; Galparsoro et al, pp. 3).* Importantly, impacts mentioned should be recognized as case-specific, as the potential for high geographical and species-specific variation must be recognized when applying local conservation targets *(Galparsoro et al, pp. 3).*

Marine protected areas (MPAs) around wind farms in the UK may create conflict between climate objectives and fishing outcomes. The primary economic concern relates to profitability of fisheries, whilst ecological issues derive from over-fishing and fish populations. MPAs are an optimal policy when the value gained from greater catch spillovers from the zone exceeds the value from fishing in the zone *(Sanchirico et al, pp. 1643).* This is likely to be feasible if the area has high fishing costs and is a net exporter of fish *(Sanchirico et al, pp. 1643).* This condition is critical in the assessment of utilizing no fishing zones around OWFs.

The *Gordon-Shaeffer model (see Box 3.1)* is used to analyze how fish stocks respond to different levels of harvest and conveys a salient message; fishermen exert too much pressure in open-access fisheries which results in overfishing and reduces fish stocks. The need for property-rights or restricted access to fisheries is made apparent, enabling increased economic and biological prosperity. If current UK fishing activities are extracting too many fish (*more* than is sustainable), restricted fishing areas around OWFs will be beneficial both ecologically and economically. The command-and-control policy has potential costs of reduced harvest efficiency and financial costs bore by operators *(Perman et al, pp. 595).* Therefore, MPAs are not cost-efficient methods for reducing harvest and policymakers should consider the trade-off between environmental and economic objectives.

Areas that provide large proportions of total catch are less likely to have substantial stock spillovers from protection. Conversely, safeguarding populations in offshore waters that experienced extensive overfishing have high chances of increasing total catch in the long run *(Sanchirico et al, 2002, pp. 10).* Therefore, the area of protection and the policy horizon are critical in cost-benefit analysis of protection zones. These issues elucidate the notion that protecting OWFs' surrounding waters can either be net beneficial or detrimental on a case-by-case basis, with individual assessments recommended for best practice.

Section 4: Evaluating environmental impacts

Mass construction of wind farms is accompanied by environmental concerns, such as the visual impact that wind turbines have *(Skenteris et al, 2019).* A value must be assigned to these impacts to enable economic analysis. One method of valuation is a hedonic price method (HPM). HPMs give a value to non-market goods which influence the price of market goods and are otherwise are unaccounted for. House prices are often used as the "market good", relying on the assumption that their price is driven by a combination of their characteristics as well as any external factors that affect houses.

External factors may include impacts that newly built windfarms have and appear implicitly within the price of the house. The HPM allows for this implicit price to be "extracted" from market-based transactions *(Office for National Statistics, 2018).* For identical housing, differences in house price emanate from the presence (or absence) of windfarms *(Robertson, 2011, pp. 228)*. This designates a value to the environmental impacts that windfarms have, by capturing how much people pay to avoid them.

These methods can be used to evaluate both on and offshore windfarms within the UK. Whilst they effectively value external factors, their limitations must be recognised. Firstly, the construction of the model significantly effects its outcome; if it is incorrectly assembled, estimates will be inconsistent, and inference drawn from them inaccurate *(Chin and Chau, 2003)*. Secondly, characteristics of the good (houses) differ sizably and can cause variation in prices. This would be attributed mistakenly to the external factor. These include locational, structural and neighbourhood attributes, requiring large datasets which are often availability constrained *(Chin and Chau, 2003)*. Given the limitations, onshore windfarms may be better suited by to HPM evaluation since their effects are more prevalent in local communities, predominantly due to their location, with studies frequently finding no effect of offshore windfarms to property owners in coastal areas *(Dong and Land, 2022, pp. 8).*

Box 2.1: *The DICE model (Nordhaus, 1992)*

The dynamic integrated climate-economy (DICE) model is an optimization tool for approximating an optimal path of GHG reductions *(Nordhaus, 1992).* The global economy is aggregated and has an initial stock of capital and labour with incremental technological progress. Capital accumulation results from optimization, whilst population and technological growth is exogenous.

