Towards an energy theory of value? A critical assessment of the correlation between flows of primary, net and useful energy flows and monetary indicators for Canada, 1961-2022

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Contents

Abstract

My thesis examines the relationships between indicators of biophysical quality of energy sources and associated monetary indicators, taking Canada as a case-study for the period from 1961 to 2022. I test the hypothesis of a statistically significant relationship between the caloric value of energy sources (measured in joules) used in the Canadian economy and various associated monetary indicators of value (measured in constant Canadian dollars). I use three different measures of energy to test the impact of energy quality on monetary indicators: one measure not corrected for quality (primary and secondary energy flows) and two measures corrected for quality (net-energy ratios and exergy flows). I use four monetary indicators to examine the connections between biophysical quality and monetary value: price, cost of production, profitability and monetary output. I test the hypothesis at two different scales. I first test the correlation between the disaggregated standard Energy Return on Energy Invested ($EROI_{st}$) of oil sands-derived crude (diluted bitumen and synthetic crude oil) produced in open-pit mining facilities and their associated spot prices, cost of production and profitability from 1997 to 2016 in the province of Alberta, Canada, using original data. $EROI_{st}$ ratios are estimated using a hybrid of process and input-output analysis. My estimates find the weighted average of $EROI_{st}$ for synthetic crude and diluted bitumen to be 4.1:1 and 11.6:1 respectively, both increasing across the period. I test the correlation between the $EROI_{st}$ series and the prices, cost of production and profitability of each crude stream independently, using a simple econometric model using variables in first differences. The regressions for both crude streams fail to find any statistically significant correlation between monetary and biophysical indicators. I reiterate the test at the macroeconomic level. Using the theoretical framework of aggregate production functions (APFs), I build 11 log-log multivariate regression models of the Canadian economy measuring the correlation between output production measured in Canadian dollars and labor (measured in hours of work), capital (measured in annual flows of investment) and energy flows (measured in joules) for Canada from 1961 to 2022 using several measures of energy to correct for quality. I use several models to address potential non-stationarity in the dataset, dynamic effects and three different measures of energy: a measure not corrected for quality, i.e. primary and secondary energy flows and two measures corrected for quality; net-energy ratios of energy consumed and produced in Canada and exergy, i. e. useful energy flows. To assess the methodological validity of the models, I review the history of production functions and their critique by post-Keynesian and ecological economists. The first series of models (1-8) uses provincially disaggregated data on output regressed over primary and secondary energy flows of energy, labor and capital from 1997 to 2020. The models find labor and energy-use to be statistically significant, with the former bearing more impact on output growth over the latter. These models display a slightly higher predictive power over a standard, two-inputs model and show bidirectional causality between flows of primary and secondary energy and output. The price of energy is more statistically significant than energy-use in energy-producing provinces. The second series of models (9-10) uses original data on the net-energy ratio of primary energy consumed and the $EROI_{st}$ of primary energy produced in Canada from 1978 to 2022. Neither are statistically significant when regressed over output production. The model testing for $EROI_{st}$ displays a higher Adjusted R^2 over the models testing for net-energy ratios of energy consumed and flows of primary and secondary energy. The validity of the two models is circumscribed provided the number of negative coefficients yielded. One last model estimates the correlation between inputs and output of the Canadian economy using an exergy-based biophysical production function (BFP) where flows of labor and capital are modeled as sub-functions of the flows of muscle work, mechanical work and heat empowering their economic use from 1961 to 2020. Flows of capital modeled as a sub-function of mechanical work and heat are found to be statistically significant, meaning BFPs are useful modelling devices. The model finds output growth to be the cause of the growth in inputs use. However, the validity of the model is limited by its dependence on monetary figures to aggregate flows of capital.

