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Is a Green Paradox Spectre Haunting International Climate Change Laws and Conventions?

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I.
INTRODUCTION

Could the United Nations Framework Convention on Climate Change (UNFCCC),), and green laws in general, increase greenhouse gas emissions, and thus worsen the threats and risks of climate change? Many economists examining international responses to climate change fear that green laws may backfire under certain circumstances; a phenomenon known as a "green paradox.[1] In his controversial book, The Green Paradox, German economist Hans-Werner Sinn goes so far as to characterize this backfire as inevitable.[2] Must legal researchers and climate change activists fear that their legal policy efforts will lead to worsening climate conditions? Is there truly no way to avert this green paradox crisis?

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[1] See, e.g., HANS-WERNER SINN, THE GREEN PARADOX: A SUPPLY-SIDE APPROACH TO GLOBAL WARMING 196 (2012).

[2] *See id.* at 155.

Sinn explains the Green Paradox first by referencing human psychology.[3] He claims, "Resource owners aren't stupid . . . Arab oil sheikhs, Russian gas oligarchs, and coal barons all have realized that a revolution in the world's energy mix is underway."[4] As a result, he claims that resource owners are selling off more and more fossil fuel resources while legislative efforts to make alternative energy more cost-effective and popular are increasing.[5] This potential green paradox has been echoed by many other economists[6] and surely if there are mechanisms within climate change laws and conventions that give rise to green paradox results, legal researchers, legislators, and climate change policymakers should take caution and consider revamping the existing framework of international climate change conventions and associated domestic policies.

However, most of these authors rely on two economic models originally developed for studying exhaustible resources: the Hotelling and Dasgupta Heal models.[7] If these models are unreliable for green paradox research, then caution should be taken before economists begin to unravel the decades of negotiations that have enabled the existing frameworks.

The research of these circumstances requires the combination of legal requirements and economic models. This present study reviews the concern that certain economic models might be problematic in resolving the first question due to certain assumptions built into those models when they were originally designed for other research purposes. However, the analysis presented is intended for an audience of legal researchers; mathematical materials are minimized in the presentation and the evidence is presented in a format familiar to lawyers. Hopefully this research will better enable other legal researchers

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[3] *See id.* at 192-96.

[4] *Id.* at 188.

[5] *Id.* at 188-89.

[6] *See, e.g.*, Edwin van der Werf & Corrado Di Maria, *Imperfect Environmental Policy and Polluting Emissions: The Green Paradox and Beyond*, 6 INT'L REV. ENVTL. & RESOURCE ECON. 153 (2012).

[7] *See id.* at 156-58 (performing a review of 32 articles on the green paradox subject and identifying that 19 of those papers utilized some form of either a Hotelling or Heal economic model).

to engage in broader research on the potential impacts of green paradox models on future climate change laws and conventions.

II.

COULD THE UNFCCC WORSEN CLIMATE CHANGE?

The scientific community broadly holds that the cause of global climate change is primarily anthropogenic.[8] To assist in the governance of the dangers posed by global climate change, almost every nation in the world has joined the United Nations Framework Convention on Climate Change ("UNFCCC");[9] many nations have also agreed to the UNFCCC's Kyoto Protocol.[10]

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[8] *See, e.g.*, Intergovernmental Panel on Climate Change [IPCC], *Summary for Policymakers*, *in* CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS. CONTRIBUTION OF WORKING GROUP I TO THE FIFTH ASSESSMENT REPORT OF THE IPCC 17 (Thomas F. Stocker et al. eds., 2013) [hereinafter IPCC FIFTH ASSESSMENT REPORT SUMMARY] ("It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together."). The IPCC report was co-authored by approximately 830 experts selected from a nomination pool of 3,598 scientists. IPCC, *IPCC Factsheet: How does the IPCC select its authors?* August 30, 2013. Available at http://www.ipcc.ch/news_and_events/docs/factsheets/FS_select_authors.pdf. See also, e.g., NICHOLAS STERN, STERN REVIEW: THE ECONOMICS OF CLIMATE CHANGE. VOL. 30, 3 (London: HM Treasury, 2006). "An overwhelming body of scientific evidence indicates that the Earth's climate is rapidly changing, predominantly as a result of increases in greenhouse gases caused by human activities." *Available* at http://webarchive.nationalarchives.gov.uk/20100407172811/http://www.hm-treasury.gov.uk/stern_review_report.htm.

[9] *See* United Nations Framework Convention on Climate Change, May 9, 1992., U.N. Doc. FCCC/Informal/84; GE.05-62220 (E) 200705 [hereinafter UNFCCC], *available* at http://unfccc.int/essential_background/convention/items/2627.php. While presented here as primarily two sets of documents, the underlying reality of the UNFCCC is more complex and evolved; a more complete legal story should include details from the Marrakesh Accords of 2001, the 2005 Nairobi Work Program on Adaption, the 2007 Bali Road Map, the 2009 Copenhagen Accord, the 2010 Cancun Agreements, the 2011 Durban Platform for Enhanced Action, the 2012 Doha Amendment to the Kyoto Protocol, and most recently the 2013 Warsaw Outcomes. This study needs only the basic common predicates underlying all of the these efforts, and thus will limit its discussions to the earlier UNFCCC and the Kyoto Protocol. *See* source cited *infra* note 10.

[10] *See* Kyoto Protocol to the United Nations Framework Convention on Climate Change, Dec. 11, 1997, 2303 U.N.T.S. 148 [hereinafter Kyoto Protocol], *available* at http://unfccc.int/resource/docs/convkp/kpeng.pdf.

While legislators and policy makers sought to prevent the onset of worsening of climate change by the adoption of this convention and subsequent domestic enactments of similar laws, Sinn raised a concern that these green-intended conventions and laws might in fact give rise to paradoxical results that would worsen and accelerate global climate change.[11] The existence, and potential inevitability, of these green paradoxes is of grave concern to policy makers and legislators concerned with preventing climate change.

Anthropogenic climate change is driven primarily by the emission of greenhouse gases, and consequently, the adopted international conventions and enacted domestic legislations have focused on greenhouse gas emissions. The UNFCCC has a regulatory goal to achieve the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."[12] Nations that have joined under the UNFCCC are required to "formulate, implement, publish, and regularly update . . . programs containing measures to mitigate climate change."[13] Those measures are required to focus on reducing emissions and providing for sinks of greenhouse gases.[14] Under the UNFCCC, the regulated greenhouse gases are: (i) carbon dioxide, (ii) methane, (iii) nitrous oxide, (iv) hydrofluorocabons, (v) perfluorocarbons, and (vi) sulphur hexafluoride.[15]

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[11] *See* Hans-Werner Sinn, *Public Policies Against Global Warming: A Supply Side Approach,* 15 INT'L TAX & PUB. FIN. 360, 377-81 (2008) [hereinafter Sinn, *Public Policies Against Global Warming*].

[12] UNFCCC, *supra* note 9, at art. 2. While both the UNFCCC and the Kyoto Protocol have extensive language on the support of climate science and scientific monitoring, these topics do not appear to have substantial bearing on the green paradox concerns, so they have been omitted from the current review framework.

[13] *Id.* at art. 4 § 1(b).

[14] *Id.*

[15] Kyoto Protocol, *supra* note 10, at annex A. This list is not set in stone, as the 2012 Doha Amendment would add nitrogen trifluoride to that listing. *See* United Nations Framework Convention on Climate Change Conference, Doha, Qatar, Amendment to the Kyoto Protocol, U.N. Doc. C.N.718.2012.TREATIES-XXVII.7.c, Art. 1, Annex A (Dec. 8, 2012) [hereinafter Doha Amendment], *available at* https://treaties.un.org/doc/Publication/CN/2012/CN.718.2012-Eng.pdf.

The Kyoto Protocol spelled out specific obligatory mitigation strategies.[16] Parties are directed, *inter alia*, to: (i) enhance energy efficiency;[17] (ii) provide for greenhouse gas sinks and carbon sequestration;[18] (iii) research, promote, develop and increase the use of new and renewable energy sources;[19] (iv) reduce the various supports and subsidies that enable greenhouse gas emissions;[20] and to (v) limit or reduce greenhouse gas emissions.[21] Further, the Kyoto Protocol mandates that certain emission targets be reached by specific deadlines; a similar element is absent in the UNFCCC.[22]

However, as Sinn and others have demonstrated,[23] in certain circumstances, it appears that such legal policies could backfire and thus increase greenhouse gas emissions. Given the importance to prevent anthropogenic climate change, it thus becomes critical for legislators and policy makers to understand if these green paradox concerns are substantial.

This study attempts to reduce and placate some of those concerns. It attempts to review a large body of theoretical green paradox models to reveal that certain underlying modeling assumptions substantially and materially limit their applicability to the research of green paradox phenomena. As such, this article reveals that most of the existing models that find the existence of green paradox events are unreliable for legal researchers and policy makers.

This paper finds that when certain economic models are relied

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[16] *See* Kyoto Protocol, supra note 10, at art. 2 § 1(a).

[17] *Id.* at § 1(a)(i).

[18] *Id.* at §§ 1(a)(ii), (iv).

[19] *Id.* at § 1(a)(iv).

[20] *Id.* at § 1(a)(v). This concerns the green paradox research directly in that by reducing the tax credits or deductions available to energy producers the requirement effectively requires a net increase on carbon-related taxes. Depending on how those changes are implemented, they could fit well within established areas of green paradox concerns. *See infra* Part 0.

[21] Kyoto Protocol, supra note 10, at art. 2 § 1(a)(vii)-(viii).

[22] *Id.* at art. 3 § 1. The targets are to be attained by 2012. *Id.* The Doha Amendment to the Kyoto Protocol would extend that timeline to 2020 and deepen the emission cuts to be achieved. *See* Doha Amendment, supra note 15, at art. 1.C.

[23] *See* introductory dicussion *supra* pp. 1-2.

upon in green paradox research, there are underlying mechanisms that prevent law and policy makers from obtaining clear guidance. As such, increased efforts should be made to promote alternative and more diverse models of green policy impacts on exhaustible resources to better provide the necessary clarity for legislators.

III.

RESEARCH QUESTION AND METHODOLOGY

A. *Models of Exhaustible Resources and Green Policies*

This study takes note that a substantial number of emergent green paradox models are based on a small set of economic models originally developed for studying exhaustible resources.[24] Those models, known as Hotelling and Dasgupta Heal models, contain modeling assumptions that drive certain behaviors within the models. When those models are utilized to research the effects of green laws and conventions, green paradox results have been observed.

Hotelling first developed his early model on depletion rates in-between the two world wars; the policy concerns were questionable pricing by resource owners and allegations of over-extraction and wastage of exhaustible resources.[25] He attempted to provide a framework to resolve those and other related policy questions. While his work is seen as seminal today, it was not as commonly cited in its early years. It is worth noting that his models were not exclusively energy resource related, but applicable to any exhaustible resource, such as diamonds or precious metals.[26]

In the 1970s, Dasgupta and Heal expanded on Hotelling's model by focusing on depletable energy resources and adding a

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[24] *See* discussion *infra* Part 0.

[25] As Hotelling noted, one side assumed intentional underproduction and the other side assumed overproduction of exhaustible resouces. Harold Hotelling, *The Economics of Exhaustible Resources*, 39 J. POL. ECON. 137, 138 (1931).

[26] *Id.* at 152.

choice of an alternative energy source.[27] In this manner, they facilitated the energy policy discussions of replacing one fossil fuel with another or with renewable energy resources. However, despite the focus on energy resources and the potential to adopt an energy alternative, their models remained mathematically similar to Hotelling's model and inherited many of the same assumptions.

The developing awareness of anthropogenic climate change led to the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol during the 1990s.[28] In 2008, Sinn took notice that under certain conditions, the legal requirements of green energy policies, when evaluated within a Hotelling-based model, could lead to increased emissions of anthropogenic greenhouse gases.[29] Sinn's forecasted effects, of increased greenhouse gas emissions due to green energy policies, have been labeled as 'green paradox' phenomena.[30] Since his seminal observations, many researchers have developed other economic models of potential green paradox phenomena.[31]

While the potential causes of green paradox phenomena appear diverse, as discussed below at § 0, there are only a couple of economic models underlying most of the discussions. They are

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[27] *See generally* Partha Dasgupta & Geoffrey Heal, *The Optimal Depletion of Exhaustible Resources*, 41 REV. ECON. STUD. 3, 5-6 (1974); Geoffrey Heal, *The Relationship Between Price and Extraction Cost for a Resource With a Backstop Technology*, 7 BELL J. ECON. 371, 372-77 (1976) (with special attention to equations 4, 5, and 10).

[28] The Framework Convention was a direct result of the first assessment report on climate change from the Intergovernmental Panel on Climate Change ("IPCC"). *See Background on the UNFCCC: The International Response to Climate Change*, United Nations Framework Convention on Climate Change, http://unfccc.int/essential_background/items/6031.php (last visited Nov. 6, 2014).

[29] *See* Sinn, *Public Policies Against Global Warming*, *supra* at note 11, at 366-69, 389-92.

[30] Sinn provides the earliest description of green paradox results in Section 2, *see id.* at 364, and in Section 4 he provided Figure 1 labeling a pathway as a 'green paradox.' *See id.* at 375. However, it is in Section 5 that he provided the nomenclature of 'green policy paradoxes' and explained its meaning. *See id.* at 377-82.

[31] For a dicussion of a variety of green paradox models, *see infra* Part 0.

the Hotelling model of exhaustible resources and the Dasgupta and Heal backstop technology models.

In a survey of twenty articles discussing green paradox phenomena, van der Werf and Di Maria found thirty-two different models of green paradox phenomena.[32] Within those models, twelve were some form of a Hotelling model and eight were some form of a Dasgupta Heal model.[33] For those models discussing carbon prices and taxes and those models discussing the support of alternative energy technologies, only Hotelling models and Dasgupta Heal models were employed.[34] In addressing the delayed introduction of announced climate change policies, two of the three models reviewed were Hotelling models.[35] It was not until unilateral policy models were explored that Hotelling and Dasgupta Heal models became minority models, accounting for three of fifteen models,[36] but there were also only eleven articles underlying those fifteen models. Thus, the Hotelling model and its derivative Dasgupta Heal models represent at least nineteen of the thirty-two surveyed models; however, most of the remaining models are slight derivatives of Hotelling's original model.[37] Thus many, if not most, of the green paradox models are predicated on a small class of closely related economic models of exhaustible resources.

Given that the majority of green paradox models rely on Hotelling or Dasgupta Heal models, and that they share many common underlying modeling assumptions, it merits careful consideration if these models are appropriate for research questions related to green paradoxes. In particular, are they open enough to provide proper inspection of the concern, or are they inherently biased in a manner that might prevent their

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[32] *See* van der Werf & Di Maria, *supra* note 6, at 156-58.

[33] *See id.* Van der Werf and Di Maria refer to the models as Heal models due to the underlying citations to Heal's 1976 article. For the purposes of this article, we have chosen to label these models as Dasgupta Heal models due to Heal's reliance on the earlier paper. *See* discussion *infra* Part D.IV-V.

[34] *See* van der Werf & Di Maria, *supra* note 6, at 156-57.

[35] *See id.* at 157.

[36] *See id.* at 157-58.

[37] *See id.* at 156-58. Clearly, not all of the models were founded upon Hotelling or Dasgupta Heal models.

effective use for green paradox research?

The original rhetorical content of Hotelling's model, including certain key assumptions, was largely adopted by Dasgupta and Heal in their models, and has been imported into a variety of green paradox models.[38] Some of those assumptions potentially pose problems of circular results, e.g., if one assumes full depletion then full depletion results in the model make the task of evaluating whether green energy policies cause full depletion difficult to separate from the underlying model's assumption of full depletion. These problems create a situation wherein green energy policy analyses predicated on green paradox models might not be as reliable as they might otherwise appear.

This study attempts to investigate the development of the Hotelling and Dasgupta Heal models and to analyze certain critical elements of those models that might impact analyses of green paradox models. It provides a review of the major green models and establishes their connections to those certain critical elements from the Hotelling and Dasgupta Heal models. The study reveals that those major models do in fact contain those critical elements, and as such, that those models are unable to establish whether certain green paradox phenomena are present or separate from the working assumptions of their underlying economic models. As such, those models might descriptively explain how green paradoxes might occur, but fail to predict whether the green paradox events would actually occur. This paper concludes that while those major green paradox models might describe how green paradox phenomena could occur, they are potentially inappropriate for policy makers to determine if green paradox phenomena would result from certain specific green energy policies. A finding is presented that alternative economic models are needed, including falsifiable economic models, to better evaluate green paradox events and to support the needs of policy makers concerned with the impacts, both expected and unexpected, of their legislative agendas.

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[38] *See* discussion *infra* Part 0.

B. *Structure of the Study*

This study investigates the question, are Hotelling and Dasgupta Heal models problematic for the investigation of green paradox models? This study finds that those models might in fact be of concern, especially for legislators and policy makers concerned with the potential effects and side effects of prospective green energy laws.

This study attempts to trace economic models of exhaustible resources from their seminal versions to their application in models of green paradox phenomena. The study explains the central role of key assumptions of those models and how those assumptions affect the resultant analyses into green paradox phenomena. The study will reveal that the original aims and intents of the economic models remain central to their mathematical function yet frustrate efforts to definitively test the potential of green paradox phenomena.

The first part of this article provides a background to the research problem and proposes a means of addressing the issues. The research problem is identified as the practice of green paradox models to rely on a small number of closely related economic models developed for other purposes. Those models are identified as having certain assumptions that might pose problems for the identification of green paradox phenomena. The research question aims to determine whether aims to determine whether the reliance on those few models might pose fundamental problems for the study of green paradox models. The first part also provides a description of the overall study's structure.