The economy choses whether to consume goods and services, abate climate change or invest in productive capital. The discounted sum of utilities per capita consumption is maximised, characterising the choice of the economy:

$$\max_{[c(t)]} \sum_{t=1}^{T} U[c(t), P(t)](1+\rho)^{-t} \qquad (1)$$

Where:

- $U[.]$ – level of utility
- $c(t)$ – flow of consumption per capita at time t
- $P(t)$ – population at time t
- ρ – pure rate of social time preference

The maximisation is subject to two constraints: 1) economic constraints and 2) emissions-climate-economy constraints. The Ramsey model of output growth captures the economic constraints, made up of five equations including a constant returns-to-scale Cobb-Douglas production function:

$$Q(t) = \Omega(t)A(t)K(t)^{\gamma}P(t)^{1-\gamma} \qquad (2)$$

Where:

- $Q(t)$ – output
- $\Omega(t)$ – climate factor
- $A(t)$ – technology
- γ – elasticity of output with respect to capital
- $K(t)$ – capital

The environmental constraint involves a further seven equations. A combination of the cost and damage functions gives the climate factor in the production function:

$$\Omega(t) = [1 - b_1\mu(t)^{b_2}/[1 + d(t)] \qquad (3)$$

Where:

- $\mu(t)$ – emissions control rate
- b_1, b_2 – constants
- $d(t)$ – fractional loss of global output from greenhouse warming

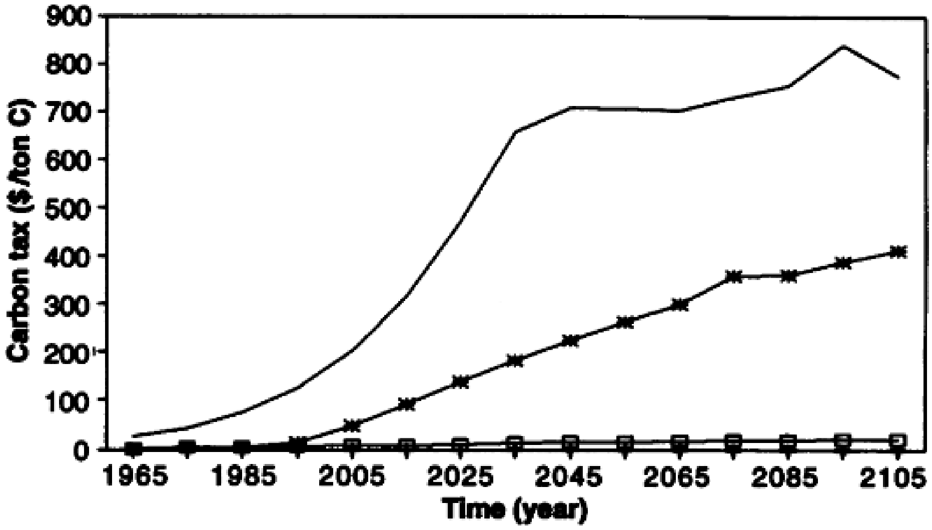
By optimizing equation (1), subject to all 12 constraints, efficient policies to slow climate change emerge, given the specification of variables used. Outcomes are quantified in terms of the net discounted value of utility of consumption from equation (1).

The potential application to changing energy composition or incentive-based policies is enormous. Simple adjustments to energy systems in the DICE model will provide definitive utility-based valuations of such policies.

Box 2.1: *The DICE model (Nordhaus, 1992)*

The same is possible for carbon incentive policies. *Nordhaus' (1992)* optimal policy can be interpreted as one where nations levy taxes that efficiently reduce GHG emissions. Policymakers may specify a taxation policy and utilize projections from the DICE model to assess outcomes in tangible terms. For reference, Figure 2.1, extracted from *Nordhaus (1992, Fig. 4.)* illustrates the dynamics of different carbon taxation policies from DICE assessment:

Figure 2.2 *(Nordhaus, 1992, Fig. 4.)*:



Box 3.1: *Open-access Gordon-Shaeffer model*

The Gordon-Shaeffer model combines a biological sub-model, expressing the natural growth patterns of a fishery, with an economic sub-model, which formulates the economic behaviour of commercial fishers *(Perman et al, 2011, pp. 562).* The biological growth model is a logistic function in the form:

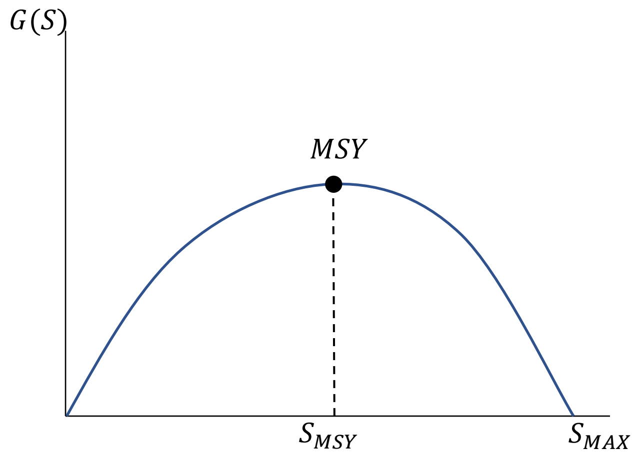
$$G(S) = g\left(1 - \frac{S}{S_{MAX}}\right)S \quad (1)$$

Where:

- $G(S)$ – naturally occurring stock changes
- g – potential growth rate
- S (S_{MAX}) – (maximum) fish stock

Figure 3.1 shows the logistic growth function, with the maximum sustainable yield (MSY) depicted. This is the point where the growth process is maximized.

Figure 3.1:



The economic sub-model involves a competitive market, a harvest function (H), which depends on the fishing effort (E) and the size of the fish stock. Total cost of harvesting (C) is a linear function of effort. Gross benefit (B) from harvesting depends on the quantity harvested:

$$H = eES \quad (2)$$

$$C = wE \quad (3)$$

$$B = PH \quad (4)$$

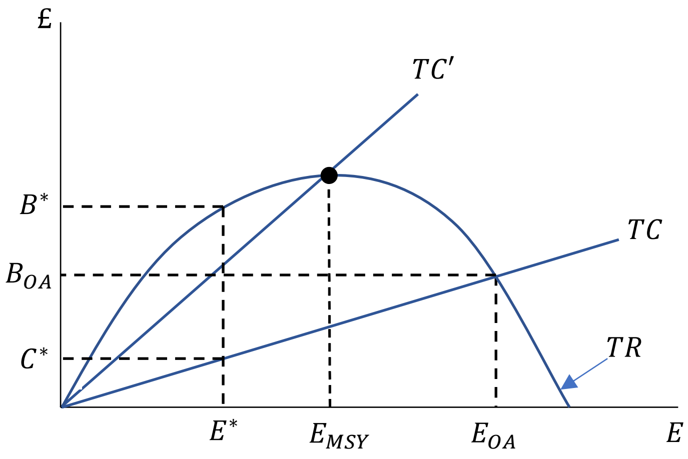
Where:

- e – catch coefficient
- w – cost per unit of harvest effort (constant)
- P – market price of fish

Box 3.1: *Open-access Gordon-Shaeffer model*

The fishery steady-state equilibrium will have a biological and economic equilibrium. The equilibrium values can be solved to obtain steady-state values. Figure 3.2 shows the relationship between effort, total benefits (revenue) and costs in the steady-state:

Figure 3.2:



When effort levels surpass E_{MSY}, total revenues and fish catch will fall *(Stavins, 2010, pp. 5).* This is the region in which the open-access (OA) fishery equilibrium will be. The efficient level of effort is where net benefit $(B - C)$ is maximized (E^*). Even if open-access fisheries are near the efficient effort level, profits made will attract new entrants and eventually driving them to zero (OA equilibrium) *(Stavins, pp. 6).* Stocks get depleted rapidly and driven to critical levels. Restricting access to fisheries will increase the marginal cost of fishing effort, pivoting the total cost curve upwards, achieving more efficient levels of effort and increased fish stocks (TC') *(Stavins, pp. 7).*

Word count: 2500

<u>References:</u>

Chau, K. W., and T. L. Chin. “A Critical Review of Literature on the Hedonic Price Method.” *International Journal for Housing Science and Its Applications*, vol. 27, no. 2, 2003, pp. 145-165, https://ssrn.com/abstract=2073594.

Dong, Luran, and Corey Lang. “Do views of offshore wind energy detract? A hedonic price analysis of the Block Island wind farm in Rhode Island.” *Energy Policy*, vol. 167, 2022, https://doi.org/10.1016/j.enpol.2022.113060.

Energy Education. “Levelized cost of energy.” *Energy Education*, https://energyeducation.ca/encyclopedia/Levelized_cost_of_energy. Accessed 27 April 2023.

Foy, George. “Economic sustainability and the preservation of environmental assets.” *Environmental Management*, vol. 14, no. 6, pp. 771-778, https://doi.org/10.1007/BF02394171.