Résumé

Ma thèse examine les rapports entre les indicateurs de qualité biophysique des sources d’énergie et différents indicateurs monétaires associés à celles-ci en prenant le Canada entre 1961 et 2022 comme cas d’étude. Ma thèse teste l’hypothèse d’un rapport statistique significatif entre la valeur calorique (mesurée en joule) des sources d’énergie utilisées dans l’économie canadienne avec différents indicateurs de valeur monétaire associés à ces sources, mesurés en dollars canadiens constants. J’utilise trois mesures distinctes de valeur calorique afin de tester l’influence de la qualité des sources d’énergie sur les indicateurs monétaires : une mesure non-corrigée pour la qualité (flux d’énergie primaire et secondaire) et deux mesures corrigées pour la qualité (taux de retour énergétique (TRÉ) et flux d’exergie). Quatre indicateurs monétaires sont employés : le prix, les coûts de production, la profitabilité et l’output mesurée en unités monétaires. L’hypothèse au centre de la thèse est testée à deux différentes échelles. D’abord, je teste la corrélation entre les TRÉ désagrégés des deux types de brut produits à partir des sables bitumineux (bitume dilué et brut synthétique) dans les mines à ciel ouvert et leur prix spot, coûts de production et taux de profitabilité entre 1997 et 2016 en Alberta, en utilisant des données originales. Les TRÉ sont estimés à partir d’une méthodologie hybride d’analyse de processus et d’analyse par entrée-sortie. Mes estimations indiquent que la moyenne pondérée du TRÉ du brut synthétique est de 4.1:1 et celui du brut dilué de 11.6:1. en augmentation au cours de la période étudiée. Je teste la corrélation entre les TRÉ et les prix spot, coût de production et taux de profitabilité pour les deux types de brut séparément en utilisant un modèle économétrique utilisant les premières différences entre les variables. Les régressions n’indiquent aucun résultat significatif entre indicateur de qualité biophysique et de valeur monétaire à cette échelle. L’hypothèse est testée de nouveau à l’échelle macroéconomique en utilisant le cadre théorique d’une fonction de production agrégée (FPA). Je construis et teste 11 modèles de régression multivariée en log-log de l’économie canadienne mesurant la relation entre l’output économique mesurée en dollars canadiens et le travail (mesurée en heures de travail), le capital (mesurée en flux annuel d’investissement) et l’énergie (mesurée en joule) au Canada entre 1961 et 2022, utilisant trois mesures distinctes de l’énergie selon la correction pour la qualité énergétique. J’emploie différents modèles afin de détecter les processus potentiellement non-stationnaires dans les données, les effets dynamiques et les trois mesures de l’énergie : une mesure non-corrigée pour la qualité (flux d’énergie primaire et secondaire) et deux mesures corrigeant pour la qualité : le TRÉ de l’énergie consommée et produite au Canada ainsi que l’énergie mesurée en termes utiles (exergie). Le potentiel des FPA de mesurer des relations économiques empiriques entre intrants et extrants est examiné à travers une revue de l'histoire des FPA, en particulier leurs critiques par les économistes post-keynésiens et écologiques. La première série de modèles (1-8) utilise des données désagrégées pour les provinces modélisant la relation entre l'output et les flux d'énergie primaire et secondaire, le travail et le capital entre 1997 et 2020. Les modèles indiquent que l'énergie et le travail sont statistiquement significatifs, le travail montrant une élasticité de production plus forte que l'énergie ainsi qu'une causalité bidirectionnelle entre les flux d'énergie et l'output. Les modèles à trois facteurs montrent une capacité prédictive très modestement supérieure aux modèles néoclassiques à deux facteurs. Le prix de l'énergie est une variable plus significative au sein des provinces productrices d'énergie. La seconde série de modèles utilise des données originales sur les TRÉ de l'énergie primaire consommée et produite au Canada entre 1978 et 2022. Aucun des deux taux n'est corrélé significativement à la production de l'output. Le modèle testant pour le TRÉ de l'énergie produite au Canada montre un R^2 ajusté plus élevé que pour le TRÉ des flux d'énergie primaire consommés. La validité théorique des deux modèles est limitée en fonction du nombre de coefficients négatifs produits. Un dernier modèle estime la corrélation entre les facteurs et l'output en utilisant une fonction de production biophysique où les facteurs de production économique sont une fonction des flux d'exergie qui rendent leur utilisation possible : le travail musculaire pour le travail et l'énergie mécanique et la chaleur pour le capital. Les flux de capital animés par les flux d'exergie mécanique sont des prédicteurs statistiquement significatifs de l'output économique, ce qui signifie qu'une FPA modélisée en unités biophysiques est un outil de modélisation utile mais limitée par son utilisation de données monétaires pour mesurer les flux annuels de capital. Le modèle indique que la croissance de l'output cause la croissance dans l'utilisation des inputs.

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Six years after starting my doctoral program, to complete it would have been impossible without financial, intellectual and personal support.

For their financial support, I acknowledge the doctoral awards received from the Fonds de recherche du Québec - Société et culture and the Social Sciences and Humanities Research Council. My dissertation was made possible thanks to numerous teaching assistantships with the Department of Economics of McGill University. I owe the chance to start my teaching career to Michael Babcock, Julian Vikan Karaguesian, Hervé Robert Horner, Paul Dickinson and Ling Ling Zhang: may they know the depth of my gratitude. Finally, for taking me as an intern while knowing full well my dire personal situation when I needed a break from the academic world, my warmest gratitude goes to Geneviève Huot, Vincent Van Schendel and Solène Martin-Déry from Territoires innovants en économie sociale et solidaire.