The second part of this article provides background on the original development of the green paradox problem and of subsequent classes of green paradox models. First, Sinn's contributions are discussed. His original model of emergent green paradox phenomena is described, and his initial and seminal reliance on Hotelling's model is discussed. Also, his concerns on the inevitability of green paradox problems are reviewed. The subsequent parts provide introductions to the four major classes of green paradox models and to one particular integrated class of green paradox models. Throughout the review of the model classes, the central reliance on Hotelling or Dasgupta Heal models is demonstrated. Even when certain models do not directly derive from those two model classes, they often include assumptions that bring their modeling functions in alignment with those two model classes, thus similar results entail.

The third part of this article provides a detailed review of the underlying Hotelling and Dasgupta Heal model classes. The discussion on Hotelling's model explores the origins and development of his original models. It explains how the models are intended to operate. It provides a detailed listing of Hotelling's central assumptions and demonstrates that Hotelling provided specific caveats on his assumptions and that other evidence can be brought to raise concerns on the applicability of those assumptions to green paradox research. Thereafter, the Dasgupta Heal models are explored with a focus on demonstrating their close affinity with the Hotelling models' assumption, and thus that they would be equally of concern for green paradox modelers. A conclusion is obtained that Hotelling was well aware of the limits of his models, that Dasgupta and Heal extended his models without substantial change to the core assumptions. Thus, the various classes of green paradox models that build on either Hotelling or Dasgupta Heal models also have inherited the same concerns for which Hotelling had previously provided caveats.

This study concludes that models researching green paradox phenomena built upon either Hotelling models or Dasgupta Heal models need to be provided with precautionary adjustments and caveats for legislators and policy makers. Additionally, the conclusion of this study will promote the use of exhaustible resource models that are not substantially based on the assumptions drawn from the Hotelling or Dasgupta Heal models for future research into green paradox phenomena.

IV.

CLASSES OF GREEN PARADOX MODELS

This section provides a review of several dominant classes of green paradox models and attempts to demonstrate their common reliance on the Hotelling models of exhaustible resources or on the closely related Dasgupta Heal models of exhaustible resources with back stop energy resources.

This section of the study begins by introducing Sinn's original green paradox concerns and his resultant Hotelling based carbon tax green paradox models. Sinn's original presentation of the idea of a green paradox is discussed. The preliminary concerns of Sinn are reviewed. Then the original carbon tax green paradox models are described, and his others sources of green paradoxes surveyed. Thereafter, Sinn's concerns on the inevitability of green paradox results are presented.

Following the Sinn discussions, reviews are provided of several major classes of green paradox models. Extensive surveys of green paradox models can be found in the literature.[39] A consensus view might be argued to support a four-fold clustering of green paradox models: (i) a class of carbon tax models, (ii) a class of backstop technology subsidy models, (iii) a

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[39] *See, e.g.*, Van der Werf & Di Maria, *supra* note 6, at 155; Frederick van der Ploeg & Cees Withagen, *On the Relevance of Green Paradoxes* 1-2 (Oxford Ctr. for the Analysis of Res. Rich Econ., Policy Paper No. 18, 2013) [hereinafter van der Ploeg & Withagen, *Relevane of Green Paradoxes*], *available at* http://www.oxcarre.ox.ac.uk/files/OxCarrePP201318.pdf; Hendrik Ritter & Mark Schopf, *Unilateral Climate Policy: Harmful or Even Disastrous?* 1-4 (Otto von Guericke Universität Magdeburg Faculty of Econ. and Mgmt., Working Paper No. 10, 2013), *available at* http://www.fww.ovgu.de/fww_media/femm/femm_2013/2013_10.pdf; Thomas Michielsen, *Brown Backstops Versus the Green Paradox*, 68 J. ENVTL. ECON. & MGMT. 87, 87-88 (2014); Carolyn Fischer & Stephen W. Salant, *Limits to Limiting Greenhouse Gases: Intertemporal Leakage, Spatial Leakage, and Negative Leakage* 2-5 (May 9, 2013) (unpublished paper), *available at* http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.384.1648 (click on "PDF" hyperlink on upper right of page).

class of pre-announced policy models, and (iv) a class of international carbon leakage models.[40] Each class of models will be reviewed to demonstrate the extent of their reliance on Hotelling or Dasgupta Heal models.

Finally, a separate model by Michielsen that provides a unifying framework of green paradox discussions is also shown to rely in part on similar economic assumptions to the Hotelling paradigm.

Thus, it will be demonstrated that many, if not most, of the recently published green paradox models rely on the underlying economic assumptions embedded in the earlier models of Hotelling as well as Dasgupta and Heal.

As will be demonstrated below, the green paradox models based on Hotelling models generally found green paradoxes possible, those based on Dasgupta Heal models found them less often, and those based on general equilibrium models were significantly less likely to find green paradoxes. The reasons for this stark and simple result, the dependency on the underlying model form for finding green paradoxes, is reviewed in the following §§ 0 through 0.

A. *Sinn's Carbon Tax Green Paradox Models*

1. Anthropogenic Climate Change Created by Market Failures

Sinn explored the problem of anthropogenic climate change as a result of market failure. To evaluate those green policies designed to control carbon emissions, Sinn began with a Hotelling based model of extraction.[41]

Sinn extended the Hotelling analysis to include a production function that includes land-based capital, such as existing fossil fuels, regular accumulated capital, the carbon-free quality of atmosphere, and time as inputs.[42] The model thus assumes

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[40] *See* sources cited *supra* note 39.

[41] Sinn, *Public Policies Against Global Warming*, *supra* note 11, at 367.

[42] *See id.* at 372 eq. 8 (listing Equation 8 as $Y=f(K,R,S,t)$, where S is the atmosphere quality and $f_s>0$, $f_{ss}<0$). In Sinn's Equation 8, K is ordinary capital and R is the resource capital. *Id.* at 367 (identifying these two variables in the

positive and increasing marginal damage to the atmosphere from cumulative fossil fuel use.

Sinn found that there was a singular solution that prevents intertemporal discrimination for this Hotelling model.[43] This unique solution requires a deferral of fossil fuel production; when damage from anthropogenic climate change is taken into account, "a flatter extraction path with less extraction in the present and more in the future is required."[44] The greater the marginal damage to the atmosphere, the greater the reduction in extraction speed is required.

Sinn argued that this deferred production solution is compelling because "it does not involve a value judgment that derives from considerations of inter-generation equity, fairness or sustainability, but follows merely from economic efficiency considerations."[45]

Sinn stated while the world, *sans* climate change, would operate at one equilibrium,[46] the threat of climate change requires a lower level equilibrium. Nevertheless, Sinn recognized that the world was not following his economic model and its prescribed carbon consumption levels.[47] This was the first problem: the market would continue to over-consume fossil fuels because the costs of climate change were not fully accounted for in market behavior.[48] Climate change could indeed be modeled

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context of Equation 2). For more discussion on Hotelling's models, *see infra* Part D.II.

[43] *See* Sinn, *Public Policies Against Global Warming*, *supra* note 11, at 372 eq. 9. For more discussion on Hotelling's models, *see infra* Part 0.

[44] Sinn, *Public Policies Against Global Warming*, *supra* note 11, at 373.

[45] *Id.* However, it is a fair critique to mention that the model assumed that production was reduced by climate change, by the conditions required of S, f_s, and f_{ss}; there is no alternative result possible within the initial conditions as set by Sinn. While there is great consensus on the scientific impacts of climate change, there is much less certainty on the future net productivy or welfare results. The author's current study is on the effectiveness of legal policy to achieve its stated ends; the potential welfare results of those laws is left for separate research.

[46] *See id.* at 374 eq. 11 (listing Equation 11, which generally models all four behaviors discussed in this paper). *See also id.* at 375 fig. 1 (providing a graphical depiction of the four variants of the model).

[47] *Id.* at 373 ("The problem is that society does not respect this rule.").

[48] Sinn's discovery of emergent green paradox phenomena, and their

as a form of market failure.

Sinn identified three major policy issues driving the emergence of the market failures leading to the emergence of global anthropogenic climate change:

i. Intergenerational pricing problems within neoclassical microeconomics,

ii. Equivalent dysfunction of political and economic markets, and

iii. Resource owners' problems of insecure property rights in the resources associated with greenhouse gas emissions.

First, Sinn demonstrated that neoclassical microeconomics failed to provide effective policy recommendations based on the standard model's reliance on modeling multi-generational preferences and utility functions, if known.[49] However, those utility functions and generational preferences are not known in advance of their actual emergence in the future.[50] Thus, the externalities of the carbon emissions could not be appropriately priced and managed by the marketplace due to the lack of complete and accurate information in contemporary time periods.

Second, Sinn posited that policies based on non-market-based ethical considerations would not perform better than the market had already performed; thus, certain political efforts based in 'nirvana ethics' would not be able to cure the market failures.[51]

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potential inevitability, would be the second problem. *See id.* at 377.

[49] Sinn sets up the intergenerational paradigm in the first paragragh of Part 3. "To understand the market failure, an intertemporal analysis is needed that concentrates on the wealth society bequesths to future generations." *Id.* at 366. The main thrust of his intergenerational model is presented within "Neoclassical optimism," at 368-9.

[50] *Id.* at 368 ("Equation (4) describes an optimal portfolio mix between man-made and natural capital to be bequeathed to future generations . . . Equation (4) does not, however, indicate how much the present generation should bequeath and what level of consumption realtive to the consumption of future generations would be efficient or fair."). Sinn's comments refelct the difficulty of intertemporal models when institutional shifts in preferences are to be expected but unforeseeable in character.

[51] *See id.* at 369-70 (reflecting the author's disdain of the sustainable economic development perspectives of Anand, Page, Sen, Solow, and Stern). That is, political actions such as the adoption of climate related laws or international legal conventoins such as the UNFCCC would fail unless they

Sinn noted that voters are the same actors as those driving the market; if the actors cannot act clearly in their market transactions, then he asks why should democratic politics result in more clarity regarding the costs of climate change? He answered that similar dysfunction would avail.[52] Thus, Sinn argued, politicians would need to find authority beyond current voters. Could they argue for the needs of future generations, and would politicians be better placed to opine for those future voters than the prospective future ancestors of those future constituents? Again Sinn argued no, that politicians do not have a claim to superior insight into the values of future voters vis-à-vis those future voters' currently voting prospective ancestors. Essentially, those actors currently in the marketplace and currently voting already took into account the effects of their actions on their future descendants.[53]

Sinn detailed the ethical concerns that certain economists have raised that free market solutions cannot be ethically relied upon because interest rates, and thus discount rates, are likely biased against future generations in over-incentivizing current consumption against long run welfare growth.[54] Sinn queried to whom the policy maker should turn to solve that dilemma. He argued that if the 'ethical economists' were correct in their concerns then there could be no solution. *Ergo*, that the position of 'ethical economists' is either wrong or irrelevant.[55] Moving past 'ethical economists,' Sinn further argued that parents did in fact take their descendants' needs into account as the parents interacted in the market, and thus, government involvement to

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receive the popular support of their underlying democracies. As Sinn warns, if politicians took actions in contrast to democractic support, "it would leave the firm ground of methodlogical individualism and get stuck in the muddy waters of Nirvana ethics." *Id.* at 370.

[52] *See id.* at 369-70.

[53] *See id.* at 370.

[54] *Id.* at 368-69.

[55] *Id.* at 369. Sinn argued that if the common citizen is errant in his understanding of climate change and the related discont rate issues, then any democratic leader chosen by an electorate of such voters would perform no more accurately than those who elected her into office. *Id.* ("These politicians will not find any mistakes in the intertemporal allocation pattern of markets and will, therefore, not take any countervailing policy actions.").

allow philosophers to advise contrary to those parents would be poor policy.[56]

Sinn proposed that weak assignment of property rights drove part of the market failure. Sinn explored the concern that resource owners often face uncertain property rights to their assets, and the temporal aspect of control led to accelerated depletion of their assets in an attempt to maximize revenues whilst in possession.[57] He focused on the role that states with dictators play in owning fossil fuel resources. Sinn highlighted that their dictators face uncertain terms in office, and that these concerns will imperil otherwise functional markets to overproduce hydrocarbons.[58]

Second, Sinn returned to his property right concerns; policies to deny current fossil fuel resource owners from the benefits of their assets would be defective because the introduction of additional risk of instantaneous expropriation from resource owners would accelerate the production of fossil fuels even more than the free market would have. Thus, climate change policies should be careful to preserve existing property rights, which in turn means that resource owners should not be faced with temporal limits of production nor should they face other bans on production and resultant profits.

Sinn introduced the idea that the market could respond to green energy policies in ways worse than the previous two results. Sinn cautioned that certain green policies could result in increased greenhouse gas emissions instead of their targeted

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[56] *See id.* at 370 (commenting that to follow the logical implication that individuals were not reliable for economic decision making would ultimately undermine the functional concept underlaying basic economics). Perhaps some middle ground might be reasonably sought between Sinn's "pure" neoclassical models and the new behavioural models of economic decision making. So long as the resultant empirical models of decision making are rational and predictable, it does not matter if the actor herself is rational *per se*.

[57] *Id.* at 370-71.

[58] *Id.* at 371 (noting that at least 70% of both crude oil and natural gas reserves were held by the dictators of the Gulf States, Venezuela and of the territories of the former Soviet Union). Additionally, from those areas he listed six dictators or monopolists by name, three of whom have been assassinated and two more of whom have been exiled since the article was written in 2008, reinforcing the validity of their short tenure as resource owners. *Id.*

reductions of the same; this type of unexpected policy backfire he called a 'green paradox.'[59]

2. Rising Carbon Taxes Could Induce Green Paradox Effects

Sinn began his study into green paradoxes by adopting the Hotelling model.[60] Sinn's variant on this model assumed constant marginal costs, but he also assumed that the costs of extraction increased as overall depletion occurred.[61] Sinn also added a tax cost to the extraction costs. Several cases are notable:

i. A constant tax left the production volumes in their original schedule at their original volumes, but with a drop in price. Overall emissions remain unchanged. [62]

ii. A tax that increased in latter periods would require a shift of production from those latter expensive periods into earlier periods due to the arbitrage assumed by Hotelling's rule to equate net revenues from all time periods.[63] However, the initial price of the fossil fuel will be reduced in the earlier periods, in contrast to the equilibrium price without a tax. [64]

Sinn's observation was that Hotelling's rule has perverse

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[59] *See id.* at 375 fig. 1. In some ways, the idea of the green paradox is an exaggerated form of the instantaneous expropriation concern, in that resource owners suddenly find themselves at potential loss of their profits from their property rights under carbon taxation.

[60] *See id.* at 377-80 (presenting models for green policy paradoxes). The price of exhaustible resources is controlled by a relationship referred to as Hotelling's rule. *Id.* at 370 eq. 7, 381 (listing Equation 7 and later defining it as a modified version of the Hotelling rule). *See also* discussions on Hotelling's model of exhaustible resources *infra* at Part 0.

[61] *See id.* at 366, where Sinn sets the costs of unit extraction as $g'(S)<0$, wherein S is the total remaining stock of fossil fuel. As S were to be depleted and reduced, the costs g would increase. Similar assumptions can be found within Part 4's "simplified interpretation," *id.*, at 374. Sinn did include technical modeling that assumed eventual complete depletion of the reserves both with and without carbon taxes. *See* Robert D. Cairns, *The Green Paradox of the Economics of Exhaustible Resources*, 65 ENERGY POL'Y 78, 80 (2014) (the assumption of full depletion enabled the result of higher fossil fuel production under a carbon tax).

[62] *See* Cairns, *supra* note 60, at 80 eq. 2; *see also id.* at 79-80 (defining the constants and variables).

[63] *See id.* at 80 eq. 3.

[64] *Id.* at 80.

effects on green energy policies that attempt to reduce emissions by providing negative incentives via carbon taxes. While constant carbon taxes under Hotelling's rule would not reduce production volumes, rising carbon taxes would shift extraction to earlier time periods. This second result was Sinn's primary green paradox.[65] Because the Hotelling model assumed that the fossil fuels would be fully depleted,[66] an increase in production during one time period will cause a corresponding decrease in another; high costs in a latter period encourage activity to occur earlier. This gave rise to Sinn's central concern:

> "However, if firms react to a change in demand today by extracting less, they must extract more tomorrow, and *vice versa*, and it is by no means obvious that the demand-reducing measures discussed in Sect. 2 will be able to tilt the extracting path in the right direction."[67]

Thus, Sinn demonstrated that Hotelling's model could be leveraged to demonstrate the existence of green paradoxes;[68] however, those demonstrations should come with Hotelling's caveats. Green paradoxes appear to result from the temporal arbitrage built into the model by its reliance on Hotelling's rule.[69]

Sinn considered two different tax models to validate his green paradox concerns:

(i) A cash flow carbon tax,[70] and

(ii) An "ad valorem sales tax on extraction."[71]

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[65] For more discussion on Sinn's green paradox as motivating this study, *see supra* pp. 1-2.

[66] The original model assumes that full depletion will occur. The model can be modified to recognize less than full resource depletion, but the ex ante determined replacement limit will continue to be fully depleted. Thus, the temporal problem of Hotelling models is endemic to the model. *See* discussion *infra* Part 0.

[67] Sinn, *Public Policies Against Global Warming*, *supra* note 11, at 377 (emphasis added).

[68] *See supra,* at note 60. Hotelling's model made finding a green paradox too readily feasible; this analysis suggests that researchers might seek alternative foundations for investigating green paradox phenomenon.

[69] For a discussion of Hotelling's assumptions, *see infra* Part 0.

[70] *See* Sinn, *Public Policies Against Global Warming*, *supra* note 11, at 377 eq. 13.

