Capacity Constraints on Renewable Energy Resources: Modelling through a Green Ramsey Model

PhD Thesis (Working Draft Paper)

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Presentation Outline

- Introduction (aim and research contribution)
- Brief Literature Review
- Chapter 1 (Benchmark Model Setup and Results)
- Chapter 2 (Model setup in a different context and Results)
- Chapter 3 (extensions)
- Concluding Remarks

Introduction

Background

- If renewable energy (RE) sources exist forever, then why we cannot all be 100% dependent on this energy and abandon exhaustible resources (e.g. oil) (saving them for a rainy day)?

- RE sources may theoretically exist forever, but factors such as nature constraints and limited equipment, land, human/market resources etc. prevent achieving the desired renewable energy output(Amigues et al., 2015; Wang & Zhao, 2018).

- All these restrictions are examples of the **physical/capacity constraints.**

Introduction

Research Aim: Study the capacity constraints in the renewable energy context.

Contribution: The literature in the specific topic is quite a little, seek to expand the knowledge over the implications of capacity constraints in the optimal climate policy framework.

Literature Review

- Macias & Matilla-Garcia (2012): Ramsey-Hotelling-EROI model with CES production function -> When energy is scarce, the energy sector size decreases, stays constant, or increases depending on the sign of capital-energy substitutability.
- Amigues et al. (2015): transition from non-renewable to renewable energy under capacity constraints. -> smooth transition, investing begins before producing RE or till the price is sufficiently above the cost.
- Wang & Zhao (2018): impacts of renewable energy support policies on energy prices, exhaustible energy supply and carbon emissions from fossil fuels and climate change. -> are dependent mostly on RE capacity, as well as market power in the fossil fuel sector.

Literature Review

van der Ploeg & Withagen (2014): Green Ramsey Model, optimal energy use in different regimes:

- Regime I: Only-oil to only-renewable (carbon tax rises, renewables subsidy cause more oil use (Green Paradox)
- Regime II: Only-oil to oil-renewable (carbon tax declines, more oil is left in situ)
- Regime III: Only-renewable to oil-renewable
- Regime IV: Only-renewable phase forever

Regimes III and IV are unlikely to occur till there is a renewable breakthrough technology.

The Green Ramsey Model

Assumptions and Variable Inputs

- two different energy sources: an exhaustible (oil) and a renewable (e.g. solar panels, wind turbines etc.) which are assumed to be perfect substitutes.
- $O(t)$: Oil energy
- $S(t)$: Oil stock
- $G(S(t))$: unit cost function of oil extraction (decreasing and convex)
- $E(t)$: atmospheric carbon stock
- $K(t)_R$: Renewable capital
- $R(t)$: Annual investment in renewable capital stock
- $\bar{K}_R < +\infty$: maximum productive capital stock limit land can support.
- $h(K(t)_R)$: renewable production function (increasing and concave, $h(\bar{K}_R)$) is the maximum renewable quantity.
- $K(t)$: man-made capital stock
- $F(K, O + K_R)$: Total production Function

Chapter 1: Social Planning

$$\max W = \int_0^{\infty} e^{-\rho t}\left(U(C) - D(E(t))\right) dt \quad (eq.1)$$

s.t.

$$\dot{S} = -O, \qquad S(0) = S_0 > 0 \ (eq.2)$$

$$\dot{E} = O - gE, \qquad E(0) = E_0 > 0, 0 < g < 1 \ (eq.3)$$

$$\dot{K} = F\left(K, O + h(K_R)\right) - R - G(S)O - C - \delta K, \qquad K(0) = K_0, 0 < \delta < 1 \ (eq.4)$$

$$\dot{K}_R = R - \delta K_R, \quad K(0)_R = K_{0R}, 0 < \delta < 1 \ (eq.5)$$

and the pure state constraint

$$0 \le K_R \le \bar{K}_R$$

$$\tau = \frac{\mu_E}{\mu_K} = \frac{\int_t^{\infty} e^{-\rho(s-t)} D'(E(s)) ds}{U'(C(t))} \ (eq.7)$$

Chapter 1: Social Planning

Regime	Social Optimum	Laissez-Faire
(1) Oil → Renewables	Coordinated transition based on intertemporal efficiency	Delayed transition due to underinvestment in renewables
(2) Oil → Oil & Renewables	Balances oil depletion with renewable investment	Extended use of oil if firms underinvest in renewables
(3) Oil & Renewables → Renewables	Smooth phasing out of oil	Market failures may lead to prolonged use of oil
(4) Renewables Forever	Achieved through early investment in $K_R(t)$	Less likely due to capacity constraints and market failures