Intellectually, my thesis is the product of numerous stimulating discussions with my research mentors and colleagues. My gratitude goes to my supervisor Nicolàs Kosoy, for teaching me the meaning of pluralism in ecological economics; to my intellectual mentor until his untimely retirement, Tom Naylor; to Blair Fix for his stimulating remarks and kindness and Kent Klitgaard, who taught me how one must dig deep into a theory before pretending to criticize it. For teaching me the basics of modelling and the accounting of capital assets depreciation, my deepest gratitude to Raphaël Langevin, Mathieu Perron-Dufour and Clark Williams Derry respectively. To Louis and Alban: thank you for telling me there was some value in my work when I needed it the most. My special thanks to Raphaël for helping me design and edit the graphs in chapter 5.

On a personal level, I would not be writing these acknowledgments had I not been reminded from time to time I am not a doctoral researcher only, but also a friend. To Kate, Val, Anne-So, Renaud, Céles, Seb and Sarah: I owe you more than you know. Finally, to my closest advisors: my thanks to my father and my mother, who passed away just as I engaged in the research I am now submitting. To my uncle and aunt, Georges and Diane, please know I am grateful to you for taking care of your nephew.

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List of symbols

a: output elasticity of labor

A: Solow residual

Av: Energy availability

AP: Average price

β: Output elasticity of capital

B: Bits

b: barrel

b_b: barrel of bitumen

b_s: barrel of syncrude

b/d: barrels per day

b_{fp}: barrel of bitumen further processed

C: capita

$CAPEX_{impt}$: capital expenditures imputed on year t.

C_i: interest accumulated

C_{bf}: cost of bitumen further processed, in dollars

co_j: coal, in joule

$co_\$$: coal, in dollars

du: duration of the workday

∂: capital depreciation

Δ: first difference

E: flow of primary energy-use, in joule

e: energy intensity (joule / volume unit)

$ELEC_j$: flow of electricity, in joule

ED: Effective demand

E$: Energy spending in dollar/joule

E_K: Aggregate energy use by capital (joule of mechanical work plus heat / K)

E_L: Aggregate energy use by labor (joule of muscle work / L)

E_X^K : Final-to-useful energy conversion ratio by capital

E_X^L : Final-to-useful energy conversion ratio by labor

E_{fp}: Energy further processed from off-site

E_d: Energy density, in joule/dollar

E_f: Energy used as fuel, in joule

E_i: Energy input, in joule

EIR: Energy intensity ratio

E_{di}: Energy, direct input

E_i: Energy input

E_O: Energy output, in joule

E_p: Energy used as plant use

Ex: flows of exergy

F_p: productivity of the fossil fuel sector

Fi: Final energy

GJ: Gigajoule

HE: Heat

HL: Heat loss, in joule

i: rate of interest

I: investment, in dollars

IND_i: indirect input, in joule

$IND_{1\text{-}OS}$: dollars spent in indirect input 1 in oil sands production

$IND_{1\text{-}OSb}$: dollars spent in indirect input 1 in diluted bitumen mining

$IND_{1\text{-}OS\text{-}bop}$: dollars spent in indirect input 1 in diluted bitumen open-pit mining

$IND_{1\text{-}CON}$: dollars spent in indirect input 1 in conventional crude production

ju: disutility

K: capital

K_{phys}: Capital in physical units

k: capital/labor ratio

kWh: kilowatt-hour.

L: labor

λ: equivalence factor for electricity

Mu: Marginal utility

MECW: Mechanical work.

MUSW: Muscle work.

M_i: energy output in physical units

MJ: megajoule

M_t: mark-up

MW: Megawatt

μ: quantity of currency

n: years

ng_j: natural gas, in joule

$ng_\$$: natural gas, in dollars

ξ: monetary to biophysical conversion factor

o_j: crude oil, in joule

$o_\$$: crude oil, in dollars

P: Price, in dollars

PI: Price index

P_r: Principal

P_C: Producer consumption

PC_{cb}: Production cost of bitumen per barrel

PR_b: Price of a barrel of bitumen

PI: Price index

Q: Output in physical units

R: Aggregate natural resources

r: rate of interest

s: savings

sec: seconds

T: land

T_{co}: coal transformed into steam and oven gas

T_s: fossil fuels transformed into steam

T_{rp}: fossil fuels transformed into refined petroleum products

TE_i: fossil fuels transformed into electricity by industry

TE_u: fossil fuels transformed into electricity by utilities

χ: output elasticity of energy

u: utility

U: Useful work

V: value

W: Wages

Y: output in dollars

Y_j: output in joule

Y_{jr}: energy-deflated output

$CAN: Canadian dollar.