He relied on these two carbon tax models to demonstrate that under a Hotelling model, by providing incentives to avoid fossil fuel production in later time periods, the policies also created countervailing incentives to increase production of fossil fuels in earlier time periods.[72] "[T]he resource owners will anticipate extraction . . . to compensate for the rising tax rate. Global warming will accelerate."[73] And by 'anticipate,' Sinn clarified that the fossil fuel resource owners "will try to anticipate the price dampening effect by selling more in the present and less in the future . . . ."[74]

Thus, those two green tax policies would result in additional anthropogenic emissions of greenhouse gases: "The green paradox implies that such a policy is likely to backfire and create even more harm for the environment by speeding up global warming."[75]

Sinn stated that the green paradox could result from other causes, not merely from carbon taxes, and included these examples of alternative causes of green paradoxes:[76]

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[71] *See id.* at 378 eq. 14. Such an extraction tax is more routinely referred to as a severance tax or a production tax. Sales taxes are generally imposed downstream of the wellhead at arms' length sales points; a common location is the lease edge transfer point at the LACT meter. Property taxes called "ad valorem" are imposed as real esate taxes against the value of minerals; they exclude the value of the land surface.

[72] *Id.* at 378. Sinn analogized to a closed-loop piston system: "If only one piston is pressed down, the others go up. If, however, all pistons are pressed equally, none of them moves." *Id.* In the event of green energy policies that provide disincentives to produce fossil fuels in later periods, that later period is the piston pressed down causing the earlier period pistons of fossil fuel extraction to go up, as it were. *Id.*

[73] *Id.* at 380.

[74] *Id.* at 381.

[75] *Id.* at 380.

[76] *See id.* at 381. Cases (ii) and (iii) listed below are the original concepts from Dasgupta and Heal's back stop models and underlay a class of green paradox models. *See* Dasgupta & Heal, *supra* note 27, at 3-4 and at 18-9 (Dasgupta & Heal called renewable resources 'reproducible inputs', *id.* at 4, and 'synthetic substitutes,' *id.* at 18, as contrary to 'exhaustible resources.' They included solar energy and nuclear fusion as such reproducible inputs, *id.* at 18.); Heal, *supra* note 27, at 371-2. (Heal's model focused on resources that had both cheaper yet exhaustible sources and more expensive but 'effectively inexhaustible sources. He cited Nordhaus's study on oil from conventional reservoirs and from shale oil reservoirs as an example of such a resource, *id.* at

(i) Energy Efficiency:gains in energy efficiency could reduce energy demand from fossil fuels in future time periods;[77]

(ii) Green Energy: increased supplies from green non-fossil fuel energy sources could reduce energy demand from fossil fuels in future time periods;[78]

(iii) Non-Green Energy: increased supplies from non-green non-fossil fuel energy sources could reduce energy demand from fossil fuels in future time periods;[79]

(iv) International Leakage: differing policies between states on abating the causes of climate change.[80]

He stated that the above sources of green paradox could be strengthened by governmental subsidies, by quantity constraints, or by moral persuasion or dissuasion.[81] Additionally, the more the green paradox occurred, and thus the more anthropogenic climate change occurred, the public would increasingly support additional efforts to reinforce those policies, so long as it was contra-factually misunderstood that such policies were reducing emission.[82]

371-2.). *See also* discussion *infra* Parts 0, 0, 0. Case (iv) below is the area known as international carbon leakage. See discussion *infra* Part 0. It generally appears that both Sinn and subsequent models have focused primarily on the Dasgupta and Heal proviso that backstops might be both highly substitutable and displacing to the original fossil fuel. However, there is room to consider the case of poor substitutes or of slow adoption of a substitute back stop that might allow the newly surplus energy supplies from fossi lfuels to price compete with the oncoming back stop energy source.

[77] *See* Sinn, *Public Policies Against Global Warming*, *supra* note 11, at 364, 381. Both his first sense of efficiency (lighter cars, housing insulation) and fifth sense (*e.g.*, improved engine design) from efficiency gains, as well as the energy recovery systems such as biomass and regenerative vehicle brakes on hybrid cars, fit in this category. *Id.*

[78] *See id.* Renewable green energy sources such as wind, water, and solar voltaics. are in this category. *Id.*

[79] *See id.* at 376, 381. Herein Sinn suggested nuclear fusion as connected with supporting some form of a hydrogen economy. *Id.*

[80] *Id.* at 377. Sinn foresaw the idea of international leakage, where one country moves ahead with green energy policies and as a result of such efforts countries without green policies in place could afford to consume more fossil fuels. *Id.* ("One country's green policies just help the other country buy energy at lower producer prices.").

[81] *Id.* at 381.

[82] *See id.* ("[A]s the world becomes warmer and more and more people become afraid of the greenhouse effect, public support for such measures will

Sinn concluded that "markets unfortunately are unable to find the optimal path" to avoid anthropogenic climate change because they cannot resolve the optimal path between the stocks of carbon pre-combustion and those post-combustion.[83] The problems of incomplete climate change information in fossil fuel pricing and alternative energy pricing, plus the challenges of insecure property rights, leads to the over-extraction and over-consumption of fossil fuels.[84] Sinn expected that political efforts to address climate change will either be fiscally wasteful in not accomplishing emission reductions or worse will create green paradoxes and worsen the trend against no emission policies at all. [85]

In his conclusion, he offered no new solutions that he had not previously ranked from likely to infeasible.[86] He is left stating, "[t]here is a green paradox." [87] Sinn's sense of frustration rings clear, but it remains largely predicated on the internals of Hotelling's models and should be guided by the caveats noted below in § 0.

B. *Models of Rising Carbon Taxes*

The policy concept within this class of models is that authorities would apply some form of a carbon tax or fee upon either the extractors or combustors of fossil fuels to provide the economic incentive to reduce the usage of fossil fuels.[88]

Exemplar models of this form of green paradox include Gerlagh,[89] Hoel,[90] and Habermacher.[91] These models were built

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rise so that the demand-reducing effect caused by government interventions is likely to become stronger and stronger.").

[83] *Id.* at 388.

[84] *See id.*

[85] *Id.*

[86] *See id.* at 388-89.

[87] *Id.* at 388.

[88] *See* van der Werf & Di Maria, *supra* note 6, at 160. The discussion on this model will be lengthier than other models, because many of the model's assumption and behaviors are similar to the other models and thus can be explained once hereunder. Also, this model is the dominant green paradox model as it was the original proposal by Sinn, *see* discussion *supra* Part 0.

[89] *See* Reyer Gerlagh, *Too Much Oil*, 57 CESifo Econ. Stud. 79 (2011) .

on earlier suggestions to have a temporally increasing carbon tax to phase-out the usage of fossil fuels.[92] Van der Werf and Di Maria provided a taxonomy of this model class.[93] They reviewed both Hotelling and Dasgupta Heal versions of the models.[94]

Van der Werf and Di Maria's Hotelling model begins with a roster of assumptions about the depletion decisions of the operator. The model includes an 'extraction path' or depletion function of a stock resource,[95] an exogenously determined price for the fossil fuel per unit,[96] a tax on the carbon emissions set to match a unit usage of fossil fuel,[97] and an increasing cost of production for the fossil fuel:[98]

(i) The interest rate, r,[99] is determined exogenously.[100] This implies that they obtain capital from fully competitive capital markets, and that their internal sources of capital, if existent, are not competitive with r.

(ii) The resource owners are assumed to be price takers.[101]

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[90] *See* Michael Hoel, *Global Environmental Problems: The Effects of Unilateral Actions Taken by One Country*, 20 J. ENVTL. ECON. & MGMT. 55 (1991) [hereinafter Hoel, *Global Environmental Problems*]. Michael Hoel, *The Green Paradox and Greenhouse Gas Reducing Investments,* 5 INT'L REV. ENVTL. & RESOURCE ECON. 353 (2011).

[91] *See* Florian Habermacher & Gebhard Kirchgässner, *Climate Effects of Carbon Taxes, Taking into Account Possible Other Future Climate Measures* (CESifo Working Paper No. 3404, 2011).

[92] *See generally* WILLIAM D. NORDHAUS, MANAGING THE GLOBAL COMMONS: THE ECONOMICS OF CLIMATE CHANGE. (1994) (providing a non-green paradox model of temporally increasing carbon taxation).

[93] See van der Werf & Di Maria, *supra* note 6, at 160-65.

[94] *See id.*

[95] *Id.*, at 160. *See, e.g.*, equations (1.a) through (1.e) for the assumptions of the model's extraction path.

[96] *Id.* "Resource-owners are price takers[.]"

[97] *Id.* "$\tau(\square)$ is the carbon emissions tax (the units are set such that one unit of resources use generates one unit of emissions[.])"

[98] Id., 160-1. "$\square(\square(\square))$ is the unit extraction, which we allow to be an increasing function of the amount of cumulative extraction $\square(\square)$."

[99] From my personal experience, many operators in practice have cheaper, internal sources of capital than the exogenously determined r. Their investment decisions are not driven by external r but by other competitive investments. Hurdle rates often 15% or higher, in great excess of market levels of r.

[100] *See id.* at 160. *See also* discussion *infra* Part 0-5,.

[101] *See* van der Werf & Di Maria, *supra* note 6, at 160; *see also infra* Part 0 (discussing Hotelling's assumption on free markets).

This assumption is standard for fully competitive markets with competitive vendors of perfectly substitutable goods; the price of the resource is governed by Hotelling's rule.

(iii) The resource owners optimize inter-temporal profits by choosing an extraction path over time; but the model assumes/requires full depletion by the final time period.[102]

(iv) The model assumes that the cost of extracting units of fossil fuel increases over time as more cumulative extraction occurs;[103] i.e., the more that has already been extracted, the more expensive it will be to extract the next unit.[104]

(v) A perfectly substitutable alternative green energy source exists, known as a 'backstop technology.'[105] It has a pre-determined price; *b*. The model assumes that when the price of the fossil fuel exceeds *b*, the consumers will no longer purchase the fossil fuel at all[106]

(vi) The resource owners and operators will always be able to sell every unit of produced fossil fuel, because the model assumes that the market will continue to completely clear even as the price of the fossil fuel approaches infinity.[107]

As to these assumptions, the model operates by assuming that from time zero until the end time, the whole reservoir of fossil fuel will be depleted.[108] This provides an interesting revelation,

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[102] *See* van der Werf & Di Maria, *supra* note 6, at 160-61; *see also infra* Part 0 (discussing Hotelling's assumption on flexible rescheduling of production).

[103] *See* van der Werf & Di Maria, supra note 6, at 160-61; *see also infra* Part 0 (discussing Hotelling's assumption on rising costs of extraction).

[104] Van der Werf & Di Maria, *supra* note 6, at 160-61*; see also* van der Ploeg & Withagen, *Relevance of Green Paradoxes*, *supra* note 39, at 2-3 (discussing why extraction costs might become "more costly as less accessible reserves have to be explored").

[105] Van der Werf & Di Maria, *supra* note 6, at 161; *see also infra* Part 0 (discussing Hotelling's foreshadowing of Dasgupta and Heal's back stop alternative energy models).

[106] Van der Werf & Di Maria, *supra* note 6, at 161; *see also* van der Ploeg & Withagen, *Relevance of Green Paradoxes*, *supra* note 39, at 2-3 (discussing backstops and dirty backstops).

[107] Van der Werf & Di Maria, *supra* note 6, at 161. *See also infra* Part D.III.1 (discussing Hotelling's caveats on the potential for energy resrouce markets to not clear, i.e., that the producers might not be able to sell all of their produced volumes).

[108] *See* van der Werf & Di Maria, *supra* note 6, at 161 (defining Equation

in that the model is essentially assuming that the returns to the producer grow at the interest rate, r.[109] This condition is called the Hotelling rule, and its means that the decision maker is temporally indifferent as to when fossil fuels are produced. This is because the profits from all time periods are effectively increased at the same rate as the discount factor of net present value calculations.[110] Van der Ploeg and Withagen refer to the centrality of the Hotelling rule in establishing the green paradox models; they deny that extraction costs are relevant considerations for when crude oil is produced and that the asset value of the reserves is what determines when crude oil is extracted.[111]

Since a Hotelling model requires the complete depletion of the resource,[112] and because the model invokes the Hotelling rule, taxes on later year production and sales will provide an incentive to reschedule those volumes to years without those taxes, *i.e.* to earlier years.[113] Because the Hotelling model assumes complete depletion, a carbon tax or fee can only reschedule the production and sales of those fossil fuels, it cannot reduce their production.[114] If the carbon tax, τ, grows at the same rate as r, then no rescheduling is effected because the tax is essentially the same at all time periods.[115] If the growth of the tax rate exceeds the interest rate, then the rescheduling to the earlier time period will occur.[116] While not in van der Werf and Di Maria's model, the equation holds the interesting policy point that if the tax starts high, but then drops, producers can foresee that result

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2).

[109] *See id.* (defining Equation 3).

[110] *See id.* (defining Equation 3). The net present value calculation creates a discount from later revenues by application of ((revenue/$(1-r)^{n}$) where n is the number of future time periods. Hotelling rule suggests that the revenues numbers increase in synchronization with r over time, so the net result of time passage is null.

[111] Van der Ploeg & Withagen, *Relevance of Green Paradoxes*, *supra* note 39, at 2 ("Extraction costs do not change the picture in an essential way.").

[112] *See infra* Part 0.

[113] *See* van der Werf & Di Maria, *supra* note 6, at 161-62.

[114] *Id.* at 161.

[115] *Id.* at 162.

[116] *Id.*

then they will increase production of fossil fuels in later time periods.[117]

Van der Werf and Di Maria argued that when the carbon tax is rising, a green paradox will result because the producers will optimize their production volumes to be sold prior to the switch over to alternate green energy sources. They also argued that a green paradox would not occur if the tax grew equal or less than the interest rate.[118] However, this result would hold under any Hotelling model that faces a shortened production time-frame, regardless of causation, due to the requirement of full extraction, *above*. Thus, whenever the fossil fuel producer reasonably anticipated that the imposition of a carbon tax would suffice to price the fossil fuel higher than the alternative, the producer would be forced by the model to extract the fossil fuel prior to that point in time. Thus, relying on standard Hotelling models will result in green paradoxes, so long as the carbon tax creates an earlier endpoint of the time-frame.

The Dasgupta Heal model is introduced to enable the producer to decide to cease extraction prior to complete depletion by contrasting the cost of extraction against the price of an alternative energy technology.[119] As the model builds upon the Hotelling model, similar concerns as discussed above are inherited, and to that extent their discussion is not repeated hereunder.

For green paradox discussions, the Dasgupta Heal model has two unique effects. First, the model provides a point in time when fossil fuel will no longer be extracted due to its comparatively high costs. Second, the model enables some amount of fossil fuel to remain. These changes could reduce the

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[117] *See id.* (defining Equation 5).

[118] *See id.* The actual reference is to a "weak green paradox," which they defined as an increase in greenhouse gas emissions. *Id.*.They contrasted that against a notion of "strong green paradox," which finds a decrease in welfare as a result of that increase in greenhouse gas emissions. *Id.*, at 155. For the purposes of this paper, green paradox refers solely to the phenomenon of increasing anthropogenic greenhouse gases as a result of legislation and other legal conventions that attempt to reduce such emissions. This paper addresses the effective of positive law, potentials adverse results, and potential fixes.

[119] *Id.*

artificiality of the Hotelling results with a forced temporal shift to earlier periods simply because the model requires complete depletion.

The Dasgupta Heal model assumes a 'backstop' green energy alternative; any introduced carbon tax will effect a reduction in the price that will terminate fossil fuel extraction.[120] The model creates a trigger that the fossil fuel ceases to be extracted when the costs of extraction, after a certain amount of depletion, reaches the same price as the alternative green energy source.[121] If a carbon tax is added to the price of fossil fuel extraction, then the cost of extraction plus the carbon tax needs to remain under the price of the alternative energy source. Equivalently stated, the cost of extraction needs to remain below the price of the alternative reduced by an equivalent value to the carbon tax.[122]

The model provides that the carbon tax effectively reduces the total amount to be extracted; it also affects when that extraction occurs. If the carbon tax rises more slowly than the interest rate, then the carbon tax is more expensive in earlier periods and extraction shifts to later time periods. This also lowers net emissions; thus, no green paradox results.[123] This is also true when the carbon tax rises equally with the interest rate; again, no green paradox.[124] However, when the carbon tax rises quicker than the interest rate, making future extraction more expensive than current, then a green paradox will result.[125] In that case, time-frame fossil fuel extractions remain reduced.[126]

A two-period Dasgupta Heal model with endogenous investment in the alternative green energy source revealed that the behavior of the extraction costs determined if a green paradox resulted or not.[127] If the costs of extraction rose sufficiently fast enough, then a green paradox could result. Otherwise, under flat or decreasing extraction costs there were

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[120] *Id.* at 163.

[121] *Id.* at 162.

[122] See *id.* at 163 (defining Equation 7).

[123] *Id.*

[124] *Id.*

[125] *Id.* at 163-164.

[126] *Id.* at 163.

[127] *Id.* at 164.

no resulting green paradox results.[128]

So, the Dasgupta Heal models provide less opportunity for a green paradox than the Hotelling models allowed, above within the current section. This would primarily appear to be due to the modification to the Dasgupta Heal models to allow incomplete depletion whereas their Hotelling models required full depletion of the reserves. Thus, when presented with either economic incentives or shorter time frames, the Hotelling models required time-shifting the production schedules to the earlier time frames and ensured a green paradox for earlier time periods. The Dasgupta Heal models are not as readily green paradox yielding, in that only when certain conditions avail can green paradox results occur, especially so when modified as noted above. A green paradox could occur under a Dasgupta Heal Model only when the cost of extraction increases in later periods, due either to carbon taxes or higher costs of extraction due to depletion.

But much depends on the time value of money as measured in the interest rate versus other changing cost factors. It is perhaps not odd to find that if future costs are too high, then business owners will attempt to make more profit in earlier time periods. If the overall effect of carbon taxes is to make future production of fossil fuels more costly, then perhaps it would be reasonable to expect that fossil fuel producers would attempt to produce more in the earlier periods.