Chapter 1: Social Planning

Policy Intervention	Effect on Oil Use	Effect on Renewables	Effect on Emissions	Effect on Economic Growth
Carbon Tax	Faster decline	Moderate growth	Strong reduction	Slower growth
Renewable Subsidy	Slower decline	Faster growth	Moderate reduction	Faster growth

Parameter Change	Effect on K	Effect on K_R	Effect on S	Effect on E	Policy Impact
Higher S0	Lower	Slower Growth	Faster Growth	Higher Emissions	Delays Transition
Higher K0	Higher	Faster Growth	Faster Decline	Initially Higher	Speeds Transition
Higher δ	Lower	Slower Growth	Slower Decline	Declines Faster	Weakens Both Policies
Higher γ (G(S))	Higher	Faster Growth	Faster Decline	Declines Faster	Strengthens Both Policies
Higher g	Slightly Lower	Slight Growth	Faster Growth	Drops Significantly	Boosts Carbon Tax Effectiveness

Chapter 2: Decentralized Economy

- **Household Utility Maximization Problem**

$$\max U = \int_0^{\infty} e^{-\rho t} U(C(t)) dt$$

under the resource flow constraint

$$\dot{A} = rA(t) + w - C(t)$$

which is equivalent to

$$\dot{K} + \dot{K}_R = rK(t) + rK_R(t) + w - C(t)$$

Chapter 2: Decentralized Economy

- **Profit Maximization Problem for Final Goods Firms**

$$\max F(K(t), O(t) + h(K_R(t))) - (r + \delta)K(t) - w - p_O O(t) - p_R h(K_R(t))$$

- **Oil Firms**

$$\max[p_O - G(S(t))]O(t)$$

subject to

$$\dot{S} = -O(t), S(0) = S_0$$

- **Renewable Energy Firms**

$$\max[p_R h(K_R(t)) - R(t) - rK_R(t)]$$

subject to

$$\dot{K}_R = R - \delta K_R(t)$$

$$0 \leq K_R(t) \leq \bar{K}_R$$

Chapter 2: Decentralized Economy

Phase	Key Condition	Transition Driver
(a) Renewables Oly	$p_O > p_R$	Oil depletion or policy
(b) Oil Only	$p_R h'(0) < \rho + \delta - r$	Cheap oil, no renewable capital
(c) Both Renewables and Oil	$p_O = p_R$	Converging prices, investment timing
(d) Renewables forever	-	No transition

Phase	Steady State	Stability	Key Behavior
(a) Renewables	Yes	Locally Stable	Converges to K_R^*
(b) Oil Only	No (depletion)	Inherently Unstable	Resource depletes, no long-run energy
(c) Mixed	Quasi-steady (BGP)	Transitional / Unstable	Transits toward renewables only phase

Chapter 2: Decentralized Economy

Comparative Dynamics

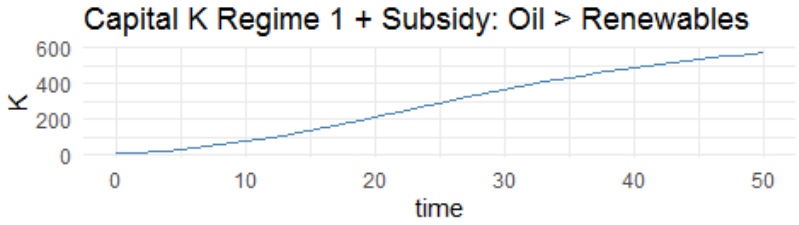
Case	Initial Conditions	Initial Regime	Transition Time T^*	Final Regime
1	$K_0 < K^*$, $K_{0R} < K_R^*$	Oil-only (later mixed use before T*)	$p_0 = \frac{p_R}{h'(K_R)}$	Renewables -only
2	$K_0 < K^*$, $K_{0R} > K_R^*$	Renewables -only	No transition	Renewables -only
3	$K_0 > K^*$, $K_{0R} < K_R^*$	Mixed use	When oil depleted or too costly	Renewables -only
4	$K_0 > K^*$, $K_{0R} > K_R^*$	Renewables -only	No transition	Renewables -only