~: regressed over.

List of acronyms

AER: Alberta Energy Regulator

AP: Average product

APF: Aggregate Production Function

API: American Petroleum Institute

BPF: Biophysical production function.

CAPEX: Capital expenditures

EIA: Energy Information Administration

EROI: Energy Return on Energy Invested

$EROI_{st}$: Standard Energy Return on Energy Invested

$EROI_{pou}$: Energy Return on Energy Invested at the point of use

GDP: Gross Domestic Product

LHS: Left-hand side.

LINEX: Linear exponential.

MP: Marginal Product

MPP: Marginal Physical Product

MPP_L: Marginal Physical Product of labor

MPP_K: Marginal Physical Product of capital

MRTS: Marginal rate of technical substitution

MROI: Monetary Return on Investment

NER: Net-energy ratio

OPEX: Operation expenditures

PRR: Power Return Ratio

PtC: Price to cost ratio

ROE: Return on Equity

Contribution to knowledge and contribution of authors.

The body of the thesis starts with a comprehensive literature review (Chapter 2) discussing the historical attempts to explain the connection (or lack thereof) between biophysical flows of energy and monetary flows. I am the only author of Chapter 2, which is followed by four original research chapters written in manuscript format following the guidelines from the Graduate and Postdoctoral Office of McGill University. The thesis ends with a discussion of the findings and limitations of the research. (Chapter 7).

Chapter 3 contributes to the literature on net-energy analysis and biophysical economics by producing original results on the disaggregated series of $EROI_{st}$ ratios of the two crude streams produced from oil sands extracted via open-pit mining for the period 1997-2016: crude bitumen and synthetic crude. Past research on the $EROI_{st}$ of oil sands either focused on the $EROI_{st}$ of one of the two crude streams only or on the aggregate $EROI_{st}$ of the two crude streams produced by the oil sands sector, summing the output of open-pit and in-situ mining. Original contribution to knowledge in Chapter 3 is to provide original, disaggregated series of $EROI_{st}$ ratios for the oil sands, one for each crude stream, produced via one mining method only. The chapter argues this method makes the comparison of each crude stream’s $EROI_{st}$ easier. Unlike several studies on net-energy analysis of fossil fuels, it finds the $EROI_{st}$ ratios of the two crude streams to increase over the period studied. I am the sole author of Chapter 3.

Chapter 4 contributes to the literature in biophysical and ecological economics on the connection between indicators of biophysical quality of energy flows and monetary indicators. The original contribution of the chapter stems from the original data it uses, the regressions performed on the datasets and the original results produced. It uses the original data on the $EROI_{st}$ of oil sands-derived crude produced in Chapter 3 regressed over disaggregated series of each crude stream’s spot prices in Canada prior to delivery (Western Canada Select for diluted bitumen and Edmonton Light for Synthetic crude), cost of production (depreciated capital and operation expenditures) and profit (price-to-cost ratio). The chapter uses a simple econometric model in first differences to estimate the correlation between the two original series of indicators for each crude stream, using original data for both dependent and independent variables. Unlike several papers reviewed in the chapter’s literature review, the regressions performed find no statistically significant relationship between the variables.

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Author 1: a) conceptualization of the chapter's original idea; b) literature review; c) conceptualization of the general hypotheses; d) data collection; e) data analysis; f) interpretation of the results; g) review and editing.
Author 2: a) conceptualization of the specific hypotheses (section 4.2.2); b) construction of the econometric model; c) data analysis; d) interpretation of the results.

Chapter 5 is a contribution to the history of economic thought with a special emphasis on the contribution of ecological economics to the history of major debates within economics. It reviews the history of aggregate production functions (APF) from their creation by early marginalist economists to their systematization in the 1950s by Robert Solow and their critique by post-Keynesian and ecological economists. The chapter discusses two different theoretical responses to the sustainability challenges raised by the Meadows Report in the 1970s: the incorporation of natural resources as a third input to standard APFs and the use of biophysical units of measurements to build ‘’biophysical production functions’’ (BFPs) where the technical relationships between economic output and inputs (man-made and natural) are expressed in biophysical units of measurements (namely, in joule). The chapter discusses three theoretical proposals of BFPs. The chapter's original contribution stems from its emphasis on the attempts to incorporate natural resources within the framework of APFs in both orthodox and heterodox Economics, while addressing whether BFPs address the post-Keynesian critiques of neoclassical APFs satisfactorily. I am the sole author of Chapter 5.