C. *Models of Backstop Technologies*

The policy concept within this class of models is that authorities would apply some form of a subsidy to stimulate the development and feasibility of alternative green energy sources to provide the economic incentives to reduce the usage of fossil fuels.[129] Exemplar models of this form of green paradox include van de Ploeg and Withagen,[130] Gerlagh,[131] Grafton et al.,[132]

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[128] *Id.*

[129] *Id.* at 165-66.

[130] *See* Frederick van der Ploeg & Cees Withagen, *Is There Really a Green Paradox?*, 64 J. ENVTL. ECON. & MGMT. 342 (2012) [hereinafter van der Ploeg & Withagen, *Is There Really a Green Paradox?*] .

[131] *See* Gerlagh, *supra* note 88..

Hoel,[133] Hoel and Jensen,[134] and Strand.[135] Not everyone agrees that these models are distinct from the previously examined carbon tax models,[136] in that taxes and subsidies can be seen as two means to the same economic policy ends.[137]

The models assume economic support in the form of government provided subsidies to reduce the effective price of alternative green energy sources.[138] Again, the Hotelling and Dasgupta Heal models are the dominant templates for research.[139]

The first major assumption of the subsidy model, under a Hotelling depletion model, is that the final price of depleted units will equal the price of the backstop technology of the alternate energy source.[140] It follows that the lower the effective price of the substitute, the earlier that fossil fuels will be priced out of the market;[141] thus the policy becomes how to lower that price, *b*. However, under the Hotelling depletion model, the resource owner would need to accelerate the production of the

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[132] *See* R. Quentin Grafton et al., *Substitution Between Biofuels and Fossil Fuels: Is There a Green Paradox?*, 64 J. ENVTL. ECON. & MGMT. 328 (2012)..

[133] *See* Michael Hoel, *The Supply Side of CO2 with Country Heterogeneity*, 113 SCANDINAVIAN J. ECON. 846 (2011) [hereinafter Hoel, *Supply Side of CO2*] .

[134] *See* Michael Hoel & Svenn Jensen, *Cutting Costs of Catching Carbon—Intertemporal Effects Under Imperfect Climate Policy*, 34 RESOURCE & ENERGY ECON. 680 (2012).

[135] *See* Jon Strand, *Technology Treaties and Fossil-Fuels Extraction*, 28 ENERGY J. 129 (2007).

[136] *See* van der Ploeg & Withagen, *Relevance of Green Paradoxes*, *supra* note 39, at 2-3 (intertwining the two classes of models). the differences are recentralized on the Hotelling "full depletion in all cases" models versus the Heal "costly extraction" models. The argument provided is that Hotelling models provide sure green paradoxes, but that Heal models are less likley to produce green paradoxes. *Id.*

[137] To tax the producer of A or to subsidize the producer of B would provide much of the same effect, in that A becomes more expensive than B to producers.

[138] *See* van der Werf & Di Maria, *supra* note 6, at 165-66.

[139] *See id.* at 166-173.

[140] *See id.* at 166-67. The value of the unit fossil fuel price will equal the price of the alternate energy substitute; the fossil fuel price being based on a price from the initial time period as affected by cumulative depletion under the Hotelling rule resulting in increasing costs of extraction. That is, $p(0)e^{rt}=b$. *See id.* For a discussion of the impact of choosing the function e^{rt}, *see infra* Part 0 (critiquing the Hotelling model of depletion).

[141] Van der Werf & Di Maria, *supra* note 6, at 167.

fossil fuel to meet that new alternative energy price.[142] That reaction would lead to both additional volumes of fossil fuels production at each time period and also to reduced prices for those increased volumes of fossil fuels.[143] A green paradox is sure to occur. The stronger the subsidy-effect on the alternative energy source, the stronger the resultant green paradox.[144] A similar model was extended to consider the role of increasing extraction costs and of damages from cumulative carbon emissions.[145] That model found that the marginal cost of the backstop technology was determinative in whether the fossil fuel fields were fully depleted or not due to the green policy of subsidizing the backstop technology. As might be expected, the Hotelling depletion model found that the field would be fully depleted, but the Dasgupta Heal model found that the field would not be fully depleted; thus the Hotelling model provided an assured green paradox but the Dasgupta Heal model was dependent on the marginal costs of the backstop technology in creating a green paradox.

A form of international leakage can be seen within this context, if two countries set subsidies that effectively create different backstop prices, *b*s, for their domestic consumers.[146] In that case, one country will be delayed in the switch to the backstop and additional fossil fuel will be extracted alongside additional carbon emissions; a green paradox will result.[147]

When the Hotelling model is modified to enable incomplete depletion and competition between the fossil fuel and the

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[142] *Id.*

[143] *Id.*

[144] *Id.* This is a functional result that follows from the earlier observation that any policy that provides an earlier end to the potential production time frame will result in all of the potential production volumes being produced earlier. It is an artifact of the Hotelling assumtion of complete depletion based on Hotelling's rule.

[145] *Id.* (describing and discussing the model used in van der Ploeg & Withagen, *Is There Really a Green Paradox?*, *supra* note 126).

[146] *Id.* at 168 (describing and discussing the model used in Hoel, *Supply Side of CO2*, *supra* note 129).

[147] *Id.* (describing and discussing the model used in Hoel, *Supply Side of CO2*, *supra* note 129).

backstop technology,[148] there are interesting results.[149] The optimal carbon tax would not be an exponentially rising tax, but a carbon tax growing at a slower rate than the interest rate.[150] This is to encourage the delay of production by making near-term volumes effectively more costly to produce than latter period production volumes.[151]

But that model then analyzes the next best policy if carbon taxes are not feasible; however, the analyses are welfare driven, not emission volumes driven.[152] It discovers that there are two cases: (i) when fossil fuels are cheaper than the backstop; and (ii) when the backstop is cheaper than fossil fuels.[153]

i. When the backstops are more expensive, the model suggests optimal policy would be to increase the price of the backstop by taxing it. [154]

ii. When fossil fuels are more expensive, the model suggests optimal policy would be to decrease the price of the backstop by subsidizing it.[155] The lower the backstop cost, the greater the potential for incomplete depletion of the fossil fuel reserves.[156]

These policy results reflect a green welfare function,[157] not an

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[148] *See, e.g.,* van der Ploeg & Withagen, *Is There Really a Green Paradox?*, supra note 126, at 346. The authors use Equation 3(a) for their modified Hotelling model and Equation 3(c) for the potential delpetion boundary condition. *Id.* Under Equation 3(a), while depletion might be incomplete, the total expected depletion is foreseeable and thus the operator can reschedule production volumes just as they would under simpler Hotelling models; policy effectively creates smaller depletable stocks. *See id.*

[149] *Id.* at 345-46, 351-53.

[150] *Id.* at 351.

[151] *See id.* (stating Proposition 5).

[152] *Id.* at 351-53.

[153] *Id.*

[154] "The higher the tax and the cost of the backstop, the smaller is the initial rate of fossil fuel extraction and the later exhaustion of fossil fuel reserves takes place." *Id.* At 352-53, 361.

[155] *Id.* at 351. *See* Proposition 6, "With the functional forms given in (6) full exhaustion takes longer (T larger) if the initial fossil fuel stock S_0 is high, the cost of the backstop net of the subsidy $b - \sigma$ is high, the maximal marginal extraction costs g is high and the choke price for fuel a is low. In case of partial exhaustion, the transition occurs slower if a, g or s are marginally lower and S_0 and b marginally higher."

[156] *Id.* at 353.

[157] *Id.*

overall emissions concern, so the findings are not determinative, directly, of the incidence of green paradoxes. The overall result is that initial conditions are critical and complicated, green paradoxes may result under certain conditions. But overall, the Hotelling paradigm of full depletion causing models to suggest green paradoxes remains a concern.

D. *Models of Delayed Implementation After Green Policy Announcements*

The types of models presented hereunder are models that study the behavior of exhaustible resource producers if the actors, be they producers or consumers, learn of upcoming policies prior to the implementation of those policies.

> "In reality, most environmental policies (or even government policies in general) do not come as a surprise. Coming to an agreement (within a government, or between different governments) and administrative procedures cost time."[158]

In those scenarios, the producer has at least one time period without the implementation of the new policy, but with awareness that such policy will be implemented in a later time period; thus, the producer can make strategic use of that knowledge to ensure maximum profits. The first two models are Hotelling models with forced full depletion. The producers are limited in the time periods within which to complete depletion so they accelerate and increase emissions in the term prior to the implementation of the policies. The other model presented demonstrates that the environmental policies have impacts on consumption and cause a reaction to accumulate capital to prevent reduced consumption. This savings strategy in turn accelerates demand for fossil fuels due to their capital efficiency even without the Hotelling assumption of forced full depletion.

Van der Werf and Di Maria found that the dominant model type used in this line of research was the Hotelling model of exhaustible resources.[159] Di Maria *et al.* relied on a Hotelling

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[158] Van der Werf & Di Maria, *supra* note 6, at 174.

[159] *See id.* at 157 tbl. 1.

model[160] and Eichner and Pethig's general equilibrium model was an extension of the Hotelling framework.[161]

Di Maria *et al.* provided a time before and after the imposition of a carbon tax. In effect, they studied a particular form of a rising carbon tax, one that had a period of zero tax rate.[162] The carbon tax acts as a constraint against production, and making the Hotelling assumption of forced full depletion, the model derives that production will be rescheduled to an unconstrained time period. If the tax rate is rising as in this model, then emissions will be accelerated causing a green paradox.[163]

Eichner and Pethig's general equilibrium model relied on a three-state Hotelling model that included two time periods.[164] This model broke out the regions into a fossil fuel exporting state, a state with enforced green policies, and a state lax in green policy enforcement.[165] Again, the models make the Hotelling assumption of forced full depletion.[166] Also, the green policies are only imposed in the second time period.[167] So, although Eichner and Pethig set their model in a general equilibrium setting, instead of the partial equilibrium setting of Di Maria *et al.*, the overall result is the creation of a policy incentive to produce more carbon emitting fuels in an earlier time period because of *de jure* limits to production in the later time period.[168]

Smulders *et al.* took a different approach in avoiding the

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[160] *See id.* at 174, (discussing the model used in Corrado Di Maria et al., *Absolute Abundance and Relative Scarcity: Environmental Policy with Implementation Lags*, 74 ECOLOGICAL ECON. 104 (2012)).

[161] *See id.* at 175 (discussing the model used in Thomas Eichner & Rüdiger. Pethig, *Carbon Leakage, The Green Paradox, and Perfect Future Markets*, 52 INT'L ECON. REV. 767 (2011)). .

[162] *See id.* (citing Di Maria et al., *supra* note 157).

[163] *See id.* at 174-75, (citing Di Maria et al., *supra* note 157).

[164] *See id.* at 175 (citing Eichner & Pethig, *supra* note 158).

[165] *See id.*

[166] *See id.* (discussing the model used in Eichner & Pethig, *supra* note 158) ("As in the Hotelling model introduced in Section 2, the entire resource stock will get exhausted over time.").

[167] *See id.* (citing Eichner & Pethig, *supra* note 158).

[168] *See id.* (citing Eichner & Pethig, *supra* note 158).

exhaustible resource model.[169] They explicitly did not assume forced full depletion, what they refer to as the 'scarcity condition.'[170] Instead, they looked to the scarcity of capital and of the decisions leading to its accumulation.[171] By taking this approach they shifted the focus from energy supply to energy demand.[172] Their model demonstrates that when capital accumulation can offset limited energy supplies, and when consumers can react to accumulate capital to prevent loss of future consumption opportunities, a green paradox will result from the increased savings in the near term.[173] It is direct because consumers do not want to experience a decline in energy consumption that fossil fuel consumption will increase in the near term.[174] What appears to be driving this model, deeper than the capital efficiencies of different energy supplies or their intertemporal elasticities of substitution, is that the consumers are facing a shortage of time to accumulate capital, which is derived from the cheaper fossil fuel.[175]

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[169] *Id.* at 176 (citing Sjak Smulders et al., *Announcing Climate Policy: Can a Green Paradox Arise Without Scarcity?*, 64 J. ENVTL. ECON. & MGMT. 364 (2012).

[170] *See* Smulders et al., *supra* note 166, at 365 ("[W]e abstract from scarcity of energy resources, i.e. there is no stock of energy resources that owners are eager to deplete. While the papers cited above all rely on the scarcity of the polluting input to generate the paradoxical announcement effect, we show that scarcity is not required.").

[171] *Id.* ("The build-up of capital is time-consuming so that investment behavior is forward looking. When the climate policy is announced, investment responds and the change in capacity affects energy demand before the climate policy is implemented. The existing literature typically assumes the resource stock to be the only predetermined stock variable").

[172] *Id.* ("We thus pay attention also to the dynamics at the energy demand side, rather than focusing on the supply side.").

[173] *See id.* at 372 (describing Proposition 3).

[174] *See id.* at 371-72.

[175] *See id.* at 366-67. In Smulders et al., Equation 2.1 establishes the production function as predicated on energy, Equation 2.2 makes solar and fossil fuels perfect substitutes, and Proposition 1(i) establishes the fossil fuel economy so long as the marginal costs of fossil fuel are less than those of solar energy. *Id.* The authors also make the assumption that the initial economy without a carbon tax relies on fossil fuels, because "otherwise, no intervention is needed." *Id.* at 371.

E. *Models of International Carbon Leakage*

International carbon leakage can be broadly summed up as the idea that if fossil fuels are not used in one location, then they might be used elsewhere. The concern of an emissions-increasing green paradox as a result of the relocation of that usage is a secondary level of analysis separate from the original leakage analysis. Leakages occur because of economic incentives to relocate the usage of fossil fuels; there are multiple potential incentives discussed in the literature.

Van der Werf and Di Maria identify five basic channels of carbon leakage.[176]

First, the *marginal damages* channel encompasses the concept that while emissions abatement might be unilaterally undertaken, the benefits of that abatement will accrue to everyone globally since it is the total amount emitted to the whole atmosphere that determines climate change hazards.[177] One country underwrites the benefits of all, thus creating the opportunity for many to free ride those unilaterally-paid costs. Assuming that countries set their marginal costs of abatement equal to their marginal benefits of reduced climate change hazards, Hoel has found that the spill-over benefits from a unilateral reduction in emissions will impact the marginal analysis of other countries.[178] Nevertheless, when countries behave uncooperatively, Hoel found that overall emissions were reduced. Thus, the marginal damages channel was not likely to result in green paradox phenomena. [179]

Second, the *energy market* channel captures the effect of a unilateral reduction in emissions on the global market for conventional fossil fuels.[180] For example, if one country reduces its purchases of conventional fossil fuels, more quantity will remain on the market for others to purchase. The results depend

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[176] Van der Werf & Di Maria, *supra* note 6, at 179.

[177] *Id.* at 179-80.

[178] *See id.* at 180 (discussing Hoel, *Global Environmental Problems*, *supra* note 89).

[179] *See id.* (discussing Hoel, *Global Environmental Problems*, *supra* note 89).

[180] *Id.* at 180-81.

on price elasticities of demand and cross-price elasticities of demand.[181] Of the four models reviewed, three of the four were Hotelling or Dasgupta Heal models; the remaining model was a static adjusted general equilibria model (AGE).[182] The two Hotelling models found possibilities of green paradox phenomena, which is no surprise.[183] The Dasgupta Heal model introduced a new policy option: states could acquire reserves-in-place and decide to sequester the reserves permanently and prevent the carbon from ever being emitted.[184] Thus, the results of the energy market channel models depended heavily on the underlying models of exhaustive resource utilization; those that found substantial likelihood of green paradoxes were likely to be based on Hotelling models.

Third, the *terms of trade effect* channel is similar to the previous *energy market* channel, except that it examines the spillover consequences for products made or transported using fossil fuel inputs.[185] The policy concern is that while a country might ban the use of fossil fuels in its own jurisdiction, its citizens might import products from countries without that

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[181] *Id.* at 181. However, if the fundamental supply function is inelastic with regards to price, at least in the short run, then the volumes available for consumption will not be increased and thus carbon emissions would not increase. This is potentially the case when fossil fuels are constrained by transportation and distribution systems that might need long lead times to be expanded. An additional concern could be the lead time to explore and initate production from new wells or fields. For most fields in production, these are routine constraints as the fields were designed to market as much product as could be extracted; thus, there is not much upward slack designed into their systems.

[182] *See id.*, at 181-83. A more updated look at an AGE model is provided below in the discussion on the Michielsen article. *See infra* Part 0.

[183] *See van der Werf & Di* Maria, *supra* note 6, at 181-82.

[184] *See id.* at 183 (discussing the model used by Bård Harstad, *Buy Coal! A Case for Supply-Side Environmental Policy*, 120 J. POL. ECON. 77 (2012)). However, the Harstad model does not answer what the former resource owner would do with the capital received for the reserves; one wonders if the former owners might not seek out new fields to find to sell in-place?

[185] *Id.* at 183-85. Products may be made directly from fossil fuels, as in plastic components, or the fossil fuels may be used only indirectly in the manufacturing and/or transportation of the product, as in transported foodstuffs.

policy and defeat the policy's purposes.[186] A key concern is the substitutability of the goods between countries and the incidence of transport costs.[187] Paltsev reported finding it very difficult to identify green paradoxes even with high substitutability, while Burniaux and Oliviera Martins found negative leakage (i.e. net emission reductions) from products with low substitutability.[188] A variety of studies have been undertaken; negative leakage is generally seen as more likely than positive leakage, and much more likely than the possibility of green paradoxes.[189]

Fourth, the *international trade in factors of production* channel – which perhaps should have been called the *international capital* channel – examines the movement of capital when some countries constrain the use of fossil fuels and other countries do not.[190] The primary concern, is that capital might move to follow ease of use and flow to those countries with more lax green policies. It is also important to note that the surveyed models are the same models surveyed for the *terms of trade effect* channel; thus, the lack of a green paradox finding is extended to these models. [191]

Finally, the *technology change/technology spillover* channel is presented;[192] however, this is a more hopeful topic than the worrisome lines of research explored above. The *technology change/technology spillover* channel explores the potential for unilateral action on green energy policies to spill over into other countries. In this scenario, technology to reduce emissions becomes distributed across countries that did not invest in the

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[186] *Id.* at 183-84.