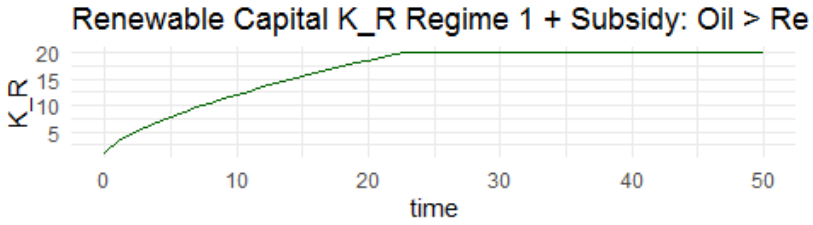
Chapter 2: Decentralized Economy

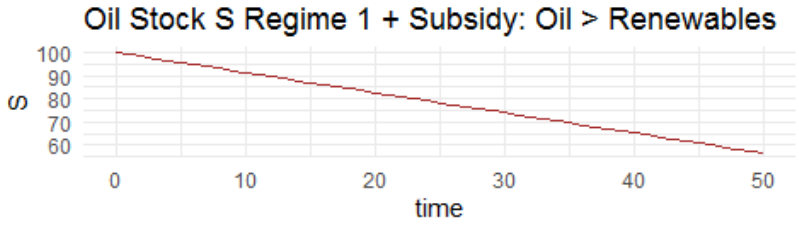
Climate Policy

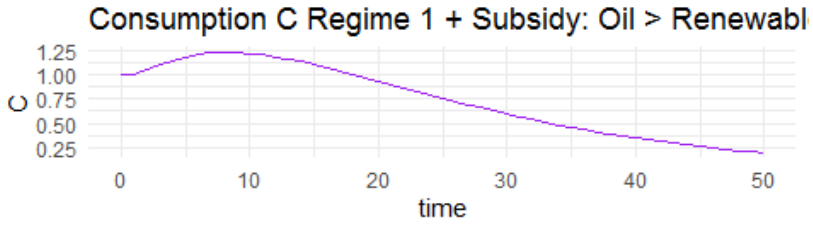
Policy Type	Instruments	Effectiveness	Decentralizes Social Optimum?
First-best	Carbon tax $\tau(t) = SCC$	Fully internalizes externality	Yes
Second-best	**Subsidy $\upsilon(t)$**	**Shifts relative prices**	**No**
Delayed tax	Future $\tau(t)$	May accelerate oil use	No — risk of Green Paradox