Chapter 6 contributes to the field of Ecological Macroeconomics by building, interpreting and systematically comparing 11 log-log multivariate regression models of output production in Canada regressed over labor, capital and various measures of energy inputs corrected for energy quality: a) primary and secondary energy flows; b) net-energy ratios of energy consumed and $EROI_{st}$ ratios of fossil fuels and electricity produced in Canada and c) exergy-flows. To build the model testing for c), it uses a biophysical model of economic growth (Keen et. al., 2019) and an original exergy-flows time-series (Marshall et. al. 2024). The chapter's originality stems from a) the systematic comparison of the effects of three distinct measures of energy quality on output growth; b) the comparison of the correlation of output growth regressed over net-energy ratios of energy produced and consumed in Canada using original time-series; c) the use of a new time-series on exergy flows in Canada to test a theoretical model.

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Author 1: a) conceptualization of the chapter's original idea; b) literature review; c) data collection; d) construction of models 7-11 based on author's 2 original model (Model 3); e) interpretation of the results f) econometric testing for co-integration and stationarity of the time series and causality in the models.

Author 2: a) conceptualization and construction of the original model (Model 3); b) proposal of a hypothesis testing methodology (counterfactual); c) writing of the original version of the R-code used for graph generation (Figure 39 and 40); c) interpretation of the results, Models 3-6.

Publication of thesis components

Chapter 3 was published in the peer-reviewed journal *Biophysical Economics and Sustainability*, Volume 8, article number 2 in 2023, doi.org/10.1007/s41247-023-00109-5.

Chapter 4 was published in the peer-reviewed journal *Ecological Economics*, Volume 217, March 2024, https://doi.org/10.1016/j.ecolecon.2023.108072.

Chapters 5 and 6 are in the process of rewriting into a chapter to be submitted for a collective book, *Net-Energy Analysis: The State of the Art*, edited by Louis Delannoy. The chapter, tentatively titled *What NEA can and cannot tell for economists*, will be cowritten with Alban Pellegris and is planned to be submitted in the Fall of 2024.

To my mother Ginette and my intellectual mentor, Robin Thomas Naylor. I wish both had been able to see me complete this dissertation.

Chapter 1 Introduction

As of 2023, Canada is a major crude oil producer. During the 20th century, as its reserves of conventional crude became insufficient to meet demand, its unconventional oil sands reserves have become increasingly viable financially. Unconventional crude production dominates Canadian energy export, with 2.84 million barrels per day (b/d) in comparison with 957 000 b/d of conventional crude (Canada Energy Regulator, 2023). Two types of crude are produced out of raw oil sands: diluted bitumen and synthetic crude. Diluted bitumen refers to raw bitumen cleansed from solid particles after extraction and diluted with light hydrocarbons. Synthetic crude is produced via upgrading (distillation and/or cracking) of crude bitumen, resulting in a crude oil stream nearly identical chemically to conventional crude.

The energy quality of conventional and unconventional sources differs. In the context of energy analysis, ‘’quality’’ is defined as the usefulness of a unit of energy to society in terms of the physical work it can perform, the economic output it helps produce, etc. Energy Return on Energy Invested (EROI) is one indicator of quality and can be used to compare the quantity of work a unit of energy can perform over another unit (Hall and Klitgaard, 2018). Another measure is ‘’useful exergy’’, which corrects for an energy unit’s capacity to perform physical work once subtracted losses in energy-consuming processes (Heun et. al., 2017; Fix, 2015). Over the last two decades, several studies have shown a declining trend in the EROI of fossil fuels globally and in Canada (Gagnon et. al, 2009: Freise, 2011). High EROI-ratios mean that relatively little direct and indirect energy inputs are required to produce energy flows, leaving a large quantity of net-energy flows available for final demand, i. e. discretionary investment in infrastructures and consumption spending. A decline in EROI means a growing share of energy-flows are required for the maintenance of infrastructures, thus tightening the difference in energy flows otherwise used for capital accumulation and discretionary spending (Murphy et. al., 2011), ultimately leading to a decline in material standards of living (Hall et. al., 2014). With declining reserves of conventional crude worldwide, the EROI of unconventional sources of crude becomes of critical importance as they tend to deliver less net-energy flows than conventional sources, on average (Delannoy et. al., 2021). As fossil fuels provide about 80% of all flows of primary energy worldwide (International Energy Agency, 2020), the potential of unconventional sources to provide net-energy flows is of critical importance for the economy.