[187] *Id.* at 184.

[188] *Id.* (discussing Sergey V. Paltsev, *The Kyoto Protocol: Regional and Sectoral Contributions to the*
Carbon Leakage, 22 ENERGY J. 59 (2001), and Jean-Marc Burniaux & Joaquim Oliveira Martins, *Carbon Leakages: A General Equilibrium View*, 49 ECON. THEORY 473 (2012)).

[189] *See id.* at 184-85. Most of these models were some form of general equilibrium models.

[190] *Id.* at 185.

[191] *Id.* at 185-86. As above, the finding of negative leakages is fairly consistent within this class of models.

[192] *Id.* at 186.

costs of developing it.[193] Practically every surveyed model revealed negative carbon leakage, which one would assume would be the outcome.[194]

Thus, international carbon leakage models provide an interesting result: less evidence of increased emissions from green policies. Furthermore, the relationship between economic model foundations and green paradox research results was substantial: Hotelling models yielded green paradoxes, Dasgupta Heal models could yield green paradoxes, and the other models yielded evidence contrary to the presence of green paradoxes. The importance of the affinity for Hotelling models and the findings of green paradox phenomena appear to hold for this class of international carbon leakage models.

F. *Michielsen's Integrated Model of Intertemporal and Interspatial Leakages*

While most articles accommodate various causes of green paradoxes with different mathematical presentations, Michielsen presents a singular model that can accommodate both intertemporal and interspatial concerns, as well as various backstop technologies.[195] Michielsen refers to intertemporal concerns as instances of green paradoxes, but labels the spatial concerns as carbon leakage.[196] He identifies two potential causes of green paradoxes: (i) carbon taxes that increase over time; and (ii) the future development of backstop technologies.[197] He then expands the backstops category in two dimensions for a total of four possibilities; there are cheap and expensive backstops, and there are clean and dirty backstops.[198] He identifies two potential causes of carbon leakages: (i) the relocation of dirty industries from countries with effective green policies to those states lacking effective policies; and (ii) the application of green policies in one set of countries that could cause the price of

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[193] *Id.* at 186-87.

[194] *Id.*

[195] *See* Michielsen, *supra* note 39, at 88.

[196] *Id.*

[197] *See id.* at 87.

[198] *Id.* at 87 n. 1, 88.

carbon emitting fuels to fall and increase the demand for them in countries without effective green policies in place.[199]

Michielsen's basic model makes several notable assumptions:

i. the existence of an exhaustible resource, a clean backstop, and a dirty backstop;[200]

ii. the exhaustible resource has zero costs of production, but the backstops have constant marginal costs;[201]

iii. the resource owners will always fully deplete their exhaustible resource;[202]

iv. reliance on Hotelling's rule for inter-temporal valuations;[203] and

v. the energy resources are imperfect substitutes for each other.[204]

He also assumes that the prices of the exhaustible resource will be the same in both countries for his interspatial model.[205]

Michielsen's analysis of rising carbon taxes finds that Sinn's carbon-pricing green paradox occurs if the demand for the dirty backstop is inelastic with regards to the exhaustible resource in both time periods. This inelasticity means that the tax effectively reduces the price of the exhaustible resource in the earlier time period vis-à-vis the latter period.[206] If the exhaustible resource and the dirty backstop are very close substitutes in both time periods, Michielsen finds that the carbon tax raises the price of the exhaustible resource in both time periods, and increases

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[199] *See id.* at 98.

[200] *Id.* at 88. "Consider a model with three types of energy: an exhaustible resource, a dirty backstop and a clean backstop."

[201] *Id.* "The backstops are inexhaustible, supplied competitively and have constant marginal costs.8 Though the word 'backstop' is sometimes used to denote a perfect substitute for an exhaustible resource, we explicitly allow for imperfect substitutability. The exhaustible resource is supplied competitively by a group of energy exporters and costless to extract."

[202] *Id.* "For the energy exporters, it is always optimal to fully exhaust the fossil resource stock *S*.".

[203] *See id.* at 89 (providing an instance of Hotelling's rule in Equation 4).

[204] *See id.* at 89 (identifying assumptions A1, A2, and A3 and explaining how they show that energy types are imperfect substitutes).

[205] *Id.* at 90.

[206] *See id.* at 92; *see also id.* at 91 (providing the full theoretical results in Proposition 2).

emissions in the earlier period. [207] However, should demand for the dirty backstop be elastic in the latter period, then the effect of the carbon tax is to reduce prices in both time periods and to reduce emissions in the earlier time period. No green paradox results in this situation.[208]

When Michielsen expands his analysis of carbon taxes to an interspatial setting, he reports that the calculations are practically identical to those of the inter-temporal model.[209] As such, carbon leakages result in green paradoxes in the same two cases as in the inter-temporal settings. These carbon leakages are controlled primarily by the degree of product substitutability and demand inelasticity, with the proviso that the time periods are restated as the two locations.

Michielsen's analysis of backstop technology provides for ready reference against the clean backstops of Dasgupta and Heal, and against the dirty backstops of Heal.[210] Michielsen makes the assumption that once a backstop technology is available in one country, the technology would readily become available in all countries. This assumption eliminates the need to develop an interspatial analysis of backstop technologies.[211] In

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[207] *Id.* at 91.

[208] *Id.*

[209] *See id.* at 98. "Our model can be used to analyze spatial rather than intertemporal carbon leakage by relabeling 'period 2' as a climate- conscious country, 'period 1' as a non-abating country and setting the interest rate to zero."

[210] *See* discussion *infra* Parts 0., 0.

[211] Michielsen, *supra* note 39, at 98-100, "The model does not explicitly incorporate industry relocation effects, but shows how unilateral carbon taxes affect world market fossil fuel prices and thereby emissions in non-abating countries." This assumption is readily challenged; simply because a patent might be readily viewed in every country does not equal the claim that each country has equal access to capital or other critical matters of infrastructure to equallyimplement the backstop technologies. E.g., nuclear fission technology is by no means novel but remains in the effective control of a fairly small number of manufacturers and operators. Similarly, windmills are ancient technologically yet modern innovations and manufacturing capacities are similarly limited constrained. The limited capacity of each state to handle sophisicated integration of technologies is reflected in the economic theory of economic compelxity and its economic complexity index (ECI). *See generally* César A. Hidalgo & Ricardo Hausmann, *The Building Blocks of Economic Complexity*, 106 PROC. NAT'L ACAD. SCI. 10570 (2009).

developing his inter-temporal model of backstop technologies, Michielsen renews his assumption of full depletion of the exhaustible resource.[212] He finds the potential for a green paradox more likely under a backstop scenario than under the earlier carbon pricing models.[213] However, the complexities of backstop models are nontrivial. For example, a drop in the price of the exhaustible resource in the earlier period, caused by its increased production, will reduce demand for a close substitute dirty backstop; thus, overall emissions will potentially result in some cross-netting to reduce overall impact.

Michielsen demonstrates that the more perfectly the clean backstop serves as a substitute for the exhaustible resource, the stronger the likelihood that a green paradox will result.[214] He evaluates the scenario when the clean and dirty backstops are perfect substitutes for each other and finds several results:[215]

> Green paradoxes were obtained:
>
> i. When the clean is cheaper than the dirty backstop in both periods, then the dirty backstop is never used and exhaustible resource owners accelerate production and cause a green paradox.
>
> ii. When the clean is ex ante cheaper than the dirty backstop in the second period, then subsidies will reduce reliance of the dirty backstop in the earlier period and increase depletion speed of the exhaustible resource.
>
> iii. When the dirty backstop and the exhaustible resource are perfect substitutes, as conventional crude oil and shale oil are, a green paradox results when the price of crude oil in the latter period is lower than its dirty backstop.[216]
>
> But green paradoxes did not occur:

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[212] *See* Michielsen, *supra* note 39, at 93.

[213] *See id.* at 92 ("As opposed to the case of a future carbon tax, exhaustible resource owners always bring extraction forward when clean alternatives become cheaper in the future.").

[214] *Id.* at 93. Also, *vice versa*, owners of exhaustible resources are "protected" by imperfect substitutes and thus green paradox results can be avoided. *Id.*

[215] *See id.* (identifying Equation 13 and discussing its theoretical treatment).

[216] *See id.* at 93-94 (identifying and discussing Corollary 3).

iv. When the dirty backstop is cheaper in both periods, and if subsidies fail to alter that condition, then no effective change in emissions would occur.

In summary, Michielsen found a wide variety of scenarios wherein intertemporal and interspatial green paradoxes could occur, especially with the existence of backstop technologies that are the primary hopes of most green energy policies. Those findings are predicated on Michielsen's use of certain Hotelling assumptions, such as full depletion and Hotelling's rule, even though his model does differ from a traditional Hotelling model.

V.

ECONOMIC MODELS OF EXHAUSTIBLE RESOURCES

The level of reliance that so many green paradox models have on either Hotelling or Dasgupta Heal models has been demonstrated by the discussion above in § 0. This section of the analysis attempts to determine if that reliance on the Hotelling and Dasgupta Heal models is well founded.

First, the background to the origin of Hotelling's model is provided to yield insight into the function and purpose of the model. Next, the study will explain the working of the model. The focus will then turn to the assumptions of the model, the caveats that Hotelling provided against those assumptions, and to other concerns related to those assumptions. It will be demonstrated that reliance on a Hotelling model for green paradox studies might not be well founded.

Second, this section will provide a brief introduction to the origins of the Dasgupta Heal backstop models. The reliance of the Dasgupta Heal models on the original Hotelling models will be demonstrated. Similar to the previous discussion, this analysis will demonstrate that reliance on Dasgupta Heal models for green paradox studies might not be well founded. This conclusion will be equally valid for both dirty backstop models and green energy backstop models.

After Hotelling's model of exhaustible resources, backstop technology models are probably the second most common set of models discussed in green paradox research. The backstop models analyze the optimal production path of an exhaustible resource when there is a substitutable alternative energy technology available, known as a "backstop." There are two basic sets of models: those with green energy technologies, and those with carbon-emitting technologies.

Partha Dasgupta and Geoffrey Heal created these models in the 1970s;[217] the models were developed in response to concerns that exhaustion of fossil fuels could limit economic growth.[218] One model evaluated then-unconventional fossil fuels as a backstop technology while another model evaluated nuclear energy as a backstop technology choice.[219]

Both models are generalizations of Hotelling's model of exhaustible resources.[220] Thus, many of the concerns on Hotelling's model apply equally to Dasgupta Heal models.[221] Both models make the same mathematical assumptions as in Hotelling's original model: that forced full depletion will occur within the time of the models.[222] Thus, while the models are well

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[217] *See* sources cited supra note 27. Recently, Heal has added substantial context to their efforts:

> The first discussion of renewables in the economics literature was in the post-1973 oil shock era, when we rediscovered and refined Hotelling's work on resource depletion. We invented the phrase "backstop technology," a technology that would eventually replace exhaustible resources with an energy source continuing forever. Partha Dasgupta and I used the idea in our work extending Hotelling's analysis (Dasgupta Heal 1973), William Nordhaus worked with this idea in his book on the efficient allocation of energy resources (Nordhaus 1973), and so did many others. In fact, a quick search for "backstop technology" on Google Scholar produced 8,540 references. No one modeled the backstop explicitly, but clearly it was not a fossil fuel that we had in mind.

Geoffrey Heal, *Reflections—The Economics of Renewable Energy in the United States*, 4 REV. ENVTL. ECON. & POL'Y, 139, 140 (2010).

[218] *See* Dasgupta & Heal, *supra* note 27, at 3; Heal, *supra* note 27, at 371.

[219] *See* Dasgupta & Heal, *supra* note 27 (discussing unconventional fossil fuels); Heal, *supra* note 27 (discussing nuclear energy alternatives). Because both the Dasgupra Heal paper and the Heal paper utilize essentially the same models, and because the jointly authored paper came first, and because the latter tome repeated the joint effort, this present study refers to both of the underlying models as the Dasgupta Heal models.

[220] *See* Dasgupta & Heal, *supra* note 27, at 5 ("What we review here is a slight generalization of the well-known 'cake-eating' problem analysed first by Hotelling [] and later by Gale []."); *see also* Heal, *supra* note 27, at 373 ("Except for the conditoins of the supply of the resource, the model is much as in Dasgupta Heal (1974) . . . .").

[221] See infra Part 0.

[222] While one of the Dasgupta Heal models did not make the forced full

regarded for other applications within resource economics, the following analysis will demonstrate that the use of Dasgupta Heal models within green paradox settings might be less than optimal for resolving critical research questions.

A. *Background of Hotelling's Models*

Harold Hotelling wrote "The Economics of Exhaustible Resources" in 1931 due to calls for the regulation of "minerals, forests, and other exhaustible assets."[223] At that time, there were concerns that some actors were rushing to harvest exhaustible resources and causing a surplus of supply, a collapse of pricing, and great resource waste in many cases.[224] These particular concerns gave cause to the nascent conservation movement and led to calls for the government to protect exhaustible natural resources by limiting the periods and quantities of extraction.[225]

On the other hand, Hotelling also published his article in response to concerns that other actors were colluding to prevent production and to force high prices onto the public.[226] In previous years this collusion had led to the development of anti-monopoly laws, as famously applied to Standard Oil. In his article, however, Hotelling made reference to a more contemporary case from California wherein several post-break-up Standard Oil affiliates allegedly conspired to limit production and protect prices. [227]

There was clamor for laws to limit production, to encourage production, to impose taxes and royalties, and to provide legal

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depletion assumption, it did remove the potential for policy to affect the onset or pricing of the green backstop technology. Thus, that model too is problematic for application within green paradox settings.

[223] Hotelling, *supra* at note 25, at 137; see also Shantayanan Devarajan & Anthony C. Fisher, *Hotelling's "Economics of Exhaustible Resources": Fifty Years Later*, 19 J. ECON. LITERATURE 65 (1981) (providing a full discussion on the historical setting and impacts of Hotelling's modeling on exhaustible resources and listing Hotelling's main two goals as to assess conservation arguments and to improve on the then-current static models).

[224] Hotelling, *supra* note 25, at 137.

[225] *Id.*

[226] *Id.* at 138.

[227] *Id.*

guidance on mineral ownership.[228] Thus, either the resource owners and operators were overproducing, wasting, and losing welfare through excessively cheap prices, or the resource owners and operators were colluding to prevent extraction and refining to limit supply and ensure higher prices. He referred to these two complaints as the "Scylla and Charybdis between which public policy must be steered."[229]

Before he could assist in the determination of reasonable policy, he needed to build a theoretical device. Hotelling was particularly concerned with the need to handle infinities and the importance of the "calculus of variations."[230] Thus, much of his model was innovative both in its treatment of exhaustible resources and in its adoption of calculus prior to Samuelson's text.[231] Because of those factors, his model has been seminal and heavily relied upon.[232]

Given the theoretical challenges Hotelling was working against,[233] he developed a clean, clear, but perhaps very narrow, model of an exhaustible resource. But this was no accident; Hotelling repeatedly qualified the use of his model and advised its careful use: "However, there are in extractive industries *discrepancies from our assumed conditions* leading to particularly wasteful forms of exploitation which might well be regulated in the public interest."[234] This is an example of Hotelling's caveats: that his model differed from realistic decision processes, and also that his model was designed more as a tool to formulate policy that could change the way industries operated in the real world.

His models were not intended as scientific demonstrations of

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[228] *Id.*; *see also id.* at 143-44.

[229] *Id.* at 138.

[230] *Id.* at 140.

[231] *See id.*; *see also* PAUL ANTHONY SAMUELSON, FOUNDATIONS OF ECONOMIC ANALYSIS (1947).

[232] Google Scholar documents over 4,100 citations to Hotelling's study on the economics of exhaustible resources. For the number and listing of citing papers, visit http://scholar.google.com /scholar?cites=15133507373036129912 &as_sdt=5,31 &sciodt=0,31&hl=en.

[233] This is refererring to both the need to innovate a theoretical model and the need to provide mathematical tools to prevent his paper from being rejected.

[234] Hotelling, *supra* note 25, at 143-44 (emphasis added).

how things actually worked at the time; rather, the models were predictions of how industries might behave under ideal conditions. Hotelling was also trying to develop a policy perspective based on public welfare; he assumed that eventually the resource would become fully exhausted.[235] Thus, while Hotelling's model of exhaustible resources is without peer, the user must carefully determine if that vehicle is the correct manner to accommodate theoretical needs.[236]

B. *Hotelling's Model: Optimal Depletion Pathways*

Hotelling begins his model by controlling for the prices of the resource over time by relying upon Bernoulli's model of compound interest and the price of the first mineral extracted, p_0.[237] Hotelling assumes that minerals will be removed in order of the cheapest first, from a supply of the resource in place, a.[238] From these assumptions, he predicts that the quantity to be

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[235] *Id.* at 141-2 (Hotelling refers to the condition as 'final exhaustion'). *See also id.* at 157-8 (Hotelling developed conditions for the socially optimal course to final exhaustion). Levhari and Liviatan explicitly found that (i) "Hotelling assumed that the output of the well or mine is reduced to zero at the terminal point," and (ii) "Hotelling assumed that the firm alwayscontinues to produce up to the point where the resource is compeltely exhausted." David Levhari & Nissan Liviatan, *Notes on Hotelling's Economics of Exhaustible Resources*, 10 CAN. J. ECON. 177, 178 (1977). Other versions of Hotelling's models do exist. See, e.g., Roel van Veldhuizen & Joep Sonnemans, *Nonrenewable Resources, Strategic Behavior and the Hotelling Rule: An Experiment* 7-10 (WZB Berlin Soc. Sci. Ctr. Discussion Paper No. SP II 2014–203, 2014), *available at* http://bibliothek.wzb.eu/pdf/2014/ii14-203.pdf. Van Veldhuizen and Sonnemans found that Hotelling model variants included models that account for exploration or technical innovation, enable non-profit-maximzing goals, allow for less competitive conditions within general Hotelling settings. *Id.* at 5-6. They also found that other models explored divergent behaviors of marginal cost curves, especially the impacts of technological innovation or new resource discovery on short term marginal costs declines. *Id.*

[236] *See also* Margaret E. Slade & Henry Thille, *Whither Hotelling: Tests of the Theory of Exhaustible Resources*, 1 ANN. REV. RESOURCE ECON. 239, 256 (2009) (surveying the "large empirical literature that tests and applies the Hotelling model."). Slade and Thille found that circumstances of imperfect competition, distortionary taxation, risk aversion and incomplete assigment of property rights could lead to frustratoin of the Hotelling models. *Id.*

[237] *See* discussion *infra* Part 0.