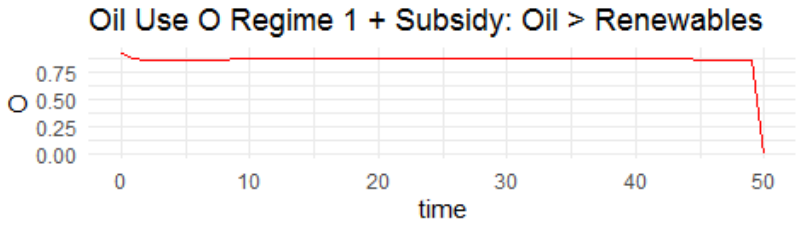
Chapter 2: Decentralized Economy

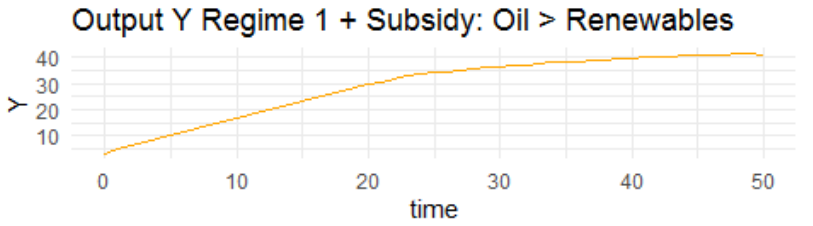








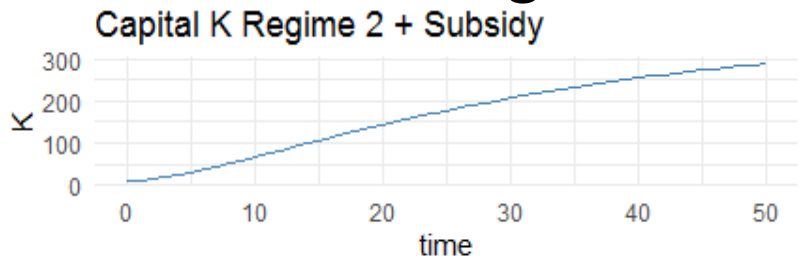


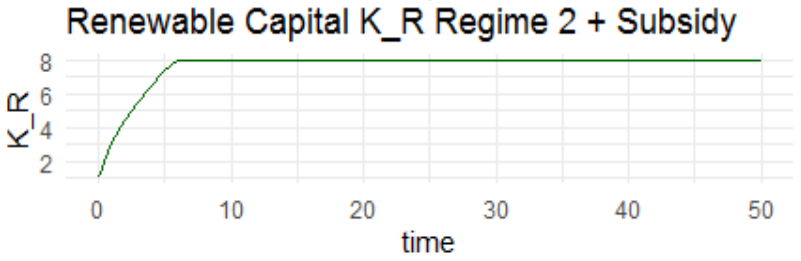


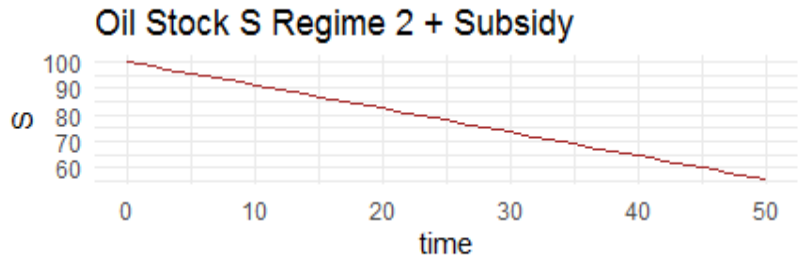
***we notice consumption gradual decline after T = 7 (due to renewables reaching a limit)**

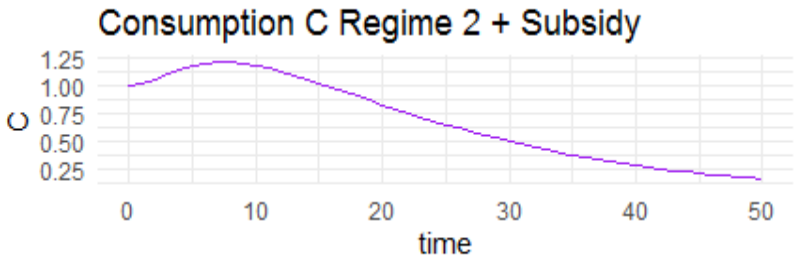
Chapter 2: Decentralized Economy

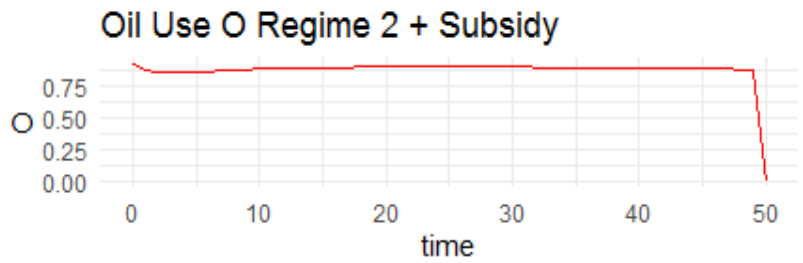
Regime II – Second-Best Policy

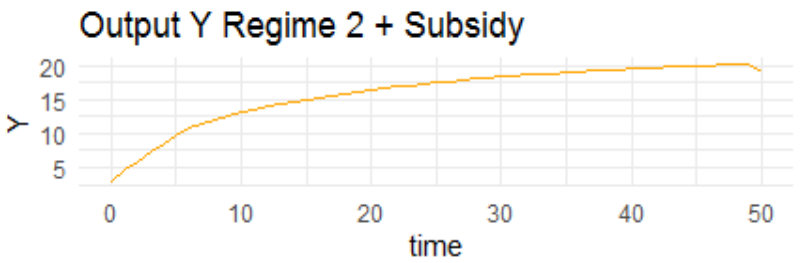












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Chapter 3: Market Imperfections on Renewables (Future work)

- Possibly include investment into renewable capital be inefficient or partially lost due to friction $\boldsymbol{\theta \in (0,1)}$ (Reichenberg et al. (2021)

- a **subsidy $\boldsymbol{\tau}$** could be missing (i.e. optimal policy not implemented) (Andor & Voss, 2014, Sendstad et al., 2022)

Concluding Remarks

- Social planning provides smoother and faster growth results than decentralized outcome.

- Capacity constraints on renewables may unlikely lead to a regime with using only renewables forever as there is a risk of reaching a limit, which may imply either new breakthroughs or relaxing the constraints from market, law, energy rivalry etc..

- Still oil energy may be useful alongside renewables.

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ΓΓΕΤ
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