1.1 Aims and objectives

Declining reserves of conventional sources and the quality of unconventional sources raise an issue of great importance: the connection between the production and use of energy and the production of economic output. My thesis examines this issue, aiming to address the following questions: *is the energetic/heat value of energy carriers reflected in their monetary value? Does biophysical quality represent the material basis of the monetary value of a resource*? *Of an economy?* Specifically:

1) Are biophysical indicators of quality (measured in joule or watts) reflected in energy resources' monetary value (measured in constant Canadian dollars[1])?
2) Is the energy quality of energy resources impacting the 2.1) price; 2.2) costs of production; 2.3) profitability generated from them?
3) Are 3.1) primary and secondary energy flows; 3.2) net energy flows and 3.3) flows of useful energy positively related to output (measured in constant Canadian dollars) growth of the geographic area (markets, countries) using them? Furthermore: are changes in energy flows *causing* changes in monetary output?

My thesis takes Canada as a case-study. Canada is the fourth crude oil producer in the world with a production of 4.6 million b/d in 2018 (Canada Energy Regulator, 2024). Its production of crude from conventional sources is steadily declining, whilst its production from unconventional sources, i.e. the oil sands, has risen dramatically, from 9.5% (on a b/d basis) in 1980 to 70.3% in 2020 of total crude oil production (Canadian Association of Petroleum Producers, 2021. My calculations). As such, if changes in the EROI ratios of crude oil sources bear an impact on monetary indicators, Canada is a suitable candidate for this investigation.

1.2 Hypotheses

My dissertation examines if biophysical indicators of quality of energy sources in Canada are reflected in and causing their associated monetary indicators of prices, costs of production, profitability and output production, or Gross Domestic Product[2], measured in constant

[1] Appendix I discusses the methodological issues surrounding the use of 'real' over 'nominal' dollar values.
[2] To remain consistent with the literature and unless stated otherwise, I use 'output' to refer to measures of Gross Domestic Product as computed by national statistical agencies such as Statistics Canada.

Canadian dollars. The hypothesis is tested at two levels: at the resource (oil sands) and national (macroeconomic) level. On these issues, I hypothesize the following:

1) Owing to the different monetary and energy intensities involved in their production, the $EROI_{st}$ ratios of synthetic crude should be lower than diluted bitumen. As synthetic crude involves the upgrading of bitumen feedstock, synthetic crude production is more energy and capital intensive than diluted bitumen production. The $EROI_{st}$ ratios of the former should be lower than the latter. The higher $EROI_{st}$ ratio of diluted bitumen should be a function of the lower embodied energy in monetary expenditures on indirect inputs to produce it.

2) At the resource-level, I expect a moderate correlation between $EROI_{st}$ and monetary indicators of oil sands-derived crude streams:

<u>$EROI_{st}$ and costs:</u> I expect a negative relationship between $EROI_{st}$ and the costs of production of energy sources. Because diluted bitumen requires less monetary and energy investment on a per-joule basis than synthetic crude, its costs of production should be lower and its $EROI_{st}$ should be higher and the relationship, negative.

<u>$EROI_{st}$ and prices</u>: I expect to find a moderately positive relationship between prices and $EROI_{st}$. Higher net-energy flows reflected by higher $EROI_{st}$ ratios should mean higher willingness to pay by energy consumers. However, the prices for fossil fuels are set internationally. Rising international benchmark prices, independent from the biophysical quality of the resources, should incentivize oil sands producers to explore and extract lower-quality deposits yielding crude of lower $EROI_{st}$ ratios. This could lead to a negative price-$EROI_{st}$ relationship at the margin. As such, the correlation will be moderate.

<u>$EROI_{st}$ and profits:</u> I expect to find a moderate connection between $EROI_{st}$ and profitability. Because I expect the costs of production of diluted bitumen to be lower and its $EROI_{st}$ higher than synthetic crude, the correlation between $EROI_{st}$ and profit should be positive. Because I expect a negative relationship between costs and $EROI_{st}$ and a moderate positive relationship between prices and $EROI_{st}$, the relationship between biophysical quality and profitability should be moderately positive.

3) On the relationships between energy quality and output at the national level: I use three measures of energy regressed over output in log-log multilinear regression models along with relevant factors of production. One is not corrected for energy quality (primary and secondary energy flows) while the two others are (net-energy consumed/produced and useful energy).

Primary and secondary energy flows: I expect to find a strong correlation between primary and secondary energy use and output production at the national level. Furthermore, I expect bidirectional causation between the two. Not only is energy-use the physical condition for work in its broadest sense, but output production generates capital goods and investments which unlocks further energy sources to be extracted and used.