[238] Hotelling, *supra* note 25, at 141.

produced or extracted at any time t is controlled by the price receivable.[239] If the moment of final, and thus full, depletion can be named T, then the total amount to be depleted can be solved as the sum of depletions from time 0 to time T; which he solved with an integral against p_0, t and the interest rate.[240]

After extending the model to include social utility and welfare, Hotelling finds that under ideal conditions the pricing structures and interest rates result in similar production schedules for both free competition and optimal-welfare depletion rates.[241] He qualified, however, that the model should not be read to support laissez-faire conservation policies for fossil fuel resources because the overall complexity and uncertainty of fossil fuel markets might result in behaviors contrary to the forecasted results: "there are in extractive industries discrepancies from our assumed conditions."[242] This was the focal point of his research: to identify if conservation policies might be required to attain the socially optimal level of production. Hotelling found that while the model said no regulation would be necessary in free competition scenarios, it was nonetheless necessary to qualify these findings and ultimately argue in favor of regulation.[243]

Hotelling also provided a monopolistic model that resulted in a finding that monopolies over exhaustible resources would lead to slower depletion of those resources than under the free competition model. This model also resulted in suboptimal welfare since monopolies would over-conserve the exhaustible resource.[244]

Hotelling's rule on exhaustible resource prices can be presented simply as the idea that the net price of a fossil fuel should increase consistent with the interest rate; the particular assumptions and their consequences are discussed below in the next section. [245] More specifically, Hotelling's rule states that

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[239] *Id.*

[240] *Id.*

[241] *Id.* at 143.

[242] *Id.* at 143-45.

[243] *Id.* at 143-46.

[244] *Id.* at 152.

[245] Cairns, *supra* note 60, at 78; *see also id.* at 79 eq. 1.

when the market is in equilibrium, the net price of a fossil fuel, *i.e.* the sales price less marginal costs and marginal taxes, should rise at the same rate as the interest rate; the net price of a fossil fuel should increase in relation to the interest rate, but remain temporally equivalent across all time periods.[246]

Hotelling assumed that the costs of extracting resources increased as the resources are depleted.[247] He compared the fossil fuel price at time *t* less the extraction costs at time *t*, as discounted by the interest rate up to that time *t* against a similar composite value at time *s*.[248] If these two values were not the same, then production volumes could, and should, be temporally shifted until net revenue is maximized across all time periods. Once that occurs, that consistent value is the temporally consistent net price for the fossil fuel; that value reflects a full and appropriate time discounting.[249]

The model is often expanded to reflect both the current level of extraction and the total remaining available reserves of fossil fuel in order to facilitate use in econometric studies.[250] The costs of extraction in such a model are said to depend on both matters.[251] Some theorists have preferred a simpler model, one that reduces complexity by assuming a constant marginal cost of extraction. [252]

Sinn's original green paradox focused on carbon taxes.[253] Hotelling addressed two forms of taxes on exhaustible resources;[254] if those resources were coal or oil then they would have been carbon taxes.

Hotelling demonstrated that unanticipated taxes on the capital value of a mine would have "no effect other than to transfer to the government treasury a part of the mine-owner's

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[246] *Id.* at 78.

[247] *Id.* at 79.

[248] *See id.*

[249] *See id.*

[250] *Id.*

[251] *Id.*

[252] *Id.*

[253] Sinn, *Public Policies Against Global Warming*, *supra* note 11, at 377; *see also* discussion *supra* Part 0.

[254] Hotelling, *supra* note 25, at 164.

income."[255] However, he also demonstrated that an anticipated capital value tax would have an effect, an effect equivalent to the mine owner facing a higher interest rate and, thus, a higher discount rate.[256] Higher interest rates and discount rates favor earlier production; thus, due to Hotelling's equivalency of capital taxes to interest rates, higher capital taxes would mandate earlier production.

In practice, certain versions of carbon taxes, called severance taxes, are currently levied against extractors or producers. Hotelling found that an announced, constant level severance tax led to conservation over a longer period of time.[257] But, Hostelling also found that the severance tax lowered prices,[258] so long as the demand function was downward sloping, i.e., that consumers would want more of the commodity when prices are low, and less when its prices are high.[259] Hotelling also demonstrated that the majority of the tax incidence would fall on the owner of the resource.[260] Because of the treble welfare benefits – a slower rate of production for a longer period,[261] a reduction in prices, and the incidence falling on the resource owner – Hotelling deemed severance taxes to be a "good tax."[262]

However, Hotelling emphasized that even a small severance

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[255] *Id.*

[256] *See id.* (demonstrating through mathematical equations that the exponent of the exponential funtion becomes the sum of the interest rate and the tax rate).

[257] *See id.* at 166 (identifying through formulae Hotelling's precise statement on the extension of the production period). Also, 'conservation' in this instance meant reduced levels of production versus otherwise uncontrolled production rates. *Id.* at 165.

[258] *See id.* at 166-67 (showing Hotelling's precise statement of the severance tax's reducing effect on prices).

[259] *Id.* at 167.

[260] *Id.* at 166-67.

[261] *See, e.g.*, Levhari & Liviatan, *supra* at note 235. Levhari & Liviatan found that when incomplete exhaustion was available to the producer, contrary to Hotelling's assumption of full exhaustion, then the results of a severance tax on the rate or duration of depletion were potentially indeterminate. *Id.* at 191-92. They also found that Hotelling's results were unique to the conditions of ex ante determined complete exhaustion. *Id.* Such a result might also change Sinn's findings of a green paradox under carbon taxation. *See supra* Part 0.

[262] Hotelling, *supra* note 25, at 167.

tax was likely to reduce overall welfare for the community.[263] In contrast to the capital tax, which expedited production and depletion, severance taxes could be used to control and delay production and depletion.

In conclusion, Hotelling developed models to explain ideal forms of behavior for exhaustible resources in competitive and monopolistic settings. He determined that certain carbon taxes could defer production and reduce prices.[264]

But he readily conceded that many of his modeling assumptions were contrary to reality, or were readily contrary to current industrial realities of carbon-rich exhaustible resources. Finally, he spent his final pages warning how complex reality actually was, and that realistic models would suffer greatly from complexity and chaos in the modern mathematical sense of those two words. These issues will be explored in greater depth in § 0, below.

C. *Hotelling's Models: Caveats and Perspectives*

In the previous §§ 0 through 0, the importance of the Hotelling and Dasgupta Heal models and their internal assumptions were made evident. The previous discussion, § 0, demonstrated the function of Hotelling's model to discern optimal depletion pathways, especially under certain tax policies. At the center of these two discussions were the internal assumptions of Hotelling's original models; the following provides a list of these significant modeling assumptions. After introducing each assumption, a discussion is provided of Hotelling's own caveats on the assumption, and of realities that directly conflict with these assumptions even though they were likely well known to him at the time.

1. Assumption of Free Market/Monopoly Conditions

Hotelling first modeled the depletion of an exhaustible resource with an assumption of free competition, and then

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[263] *Id.* at 168-69.

[264] *Id.* This determination was made despite potential adversity to social welfare sans consideration of climate change impacts.

separately with assumptions of monopoly.[265]

Despite his development of models based on either purely competitive market economic assumptions or purely monopolistic economic assumptions, Hotelling closed his paper by commenting that exhaustible resource markets were *neither* competitive, as his basic model assumed, *nor* monopolistic; instead, these markets faced a small number of resource owners that were neither competitive nor monopolistic.[266] Additionally, Hotelling explicitly recognized that the free competition conditions assumed in his models did not exist in real life.[267]

Hotelling found that commonplace economic concepts predicated on traditional supply and demand analysis might fail since the pricing space of exhaustible resources is often complex. He admitted that his own previous research suggested that more than one price might simultaneously exist in such a market; thus, the market for exhaustible energy resources might not face a "clearing market."[268] Lacking the game theoretic tools that developed decades later, Hotelling nevertheless described a game with *m* competitors each with *n* mines producing competitive (*i.e.* perfect substitutes) resources.[269] He provided a rough proof that such conditions should result in higher than equilibrium prices and lower than demanded quantity of production than at equilibrium.[270]

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[265] *Id.* at 140, 146.

[266] *See id.* at 171-75. It is unfair to label his models as unrealistic, as they were designed with other purposes in mind;. But, it is clear from Hotelling's direct caveat that modellers cannot directly export the results of those models to practical policy without further precautions to ensure that the results still hold applicable in realistic settings.

[267] *Id.* at 145-46 ("[A] different reason for caution in deducing a laissez faire policy from the theoretical maximizing of *V* under 'free' competition is that the actual conditions, even when competition exists, are likley to be far removed from the ideal state we have been postulating."). Herein, *V* denoted utility over the total time of depletion, thus the maximization of utility derived from the full depletion of the resource. *See id.* at 142.

[268] *Id.* at 171-72 (referring to Harold Hotelling, *Stability in Competition*, 41 ECON. J. 41 (1929)).

[269] *Id.*

[270] *Id.* at 173. This is so primarily because there is sound strategy for the resource owner to raise his prices to wait to sell when all of his volumes can be sold at a higher price due to the exhaustion of his competitors. *Id.*

However, Hotelling warned of "indeterminateness" existing in the economic space of exhaustible resource producers when the numbers of producers are few and in competition: "When the supplies of the complementary goods are exhaustible, the same indeterminateness exists."[271] Additionally, he wrote, "[t]hese affrays give an example of the instability of competition when variations of price with location as well as time complicate commerce in an exhaustible asset."[272]

Hotelling argued that the market price of crude oil products is complex and indeterminate, fitting no particular abstract model; modelers need to take caution that their models are either sophisticated enough or provide sufficient caveats, as Hotelling did, that policy advice must be cautiously administered.

2. Complete Information on Reserves and Depletion Schedules

Hotelling assumed that the resource owners and operators possessed complete information on the size and extent of their resources, future prices, feasible technology paths, and every other relevant consideration. "We have tacitly assumed all of the conditions fully known."[273]

It goes without saying that this was not the case in his time nor in ours. But the evidence is clearly building against the paradigm of a "stock" concept of exhaustible fossil fuels:

> "Although the total resource of hydrocarbons in the Earth's crust for all practical purposes is fixed, the fraction reported as reserves is dynamic . . . The continuous additions to reserves might seem reassuring, but historical data suggest that they rather increase the unpredictability and conceal the true prospect of future production capacity."[274]

Hotelling also assumed for his model that the full resource

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[271] *Id.* at 174 (referring to the indeterminate results of a competitively set pair of monopolists selling complementary goods). The mathematical discussion begins within a discussion on duopoly. *See id.* at 171-73.

[272] *Id.* at 175.

[273] *Id.* at 144.

[274] Kristopher Jakobsson et al., *The End of Cheap Oil: Bottom-Up Economic and Geologic Modeling of Aggregate Oil Production Curves*, 41 ENERGY POL'Y 860, 861 (2012).

base is known and will be fully depleted by the resource owner and operator.[275] Hotelling referred to both a "total supply of the substance,"[276] which he denoted as *a*, and an "upper limit *T* being the time of final exhaustion."[277]

This system of known depletion leads to a logical paradigm that the owner faces a fixed stock of resource that could be produced in any of *n* time periods, but the lack of production in one time period forces the production to other time periods.[278] If production cannot come later, then it must come now; that is the heart of most green paradox models in that incentives are found that discourage latter period production with resultant increases to current or near term production.

Yet, Hotelling admitted that (i) the volume of resource would be unknown ex ante; (ii) that time would reveal additional data on the size of the resource; (iii) that time would reveal additional information as to the quality and utility of the resource; and, (iv) that the economic value of the resource might vary over time. Thus, most of his critical assumptions for his models of exhaustible resource were functionally not seen in his research into market conditions. As he stated,

> "The problems of exhaustible resources involve the time in another way besides bringing on exhaustion and higher prices,

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[275] Levhari & Liviatan, *supra* at note 234, at 178; *see also* the discussion at note 234 on point. *See also* Hotelling, *supra* note 25, at 141-3. E.g., while the precise relationship depended on the underlying demand function, Hotelling provided a demonstration on how the intial resource base, □, could be derived from knowledge of the initial price, $\square_0$, and the time of final exhaustion, □; *see id.* at 142. Watkins disputed this paradigm of a stock of an exhaustible resource, preferring to analogize reserves as inventory produced by other means. *See* G.C. Watkins, *Oil Scarcity: What Have the Past Three Decades Revealed?*, 34 ENERGY POL'Y 508, 510 (2006). The controversy of "stock" versus "flow" was surveyed recently by Jakobsson et al. *See* Jakobsson et al., *supra* note 272, at 861.

[276] *See* Hotelling, *supra* note 25, at 141.

[277] *See id.* (describing Equation 3, wherein Hotelling derives *T* by setting the search conditions as the final price, $p_0e^{\gamma t}$, and the final depletion volume, $q = 0$, which is null, to determine T from supply function, $q = f(p,t)$). Also, "T gives the time of complete exhaustion." *Id.* at 142.

[278] See, e.g., Joseph E. Stiglitz, *Monopoly and the Rate of Extraction of Exhaustible Resources*, 66 AM. ECON. REV. 655 (1976) (providing the description of a two-period production choice, now or later).

> namely, as *bringing increased information*, both as to the *physical extent* and *condition* of the resource and as to the *economic phenomena attending its extraction and sale*.[279] In the most elementary discussions of exchange, as in bartering nuts for apples, as well as in discussions of duopoly, a time element is always introduced to show a gradual approach to equilibrium or a breaking away from it. Such time effects are equally or in even greater measure involved in exploiting irreplaceable assets, entangling with the secular tendencies peculiar to this class of goods."[280]

In another caveat, Hotelling noted that the demand curve determines if complete exhaustion would ever be completed; thus, he left room for incomplete depletion within a less-than-infinite horizon of time.[281] The determining issue was whether the demand was linear, which would fully deplete, or exponential, which would continue to deplete forever at decreasing rates.[282]

Hotelling also foresaw the potential impact of technological backstops, foreshadowing Dasgupta and Heal's models,[283] which Hotelling said could, *ceteris paribus*, greatly reduce the demand for the exhaustible commodity.[284] It only follows logically that Hotelling would have also foreseen that realistic conditions could set the demand price for the exhaustible resource below its costs of extraction and thus terminated its extraction.[285] It can now be

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[279] Adelman has argued that the fundamental paradigm of economists tracking reserves as if they were well known entities is problematic at its core, that rather the paradigm assumption should be changed form fixed stocks of exhaustible resources to that of "flows from unknown rsources into a reserve inventory." M. A. Adelman, *Mineral Depletion, With Special Reference to Petroleum*, 72 REV. ECON. & STAT. 1, 2 (1990). He has provided such a model; at its core is a capital arbitrage or option decision to invest in new field search costs or of costs to add capacity at currently known fields. *Id.* at 3, 5-6.

[280] Hotelling, *supra* at note 25, at 174-75 (emphasis added).

[281] *See id.* at 142.

[282] *Id.*

[283] *See, e.g.*, *id.* at 153-54 ("[T]he progress of science might lead to the gradual introduction of new substitutes for the commodity in question, tending to make *g* negative."). The commodity could be exhaustible coal or oil, and *g* denoted a sense of complementarity character for a good. *Id.* at 154-55.

[284] *Id.* at 154 (presenting a linear version of the demand function that integrated the role of the potential backstop).

[285] Hotelling did not develop that potential result of a backstop as its

also safely asserted that many coal, crude oil deposits are abandoned long before their technical reserves depleted.[286] Some authorities offer programs to encourage the 'adoption' of abandoned wells to return them to production.[287] Such programs are necessary because resource owners will cease production when their marginal costs of lifting exceed their expected marginal revenues; oil can become too costly to extract in certain circumstances.[288]

"gradual introduction" was likely assumed beyond the timeframe within which he was attemping to address the laws on resource waste and resource taxation.

[286] Potentially Hotelling reserved a caveat for this issue, in that he did not require the value of quantity to be produced to be a continuous function of time. *See id.* at 147 (stating that "we do not restrict *q* to be a continuous functoin of *t*, though *p* will be a continous function of *q*," wherein *q* is quantity to be produced, *p* its market price, and *t* time); *see also id.* at 151 (providing the caveat that "the rate of produciton may suffer discontinuities in spite of the demand function having a conintois derivative, these breaks will always occur during actual production , never at the end.").