Galparsoro, Ibon, et al. “Reviewing the ecological impacts of offshore wind farms.” *npj Ocean Sustainability*, vol. 1, 2022, pp. 1-8, https://www.nature.com/articles/s44183-022-00003-5.

Goodland, Robert. “The Concept of Environmental Sustainability.” *Annual Review of Ecology and Systematics*, vol. 26, 1995, pp. 1-24, https://www.jstor.org/stable/2097196.

Nordhaus, William D. “An Optimal Transition Path for Controlling Greenhouse Gases.” *Science*, vol. 258, no. 5086, 1992, pp. 1315-1319, https://www.science.org/doi/10.1126/science.258.5086.1315.

Nordhaus, William D. “Revisiting the social cost of carbon.” *Proceedings of the National Academy of Sciences*, vol. 114, no. 7, 2017, pp. 1518-1523, https://doi.org/10.1073/pnas.1609244114.

Our World in Data. “Levelized cost of energy by technology, World.” *Our World in Data*, https://ourworldindata.org/grapher/levelized-cost-of-energy. Accessed 27 April 2023.

Perman, Roger, et al. *Natural Resources and Environmental management*. 4 ed., Pearson Education, 2012, https://ebookcentral.proquest.com/lib/bristol/detail.action?docID=5173785.

Phillips, LD. “The Green Book (2022).” *GOV.UK*, 18 November 2022, https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent/the-green-book-2020. Accessed 27 April 2023.

Robertson, M. “Ecosystem Services.” *Encyclopedia of Environmental Health*, 2011, pp. 225-233, https://doi.org/10.1016/B978-0-444-52272-6.00416-5.

Sanchirico, James N., et al. “Marine Protected Areas: Economic and Social Implications.” *Resources for the Future*, 2002, p. 27, https://ageconsearch.umn.edu/record/10795.

Sanchirico, James N., et al. “WHEN ARE NO-TAKE ZONES AN ECONOMICALLY OPTIMAL FISHERY MANAGEMENT STRATEGY?” *Ecological Applications*, vol. 16, no. 5, 2006, pp. 1643-1659, https://doi.org/10.1890/1051-0761(2006)016[1643:WANZAE]2.0.CO;2.

Skenteris, Konstantinos, et al. “Implementing hedonic pricing models for valuing the visual impact of wind farms in Greece.” *Economic Analysis and Policy*, vol. 64, 2019, pp. 248-258, https://doi.org/10.1016/j.eap.2019.09.004.

Stavins, Robert N. “The Problem of the Commons: Still Unsettled After 100 Years.” *NBER Working Paper Series*, vol. NBER Working Paper No. 16403, 2010, http://www.nber.org/papers/w16403.

Stenberg, C., et al. “Long-term effects of an offshore wind farm in the North Sea on fish communities.” *Marine Ecology Progress Series*, vol. 528, 2015, pp. 257-265, https://www.jstor.org/stable/24895890.

Stern, Nicholas. “The Economics of Climate Change.” *American Economic Review*, vol. 98, no. 2, 2008, pp. 1-37, https://www.aeaweb.org/articles?id=10.1257/aer.98.2.1.

Stern, Nicholas. *The Economics of Climate Change: The Stern Review*. Cambridge University Press, 2007, https://doi.org/10.1017/CBO9780511817434.

Tol, Richard S.J., and Samuel Fankhauser. “On the representation of impact in integrated assessment models of climate change.” *Environmental Modeling & Assessment*, vol. 3, 1998, pp. 63-74, https://doi.org/10.1023/A:1019050503531.

“Value of nature implicit in property prices – Hedonic Pricing Method (HPM) methodology note.” *Office for National Statistics*, 12 July 2018, https://www.ons.gov.uk/economy/environmentalaccounts/methodologies/valueofnatureimplicitinp ropertypriceshedonicpricingmethodhpmmethodologynote#regression-results. Accessed 27 April 2023.

Weyant, John, et al. *Integrated Assessment of Climate Change: An Overview and Comparison of Approaches and Results*. Cambridge University Press, 1996, https://www.researchgate.net/publication/221678860_Integrated_Assessment_of_Climate_Change_An_Overview_and_Comparison_of_Approaches_and_Results.

Wilkerson, Jordan T., et al. "Comparison of integrated assessment models: Carbon price impacts on U.S. energy." *Energy Policy*, vol. 76, 2015, pp. 18-31, https://doi.org/10.1016/j.enpol.2014.10.011.