Net-energy flows: Canada is a major energy-producer, posing important challenges in term of how to measure the correlation between monetary output and net energy flows; a) if the objective is to estimate the correlation between net-energy ratios and the production of non-energy goods and services in Canada, then the test should focus on the net-energy ratio of energy consumed in Canada. However: b) a significant portion of energy produced in Canada is exported. This share of energy production generates monetary output, with a portion presumably reinvested in Canada to expand production, another portion paid to Canadian-based shareholders, etc. Yet, exported energy is not consumed in Canada. Standard net-energy accounting measures energy output at the mine-mouth, regardless of where it is consumed (Murphy et. al., 2011). As such, net-energy accounting can be used to build $EROI_{st}$ ratios of energy produced in Canada, but not of energy consumed.

3.1a) On the correlation between net-energy ratios of energy consumed in Canada and output production: the analysis should reveal a strong correlation and bidirectional causation between the two for the same reasons as in 3.1).

3.1b) On $EROI_{st}$ and output production: the analysis should reveal bidirectional causation from $EROI_{st}$ and output and vice-versa. However, the correlation should be weaker from the one found in 3.2a), provided not all energy produced in Canada is used there. However, I expect to observe the growth in $EROI_{st}$ (provided the recent and rapid growth in oil sands production in Canada over relatively constant investment) to be correlated to a growth in monetary output with a portion reinvested in expanding energy production. the correlation between the $EROI_{st}$ of energy produced in Canada and output should be positive and the causation bidirectional.

Useful energy: I expect a strong correlation and bidirectional causality between output measured in dollars and useful energy used in Canada, for the same reasons supporting the hypothesis for flows of primary and secondary energy. However, testing the correlation for useful energy should reveal a stronger correlation when compared with flows of primary and secondary energy, which do not account for the quantity of entropy generated in output generating energy-consumption, therefore including a fraction that is lost in output generation, something measures of useful energy corrects for.

1.3 Expected limitations

Several limitations in the research are expected. On estimating the $EROI_{st}$ of oil sands-derived crude in chapter 3, the number of estimated $EROI_{st}$ ratios I expect to produce will probably be limited due to data availability in the oil sands' open-pit mining sector, the sub-sector of the oil sands industry I choose to empirically test my hypothesis. Furthermore, to estimate the share of energy used to produce indirect inputs (material and equipment, financial services, etc.) used in oil sands production, several assumptions had to be made on the share of these inputs used in the oil sands sector using national data on the oil and gas extraction sector. The potential of the results to be used for prospective analysis should be limited as well: only 20% of recoverable oil sands in Alberta will be extracted via open-pit mining, whereas 80% are expected to be extracted via in-situ mining (Natural Resources Canada, 2024). A prospective analysis on oil sands extraction based on my results must take into account the declining share of oil sands mining produced via open-pit mining in the future.

On testing the correlation between the $EROI_{st}$ of oil sands derived crude with monetary indicators in chapter 4, the datasets used to test my hypothesis closely follows the size of the dataset generated to estimate the $EROI_{st}$ ratios of oil sands-derived crude in chapter 3. As such, the number of observations that can be used in chapter 4 will be equally limited.

The last limitation I expect relates to the hypothesized correlations between quality and non-quality corrected measures of energy and economic output at the macroeconomic level tested in chapter 6. Testing this hypothesis could be performed using a long list of production functions (Cobb-Douglas, translog, constant elasticity of substitution (CES), linear-exponential (Linex), etc.) However, my thesis focuses on a limited number of production functions (Energy-extended Cobb-Douglas and biophysical). Any results from chapter 6 must be circumscribed to the limited number of function forms of production functions used to test the hypotheses. Future research should reiterate the hypothesis testing using several other functional forms of production functions.

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PREFACE TO CHAPTER 2

Chapter 1 outlined the aims, objectives, hypotheses, research questions and expected limitations of the research. Before I start testing my hypotheses on the correlations and causal chains between corrected and non-corrected measures of biophysical quality of energy sources and their associated monetary indicators in chapters 3-6, chapter 2 provides an extensive literature review of the relevant academic fields of study. I start with a review of the literature in economics (neoclassical and ecological) on the connections (or lack thereof) between energy and economic processes. The review of the literature in ecological economics focuses on four important contributions, including two from the first generation of authors in the field (F. Soddy and N. Georgescu-Roegen) and more recent developments (the embodied energy and neo-physiocratic School). Chapter 2 concludes with the contribution I expect to make to to the field of ecological economics on my research questions in the context of the literature reviewed.