[287] *See, e.g.*, *Idle and Orphan Well Program*, CAL. DEP'T OF CONSERVATION, http://www.conservation.ca.gov/dog/idle_well/Pages/idle_well.aspx (last visited Nov. 8, 2014) (describing California's "adopt a well" program to adopt abandoned oil wells that have remaining producible volumes but were previously plugged and abandoned); *2014 Orphan Well List*, Cal. Dep't of Conservation, ftp://ftp.consrv.ca.gov/pub/oil/orphan/Current %20Orphan %20List.pdf (last visited Nov. 8, 2014) (providing a list of adoptable oil wells); *Two Severance Tax Incentives Extended the Two-Year Inactive Well Incentive for Oil Wells and Gas Wells and the High-Cost Gas Incentive*, R.R. COMM'N OF TEX., http://www.rrc.state.tx.us/oil-gas/publications-and-notices/notices-to-industry/notices-to-industry-1994-1999/two-severance-tax-incentives/ (last updated May 21, 2014) (outlining Texas's tax incentive to achieve similar results from 2-year inactive wells).

[288] While crude oil reserves are positive value assets, the costs to extract, transport, and market are non-trivial and might sum to prevent the exploitation of the reserves. "It is more likely, as is true of many cases in the real world, that the firm will stop producing at a stage where 'reserves' still exist but under conditions which make further extraction too costly." Levhari & Liviatan, *supra* at note 235, at 178. See, e.g., IRC § 45I, wherein a tax credit is provided for those oil wells whose costs might exceed their limited revenues due to their fallen and thus 'marginal' levels of production during periods of low market prices for crude oil. Indeed, the concept of reserves itself recognizes the role of commercial feasability in the role of production; if reservoir volumes cannot be produced commercially, i.e. profitably, then they do not qualify as "reserves." *See, e.g.*, "Reserves are estimated remaining quantities of oil and gas and related substances anticipated to be economically producible, as of a given date, by application of development projects to known accumulations. In addition, there must exist, or there must be a reasonable expectation that there will exist,

Overall, one of the central tenets of Hotelling's model, that of foreseeable or predictable depletion paths, was extensively caveated by Hotelling himself and reasonably should be handled with caution by other modelers.

3. Conflagration of Full Depletion and Profit Maximization

Hotelling makes a complicated assumption, combining several ideas: resource owners will maximize the net-revenues from each unit of exhaustible resource,[289] while also fully depleting their assets.[290] His main control against full depletion was a concern for whether the time frame was finite or infinite, not per se if fully depleted or not.[291]

Hotelling did take notice of the vast wastage occurring when markets are in formation or when unclear property rights encourage overproduction.[292] Thus, he did recognize that the resource owners were not fully aligned with profit maximization, at least not as reflected in his model based on free competition.

Further, in the introduction to his 1931 article, he referred to artificial conspiracies to limit the volumes of production to achieve lower prices in the market.[293] He also spent extensive efforts developing theories of monopolies and duopolies which might delay production over infinite horizons.[294]

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the legal right to produce or a revenue interest in the production, installed means of delivering oil and gas or related substances to market, and all permits and financing required to implement the project." 17 CFR 210.4-10(1)(26). *See also* Hotelling, *supra* note 25, at 142 (analyzing the depletion path under free competition).

[289] "We shall assume always that the owner of an exhaustible supply wishes to make the present value of all his future profits a maximum." Hotelling, *supra* note 25, at 140.

[290] *See id.* at 140-42 (identifying modeling assumptions from the discussion on free competition).

[291] *Id.* at 142. Hotelling provided two formulae in response; "if $q = a - \beta p$, all will be exhausted in a finite time." *Id.* In general terms, if the price at price at near-depletion is expected to be very high, then the period of depletion becomes longer in duration; but in most cases full depletion would face a finite time frame. *Id.*

[292] *Id.* at 144 ("[G]reat volumes of natural gas and oil are lost because of the suddenness of development makes adequate storage impossible.").

[293] *Id.* at 138.

[294] *Id.* at 146, 171 (discussing the potential "remarkable" intricacies of

However, these deviations from his initial assumption are to be expected, as in classical microeconomics, a producer will increase production so long as marginal revenues are in excess of marginal costs to do so, and the producer will attempt to not go beyond the point wherein its marginal costs and revenues are equivalent. Thus, it is reasonable to expect that certain circumstances could lead to cessation of extraction and production if the marginal costs of a fossil fuel were sufficiently high vis-à-vis their marginal revenues.[295] Models reflecting this have been developed; Levhari and Liviatan modified a Hotelling model to accommodate incomplete depletion or the possibility that production would terminate with positive reserves left in the ground.[296]

Thus, while the idea of full depletion might be motivated by the idea of maximizing sales volumes, it would be constrained by marginal analysis to less than complete depletion.

4. Hotelling's Rule Part I – Value of Resource

Hotelling relied on Bernoulli's model of compound interest; it served as the foundation of the so-called 'Hotelling's rule.' His rule modeled that an initial price p_0, given t years, with interest rate γ, will achieve the final value of $p_0 e^{\gamma t}$.[297] And in reverse, that the discount effect can be rendered by $p_0 = p_t e^{-\gamma t}$.[298] Hotelling also assumed for his model that the units of exhaustible resource are of equal utility and value at each and every time period into

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"bargaining, bluff, and bluster" that can become engage in semi-monopolistic settings, all of which could lead to fields not being properly or fully depleted for long or permanent periods).

[295] *See, e.g.*, Jakobsson et al., *supra* note 272, at 862-63 (discussing marginal and average costs of production).

[296] *See* Levhari & Liviatan, *supra* note 235, at 178-79 (naming their model as one of incomplete exhaustion).

[297] Hotelling, *supra* note 25, at 140. Much of Hotelling's rule is actually just the assumption of temporally equivalency via Bernoulli's compounded interest formula; that resources from all time periods were of equal value. Given economies of changing technological functions, as we see in the real world, there are many ways in which this assumption might not hold true for exhaustible resources over medium-term to long-term time-frames. For additional related information and comments, *see* source cited *infra* note 299.

[298] Hotelling, *supra* at note 25, at 140.

which they might be produced.[299]

Industrial practitioners generally disavow its relevance, accuracy, or utility of Hotelling's rule to determine the values of petroleum resources.[300] Adelman and Watkins found that long-run net-oil prices ran apposite to Hotelling's model.[301] Gaudet did not argue for the invalidation of Hotelling's rule, but he did find that in a century's worth of data, the trends found were "certainly not" those forecasted by Hotelling's rule.[302] Most modelers who want to rely on Hotelling's rule need to add many additional data streams to provide better model fit, which is frankly a frustration to the *raison d'etre* of the rule.[303] Halvorsen and Smith found that there were extensive difficulties in employing econometric models to test the accuracy of Hotelling's rule due to a lack of appropriate *in situ* mineral value pricing data;[304] however, to the extent of available data they found that the "empirical implications of the theory of exhaustible resources are strongly rejected."[305]

Gronwald demonstrated that when oil prices are tested on a GRACH model, oil prices did not display upward trends as expected by Hotelling and peak oil models, but rather displayed a flat trend line with much turbulence.[306] "[O]il prices do not

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[299] *Id.* Hotelling saw value as the integral of utility over a time period. *See id.* at 143.

[300] *See, e.g.*, Cairns, *supra* note 60, at 80 (observing that "[p]ractitioners, whose conscious, rational decisions are supposed to implement the rule, flatly and (to this author's knowledge unanimously) deny its relevance.").

[301] *See* M.A. Adelman & G.C. Watkins, *Reserve Prices and Mineral Resource Theory*, 29 ENERGY J. 1, 5-6 (2008) (finding that "there is no such thing" as the assumed premise of full depletion within a time frame of two periods).

[302] Gérard Gaudet, *Natural Resource Economics under the Rule of Hotelling*, 40 CAN. J. ECON. 1033, 1037 (2007).

[303] *See id.; see also* van der Ploeg & Withagen, *supra* note 39, at 2 (providing the caveats necessary to make Hotelling's rule functional).

[304] *See* Robert Halvorsen & Tim R. Smith, *A Test of the Theory of Exhaustible Resources*, 106 Q. J. ECON. 123, 126-28 (1991).

[305] *Id.* at 137.

[306] *See* Marc Gronwald, *A Characterization of Oil Price Behavior – Evidence From Jump Models*, 34 ENERGY ECON. 1310, 1314-16 (2012).An autoregressive conditional heteroskedasticity (ARCH) model tracks a time series of data that is expected to have error rates that themselves may contain structure or probablistic characteristics. A generalized autoregressive

exhibit a stable and predictable behavior,"[307] but they are "marked by 'discontinuous' shifts."[308] He summarized that if combined with Holland's model of price-determined scarcity for oil, these GARCH results revealed a non-scarce supply of petroleum over time.[309] Gronwald found this difference from Hotelling's assumptions problematic for Sinn's green paradox models.[310]

Were the assumptions on intertemporal pricing and 'Hotelling's rule' on how intertemporal rates were to be determined well founded? It appears not. The centrality of Hotelling's rule itself to affect prices has been studied. The intertemporal arbitrage, centering on the discount rate, appears to be less central to fossil fuel pricing than other factors such as technological change, revisions to reservoir scale, and market structure.[311] Additionally, there is nothing *per se* about Hotelling's rule that is uniquely fossil fuel *cum* exhaustible resource motivated, rather, the same rule could apply to a wholesale vendor trying to clear a warehouse prior to a next period inventory tax. [312] It is merely a rational model on profit optimization, with additional constraints added for depleting or depreciating a stock of capital or inventory.[313]

In establishing his theory of resource value, Hotelling committed a *faux pas*, from a postmodern perspective, in declaring that valuable metals are better used for industrial purposes than artistic or other less obviously productive means.[314] He defended his position, stating that utility is better defined by goods that serve the poor,[315] yet provides no welfare

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conditional heteroskedasticity model (GARCH) is an ARCH model with an error rate determined by a autoregressive moving average (ARMA) model.

[307] Gronwald, *supra* note 304, at 1314.

[308] *Id.* at 1316.

[309] *Id.*

[310] *Id.*

[311] Cairns, *supra* note 60, at 80.

[312] *Id.*

[313] *Id.*

[314] Hotelling, *supra* note 25, at 145.

[315] *Id.* (stating that utility and happiness "depends on the distribution of wealth, and is greater if the products of the mine benefit chiefly the poor . . . .").

theorem or function to back-up that rhetorical comment. This was potential for an artful dodge to Sinn's 'ethical economists' query as to in which generation the greater value of the resource lies;[316] but it forces a mathematical result that utility cannot be of more or less value for different cultures and different stages of technologies.[317]

Additionally, many resource owners, such as the owners represented by OPEC, are generally held to have some ability to affect short-term market volumes and derivatively crude oil prices. Similar assumptions were held in Hotelling's era, as per the concerns on the oil trusts restricting production to support higher prices; Hotelling said much the same, "[a] large producing company can very commonly affect the price by varying its rate of marketing."[318]

In short, Hotelling's basic assumptions on pricing and valuation for exhaustible resources might not be applicable to all forms of exhaustible resources and were specifically caveated for fossil fuels by Hotelling himself. Further, Even Hotelling gave credit to the idea that the producers could manipulate the prices of the resources, further challenging the influence of Hotelling's rule for fossil fuels from exhaustible resources.

5. Hotelling's Rule Part II – Flexible Schedule of Extraction

Hotelling wrote that "it is a matter of indifference to the owner of a mine whether he receives for a unit of his production a price p_0 now or a price $p_0e^{\gamma t}$ after time t,"[319] establishing that mineral owners are functionally indifferent to when minerals are extracted, except for the price borne by the market at the time of

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[316] *See* Sinn, *Public Policies Against Global Warming*, *supra* note 11, at 369-70.

[317] For example, most climate law researchers hope for an era where hydrocarbons have no economic utility as a fuel due to superior market choices in the same way that no one continues to hunt whales for lamp fuel today. Perhaps whales are just as valuable as they ever were, but it would an awkward economic argument to suggest that they are as economically central to market pricing as they once were. Similarly, it might be errant that all exhaustible resources retain their identical value across all time periods

[318] Hotelling, *supra* note 25, at 146. Marketing refered to the volumes sold, and not to advertising.

[319] *Id.* at 140.

the sale. Also, production could be disrupted and delayed, without consequences within the model.[320] This presents the rhetorical result that fossil fuel producers could freely reschedule production volumes to accommodate, or be responsive to, effects caused by green energy policies.[321]

Was Hotelling correct that producers could flexibly reschedule production? No, basic geo-physics prevents that in most oil and gas fields. The intertemporal flexibility assumed by the Hotelling model is also questionable. Field production volumes might not be readily re-schedulable;[322] both physical engineering problems and institutional legal constraints limit flexibility to reschedule production to optimal periods. [323]

Exploration and development are also time-consuming; they might take years to implement once a financial investment decision is made. In contradiction to the assumption of Hotelling's rule temporal arbitrage to seek λ, intertemporal re-scheduling is not readily available at all times and production volumes might be locked-in for a material period of time. Once production capacity is installed, generally, a field is allowed to produce for a long period and enter into natural decline before, if ever, additional capital commitments are made to provide for secondary or tertiary recovery.[324] When natural decline is modeled against the price of the fossil fuel over time, it can be demonstrated that the resultant price is lower than that forecast by Hotelling's rule.[325] Additionally, this analysis reveals that

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[320] *See supra* note 286 and accompanying text.

[321] The most direct reference to interruptions in production occurs in Hotelling's discussion on retardation of production levels under monopolies. *See* Hotelling, *supra* note 25, at 151-52. He employs the phrasing "may suffer discontinuities," which sounds more like functional problems than aspirational arbtirage deplays in production. *Id.* at 151.

[322] *See* Jakobsson et al., *supra* note 272, at 864-65 (discussing the industry term *maximum efficient rate*, the physically most efficient rate to produce the largest volume of resource given its particular circumstances, and its impact on production decisions). Ion efficient recovery could risk permanent loss of resource. *Id.*

[323] *See* Cairns, *supra* note 60, at 81-82 ("In sum, at any time at any producing property in the oil industry, output is constrained by a technological/geological constraint.").

[324] *Id.* at 81.

[325] *See id.* at 81-82.

physical conditions determine the extraction path and that physical motive to expel the crude oil and natural gas is another critical exhaustible resource.[326] Generally speaking, oil and gas fields begin at close to peak capacity, for both the wells and their infrastructure, and that substantially additional production volumes are not possible without substantial additional investments in additional wells and pipelines.[327] "Output can be reduced but not increased."[328] Production will not be readily increasable. In other circumstances, "output can be reduced,"[329] but there are substantial risks to overall resource recovery if a field is substantially choked or delayed in production. The wells are fed crude oil and natural gas by the motive energy of subterranean pressures and potentially subterranean gases, including methane.[330] The subterranean pressures and motives that drive well performance could be lost or reabsorbed in the reservoir zone if stabilized too long. Thus, physical engineering concerns prevent the free re-scheduling of production volumes once a field is initiated into production; thus Hotelling's rule will be frustrated and price paths will deviate from the expected pathways.

The economics that underwrote recognition of commercially viable reserves in one time period might be lacking in latter time periods and thus, a well might be abandoned and plugged while substantial technologically producible volumes remain in place in the reservoir. Additionally, there are physical limits to the temporal rescheduling of petroleum production; volumes can be permanently lost if certain production rates are not maintained. The path of depletion might not be flexible but rigid. Thus, the strategic potential to reschedule fossil fuel production to address green energy policies might be more constrained than Hotelling's model might otherwise suggest.

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[326] *See id.*

[327] From my personal experience, fields are generally left with some safety margins to enable surge production. However, generally operators are legally required to ensure production levels at best commercial practices for the resource owners.

[328] Cairns, *supra* at note 60, at 82.

[329] *Id.*

[330] *Id.* at 81.

6. Rising Extraction Costs

Hotelling assumed that the costs of extraction go from cheap to expensive; "[t]hey will be removed and used in order of accessibility, the most cheaply available first."[331] "The cost of extraction increases as the mine goes deeper."[332]

While this modeling assumption might be reasonable for some types of mining or foresting,[333] it is usually not correct for crude oil and natural gas.[334] Even where the "most cheaply available first" assumption could be used in crude oil,[335] the facts would be that of a wildcat operator that produces to a local storage tank *sans* pipeline transport to distribution networks.[336] E.g., natural gas frustrates this particular assumption of Hotelling's model because it is not well transported without extensive pipelines and thus requires large *ex ante* investments.[337]

Was Hotelling correct about the costs of extraction rising over time? Probably not, but the devil is in the details of defining costs over long time periods. The cost functions of Hotelling's model of exhaustible resource are not reflective of actual fossil fuel conditions, at least not for crude oil and conventional

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[331] Hotelling, *supra* note 25, at 141.

[332] *Id.* at 152.

[333] Hotelling mixed his metaphors, but relied heavily on mines and mining, which are quite different in engineering and development costs from oil and gas wells. *See id.* The quote above is made in conjunction to gold and diamonds. *Id.*

[334] One imagines that a coal operator retrieves those volumes first at hand by digging; or similarly within a gold mine a main vein would be worked first. But crude oil and natural gas require very large investments in development prior to the first produced volumes can be extracted; because of the high ratio of fixed costs to operating costs, the average cost of production drops as more volumes are produced.

[335] Hotelling, *supra* note 25, at 141.

[336] The stand-alone wildcatter modes of production were more common at the time of Hotelling's writing, but were already on their way to extinction. Today, such operations are extremely rare; wildcatters are now focused on the exploration and early development phases that do not require the massive fixed cost investments that development and production entail. Where one does find such stand-alone wells is usually in old fields with levels of production so low that gathering pipes is not considered repair-worthy, thus a switch to local storage tanks is desired.

[337] As such, the first produced metric cube of natural gas is arguably the most costly.

natural gas.[338] Actual fossil fuel projects face large initial fixed cost investment commitments. Thus the assumption of $C(0,Q) = 0$ is almost never accurate; their initial costs are never zero but materially substantial.[339] Hotelling even commented on the unique costs structure of oil capital costs in alignment with this observation.[340] Costs of extraction do not necessarily increase; they may well decrease over cumulative production volumes. The on-going field costs are generally a small fraction of the carried fixed costs, thus the marginal costs are often substantially below the average costs of production.[341] Marginal costs may be dropping, as capital investments decline over time and operational expenses would not be expected to increase at rates higher than the drop in marginal capital investments.[342] It is therefore reasonable to question if the assumptions of increasing costs of extraction, as cumulative volumes increase, are generally correct for crude oil and natural gas.

The assumption on increasing costs of extraction as cumulative volumes increase is met by several concerns. Many fields display the economics of natural monopolies, in that high capital costs are required a priori to initial production and that average costs and marginal costs decrease as production increases; ultimately costs may rise near the fields' end-of-life years but that might be decades out for many fields in production and beyond the timing concerns raised by Sinn.[343]

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338. Cairns, *supra* at note 60, at 81.

339. *Id.* Exploration is costly, drilling and development is costly, and the infrastructure to sustain on-going operations is costly to install; all these costs are sunk costs prior to the first volume of production.

340. *See* Hotelling, *supra* note 25, at 164. The production functions of petroluem production are said to be derived from uniquely high fixed costs prior to first production.

341. Levhari & Liviatan, *supra* note 235, at 182-83 (noting that the role of maraginal costs on depletion pathway decisions is covered within the exposition of the incomplete exhaustion model).

342. At some point, the field has virtually no field costs other than depreciation of existing capital investment and minor operational expenses, followed by plugging and abandoning.

343. Increasing prices might assume later volumes are per se on a diminishing returns function and thus would face higher marginal costs, but real world cost structure can display natural monopoly trends of declining marginal costs over production runs.

7. Eighth – Secure Property Rights

Hotelling assumed full and secure property rights in his model.

However, Hotelling acknowledged that insecure property rights could motivate wasteful behaviors. This foreshadowed Sinn's similar concerns, discussed above in § 0. "Each owner must drill and get the precious oil quickly, for otherwise his neighbors will get it all."[344]

In summary, while Hotelling's model provided useful insight into the specific questions he was researching, extensions of his models should be careful to take into account his own caveats on his models and to ensure that the underlying assumptions of his models do not frustrate the current goals of a modeler. Further, to the extent that earlier discussion revealed that many green paradox models have relied on Hotelling models, these concerns need revisiting to ensure that the models and their policy impacts are well protected from Hotelling's own concerns.

D. *Dasgupta and Heal's 1974 Green Energy Backstop Model*

Dasgupta and Heal first investigated the idea of a green technology backstop for an economy with nearly depleted fossil fuel reserves during the oil shocks of the 1970s.[345] They evaluated a model, and several of its variants, which assumed that future technological developments would enable a clean renewable alternative to fossil fuels.[346]

The basic Dasgupta Heal model assumes that the conventional fossil fuel would fully deplete while reaching the price of the backstop technology, which would then be produced indefinitely. [347] The fossil fuel and its green energy backstop are

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[344] Hotelling, *supra* note 25, at 144.

[345] *See* Dasgupta & Heal, *supra* note 27, at 6, 13, 19 (referring to Cases A and B, where Case A has a positive stock of exhaustible resource and Case B has fully depleted its stock of the same).

[346] *Id.* at 18 (describing a technology that could render "essential," i.e. without substitutes, fossil fuels into "inessential" substitute goods, listing solar energy and nuclear fusion as examples of such technologies).

[347] *See id.* at 7 (detailing in Proposition 2 the depletion of the resource until time T and the use of the backstop after time T).

assumed to be perfect substitutes within the model for simplicity, this assumption enables a perfect singular switch from fossil fuel to green energy at the right pricing point.[348] Heal later modified that family of models to consider what would today be called dirty backstops.[349] Most of the green paradox papers that rely on a Dasgupta Heal model refer to this latter article and not to the green energy backstop paper.[350]

The Dasgupta Heal models rely on extensive use of Hotelling's rule for the valuation of intertemporal net profits and resource valuation.[351] Both the simple generalization presented at § 0.3 and the production model presented at § 1.2 involved forced full depletion of the primary fossil fuel prior to the switch to a backstop technology.[352] These *ex ante* conditions bind the owner to completely produce the reserve volumes during the execution of the model. Thus an event which reduces or increases the production in one period will need be offset in another period.[353] The resultant rescheduling of fossil fuel production is therefore not a result of policy incentives but of *a priori* modeling

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[348] *Id.* at 19. Dasgupta and Heal do provide support for the idea that their model could be extended to imperfect substitutes and for modeling a switch that enables an overlapping time period. *See id.* (discussing the likelihood that the durable commodity and exhaustive resource energy sources are perfect substitutes and concluding, "In fact there is every reason to suppose that [they are] not.").

[349] *See* Heal, *supra* note 27, at 371 (referring to William D. Nordhaus's economic models on the development of shale oil as an example of a potential backstop technology for crude oil that might be in functionally unlimited supply albeit more costsly than crude oil prior to its depletion).

[350] For further discussion on Heal's dirty backstop, *see infra* Part D.V. For further discussion on various Heal dirty backstop-based green paradox models, *see supra* Part C.III.

[351] *See generally* Dasgupta & Heal, *supra* note 27.

[352] *See id.* at 6, 12-13.

[353] Dasgupta and Heal did take note of a mathematical alternative, that if the resource stock was not to reach a fully depletable state, that certain other conditions would need apply that would result in the original resource stock having been effectively infinite in scale. *See id.* at 6. While Dasgupta and Heal did not continue that intellectual thread, a similar thread has been analyzed by Stürmer and Schwerhoff. *See* Martin Stürmer & Gregor Schwerhoff, *Non-Renewable But Inexhaustible – Resources in an Endogenous Growth Model* (Max Planck Inst. for Research on Collective Goods, Paper No. Bonn 2012/09, 2012), *available at* http://www.coll.mpg.de/pdf_dat/2012_09online.pdf.

conditions.

Dasgupta and Heal did present a model within § 2 that does not *ex ante* force full depletion of the resource stocks.[354] But, it counterbalanced that modeling benefit by excluding the role of policy in creating changes to the arrival of technology.[355] Thus, the impact of policy matters is per se beyond the model and thus potentially frustrates the use of this model for other green paradox models.

Dasgupta and Heal addressed technological change and uncertainty not by providing endogenous means but by providing mathematical substitutions that depend upon correctly identifying the random mathematical process that controls when, dare *if*, the future green technology would arrive.[356] As stated in their concluding remarks, "in this paper we have supposed that the random variable is *uninfluenced by policy*; that is, that the acquisition of knowledge is costless."[357] Yet that random variable is the single determinant of the existence of green technology within the model. Thus, it might be difficult to rely on Dasgupta and Heal's technological change version of their model to analyze the effects of environmental policy on carbon emitting exhaustible resource production.

But even if one could make certain adjustments to include policy effects within their technological change mode, there would be another significant obstacle to overcome. Dasgupta and Heal suggested that the assumption of higher discounts rates could be used to offset the randomness of future uncertainty on

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[354] *See* Dasgupta & Heal, *supra* note 27, at 19-20. (presenting the main model in Equations 2.1, 2.2 and 2.3, with the prophylactic conditions to prevent "being caught short with none of the exhaustible resource before the substitute is discovered" at Equations 2.4 and 2.5).

[355] *See id.* at 19. The arrival of the green energy technolgy that will serve as the backstop to crude oil consumption is predicated upon a probability function, ω_t, that yields a singular random event between the beginning and the closure of the model's timeline. *See id.* at 19-20.

[356] *See id.* at 23 (providing a discussion on what impacts different forms of probability, for example a Poisoon distribution or a a log normal distribution, might have on the model's probability function, ω_t); *id.* at 23 (providing a method for enveloping the probability function, if one could be certain enough of the underlying probability function, as demonstrated at Proposition 12).

[357] *Id.* at 27 (emphasis added).

the feasibility of green energy backstops; however, "it is generally recognized that it leads to errors."[358] To avoid those errors, their model would require some extreme market conditions. Both the capital markets and the resource markets need to reflect zero valuations to prevent market errors.[359] Thus, to the extent that one was able to overcome the previous difficulties, one would need to be able to demonstrate that the effects of a green paradox under this particular form were capable of being distinguished from both the effects of incorrectly anticipating the probability function's distribution and of relying on higher discount rates to offset the issues of the probability function.[360]

In closure, Dasgupta and Heal's models assumed many aspects of Hotelling's models and as such should retain the caveats attending his efforts. Further, their models introduced new concerns that might potentially frustrate research into green paradox phenomena.

E. *Heal's 1976 Dirty Energy Backstop Model*

Heal developed a backstop model wherein an alternative fossil fuel was employed as the backstop, in lieu of green energy alternatives. He described his dirty backstop model as an analysis of "the optimal strategy for consuming a resource whose total availability is infinite, but whose cost of extraction is an increasing function of the total already extracted."[361] He broke down crude oil into two segments, volumes from conventional

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[358] *Id.*

[359] *See id.* at 22-23, 27.

[360] Dasgupta and Heal revisited this topic in 2004, stating:

> The presence of nonlinearities compounds the importance of uncertainty. The biophysical impacts associated with the loss of natural capital can be highly nonlinear: these impacts may be small over a considerable range, and then become immense once a critical threshold is reached. Crossing the threshold leads to a "bifurcation," a situation where the characteristics of the natural system change fundamentally.

Kenneth Arrow et al., *Are We Consuming Too Much?,* 18 J. ECON. PERSP. 147, 168 (2004).

[361] Heal, *supra* note 27, at 371-72.

crude oil and volumes derived from shale oil.[362] The first resource faces increasing extraction costs and the second with a constant extraction costs.[363] Just as within Dasgupta Heal (1974),[364] Heal relied on Hotelling's rule to provide intertemporal stability of net profits.[365] By providing a ceiling to the price of crude oil, being limited by the constant extraction costs of shale oil, Heal demonstrates an argument that crude oil prices should begin higher than equilibrium prices and drop towards their marginal extraction costs over time.[366]

The central problem with the model is that it is designed to first deplete a certain *ex ante* determined stock of its conventional crude oil before the model would switch to continuous production of petroleum from shale oil rocks. The ultimate question of how much conventional crude oil to produce is pre-set exogenously.[367] The model assumes that there is a specific volume of conventional crude oil that can be extracted before the costs of extraction reach the costs of producing from shale oil.[368] That volume of conventional crude oil, *z-bar*, is unchangeable within the model, there is no endogenous mechanism to adjust it.[369] While this is not a forced full

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[362] *See id.* at 373 eq. 2.

[363] *See id.* at 373 fig. 1 (illustrating the rising costs to extract crude oil which are eventually cut-off by the ceiling of constant extraction costs for producing shale oil). Heal presented no evidence that shale oil would actually have such an extraction costs function, which is a substantial deviation from the traditional Hotelling assumption of rising extraction costs for all exhaustible resources. *See id.*

[364] *See id.*

[365] *See id.* at 375 eq. 10.

[366] *See id.* at 372-73. By doing so, Heal was able to argue that oil prices were functioning well in contrast to claims by other economists that then current prices of crude oil might have suggested monopolistic over-conservation of crude oil to inflate prices and obtain monopoly profits. *Id.* (referring to previous research on that topic).

[367] *See id.* at 373 fig. 1 (depicting the switching event); see also id. at 373 eq. 2 (presenting the two-phase cost of extraction formulae).

[368] *See* id. at 373 eq. 2. (defining the boundaries of *z*, the volume of conventional oil to be produced before the cost structures of shale oil (denoted as β) permanently cause the switch to shale oil).

[369] *See id.* at 374 (dismissing the potential of a different volume, stating: "The alternative is that cumulative extraction over the entire horizon does not exceed *z-bar*: conditions sufficient to rule this out are self-evident.").

depletion *a la* Hotelling, it is essentially the same mathematical form and will result in a similar effect: policies to alter the timing of the switch to the backstop will not affect the total volumes of conventional crude oil to be produced; those volumes will simply be accelerated or delayed, not reduced. The model receives the price of the backstop exogenously,[370] as it does the resultant quantities of accumulated production from conventional crude oil,[371] but it would be reasonable to assume that lower backstop prices imply fewer produced volumes; a green paradox model would need to provide the necessary mechanisms.

In conclusion, the Heal models for dirty backstops strongly follow the models developed earlier by Dasgupta and Heal, and thus contain many of the same concerns for green paradox modelers as for those models.

VI.
CONCLUSIONS

Concerns have been raised that certain international conventions and domestic legislations driven by green policies to mitigate anthropogenic climate change could backfire by increasing greenhouse gas emissions. Researchers have developed economic models to analyze if and when such green paradox phenomena might be obtained from green energy policies. Most of the current models that demonstrate potential green paradoxes rely on economic models originating in studies on the optimal depletion of exhaustible resources. One common class of models used in green paradox research is the Hotelling model of exhaustible resources. The Dasgupta Heal classes of models, of exhaustible resources with technological backstops, are another common class of models found in green paradox research. The Dasgupta Heal models are in large part extensions of the Hotelling models.

The Hotelling and Dasgupta Heal models share certain

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[370] *See id.* at 373 (defining in Equation 2 the transition price as β).

[371] *See id.* (defining in Equation 2 final accumulated production of conventional crude oil as *z-bar*).

economic modeling assumptions that induce certain behaviors; this paper has investigated the fitness of those model classes for research into the potential emergence of green paradox phenomena. This research has revealed that these model classes are problematic in such research. These findings are in alignment with other researchers. Gronwald said his findings that Hotelling's rule did not forecast oil prices well "create[d] additional concerns regarding the adequacy of Hotelling-type models for oil price modeling purposes . . .that researchers and politicians alike should be aware of the behavior of the price of oil when designing and evaluating climate policies."[372]

This study has questioned the ability of certain green paradox models to accurately determine where such phenomena might arise and thus the study has questioned the ability of those models to accurately inform lawmakers and policy setters of the consequences of their legislative actions. In particular, models researching green paradoxes that build on top of Hotelling or Dasgupta Heal models of exhaustible resources should be aware of the caveats provided by Hotelling.

The present study has provided a demonstration that a wide variety of green paradox models rely on the Hotelling and Dasgupta Heal models. Sinn's original model of carbon taxes inducing green paradox results was an extension of Hotelling's model. Thereafter, it was shown that four major classes of green paradox models mostly relied on the same two classes of exhaustible resource models. There did appear to be a sliding scale; models based on Hotelling routinely found green paradoxes, Dasgupta Heal models found paradoxes less often, and models based on exhaustible resources models other than those two classes found few green paradoxes. The evidence of affinity between underlying model choice and green paradox findings was demonstrated.

Next, an investigation into the underlying models of Hotelling, Dasgupta and Heal was undertaken. An extensive discussion was drawn on Hotelling's research program, his economic model of exhaustible resources, and of the central assumption within

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[372] Gronwald, *supra* note 305, at 1316.

his model. A detailed review of those assumptions, of his caveats to them, and of other relevant information on the accuracy of those assumptions was presented. It was found that Hotelling operated his model with caution and extensive caveats; he found the pricing space of exhaustible resources, particularly of fossil fuels, to be complex and indeterminate and thus difficult to model accurately. The green energy backstop models of Dasgupta and Heal and the dirty backstop models of Heal were demonstrated to have built upon and extended Hotelling's models without substantial change to his models underlying assumptions. As such, use of their models inherits the same need for caution and caveat as Hotelling's models would.

Thus, it was demonstrated that Hotelling's models require cautious use and should include caveats unless sufficiently modified.[373] It was demonstrated that Dasgupta and Heal extended Hotelling's models while retaining the bulk of his models' assumptions. Thereafter, modelers of green paradox research have built upon those foundations and incorporated the assumptions of the Hotelling or Dasgupta Heal models without substantial alteration.

This direct inheritance of assumptions leads to certain problems. The correlation of underlying model choice to the research results of green paradox emergence has been shown to be substantial; caution should be employed in the interpretation of choice of economic model by legislators and policy makers. Also, many of the assumptions of Hotelling's models were shown to need caveats or perhaps be revised in light of countervailing realities or practices. As such, Hotelling's models and those models based upon Hotelling's models might not readily provide certainty with regards to the emergent risks of green paradoxes.

If new laws or policies might substantially effect environmental concerns, many states and federal systems require review of those laws and policies for their environmental

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[373] However appealing the logic of the Hotelling model of exhaustible resources might have been for some energy researchers, other voices have seen it in less favorable lights – particularly those researching conventional crude oil and natural gas markets. Ironically, those critiquing Hotelling's models are often but detailing the caveats that Hotelling himself made in his own papers.

impact prior to their enactment and adoption, e.g. within the EU the SEA Directive is applicable.[374] To the extent that Sinn's concerns of a green paradox suggest review of impending laws or policies, caution should be employed to ensure that the underlying models are not solely reliant on Hotelling or Dasgupta Heal models. Conversely, if the models do rely on those economic models that the models have proper caveats and cautions made clear to the non-economist readers of the reports.

It is not the intent of the current review to suggest that green paradoxes cannot occur; indeed this paper is in earnest pursuit of how to more rigorously ascertain their existence.[375] This current research does suggest, however, that (i) more attention might be warranted in examining the underlying models in understanding why green paradoxes might be found and (ii) to encourage the inclusion of a broader range of resource models, beyond Hotelling and Dasgupta Heal models, to evaluate the potential emergence of green paradox risks.

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[374] *See* Council Directive 2001/42 of the European Parliament and of the Council of 27 June 2001 on the Assessment of the Effects of Certain Plans and Programmes on the Environment, 2001 O.J. (L 197) 30, 30-37 (EC), *available at* http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX :32001L0042 &from=EN.

[375] *See, e.g.*, *supra* note 37. (discussing the existence of certain green paradox models that are not predicated on Hotelling or Dasgupta Heal models); Adelman, *supra* note 277, at 1, 5-7 (providing an alternative model of petroleum depletion that does adopt the majority of Hotelling's assumptions, paricularly rejecting the concept that there is "an exhaustible fixed stock of oil to divide between two [or more] time periods." (citation and quotation marks omitted)).