Chapter 2 Comprehensive Literature Review

In this chapter, I comprehensively review the theoretical literature used in my research. First, I briefly review the Government of Canada's policies and commitments to greenhouse gases (GHG) reduction in recent years as well as Canada's fossil fuel industry, followed with a review of the definitions of the different theoretical concepts used throughout the research. I continue with a review of the recent history of debates between orthodox and ecological economics on the role of energy in the economy. A systematic review of the theories of value and their connections (or lack thereof) with energy within both research traditions, orthodox and ecological, is endeavored.

On December 12th, 2015, Canada signed the Paris Agreement, agreeing to participate in the global efforts to limit the rise in global average temperature below 1.5^{o} C above preindustrial levels (United Nations; Climate Change)[3] and pledging to reduce its (GHG) emissions by 30% below their 2005 level by 2030. The same year, Canada emitted 707 megatons of greenhouse gases. In 2019, its emission rose to 730 megatons (Office of the Auditor General of Canada, 2021) but declining by 1% from 2022 to 2023, bringing emissions 8% below their preindustrial level in 2023 (Canadian Climate Institute, 2024). The slow decline in emissions is hardly surprising. In Canada, in 2022, 49.2% of the supply of primary energy was derived from crude oil, followed by natural gas with 32.8% (Statistics Canada, 2023), two important GHG emitters.

Economic and geological reasons will compound the challenge, Canada being the fourth largest crude oil producer and ninth largest oil consumer in the world (Energy Information Administration). On a total production of over 258 million m^3 of crude oil in 2023, 72% came from unconventional sources, i.e. the oil sands (Statistics Canada, 2024a). Of its 27 billion m^3 of reserves, only 747 million m^3 only are from conventional sources. Unconventional sources have been found to be much more GHG intensive than conventional sources, Charpentier et. al. (2009) finding synthetic crude (one of the two crude streams produced out of raw oil sands) to be more than two times (from 99 to 176 kgCO_2eq/b) more GHG intensive than conventional crude (from 27 to 58 kgCO_2eq/b).[4] The difference in GHG intensity between conventional and

[3] As of writing, the Copernicus Climate Change Service (the European Union's Earth Observation Program, has stated it is virtually certain 2024 will be the first to record an average global warming superior to the critical threshold of 1.5^{o} C (Bloomberg, 2024).
[4] The large variations stem from the production pathway of the crude oil source under analysis.

unconventional sources stems from the larger quantity of fuel required to upgrade bitumen into synthetic crude, a process conventional crude production does not need to go through. Forest loss to access hitherto untapped resources and increasing fresh water use in a region vulnerable to water-stress may exacerbate the environmental impacts of oil sands production and its growth. On fresh-water use, the production pathway from raw bitumen extracted via open-pit mining to gasoline was found to be 40 times more water-use intensive than conventional crude (Rosa, L. et. al., 2016)

Given Canada's energy reserves, Canada faces a conundrum. A key policy objective of its government is to support and facilitate the growth of its economy (Government of Canada; Department of Finance, 2024). On the other hand, the connection between economic growth and energy-use has been well documented (Ayres and Warr, 2005). One option available for governments to coherently pursue both economic growth and their commitments to limit ecological imbalances is decoupling, that is the increase in energy efficiency allowing for a decline in the quantity of energy to generate output (Moreau and Vuille, 2018). The theoretical possibility of decoupling economic growth from environmental degradation has been discussed within Economics since at least the 1970s, with some authors pointing out at genuine, albeit slow, decline in the energy intensity of advanced industrial economies whilst others point out at financialization and the delocalization of highly polluting economic activities to impoverished countries as the reason for apparent decoupling (The Conversation, 2017).

As shown in Chapter 1, my thesis investigates the correlation between monetary indicators such as output and indicators of biophysical quality of energy sources. Provided the current uncertainty and debates surrounding the possibility to decouple the production of environmental liabilities from fossil-fuel use and economic growth, my thesis is an empirical contribution to this crucial, policy-relevant question. Before delving into an empirical analysis, a review of the economic literature on the connection (or lack thereof) between biophysical and monetary indicators is conducted in the rest of this chapter, after reviewing a series of technical notions that will be used throughout the thesis.

2.1 Review of the definitions

Fossil fuels are stock-flow sources of low-entropy (i.e. ''free'') energy whose role in contemporary economies is ubiquitous (transportation, agriculture, food packaging, etc.) Once consumed, low-entropy dissipates into high-entropy energy that cannot be recycled back into low-entropy sources of energy. Entropy can be thought of as an indicator of available energy (Georgescu-Roegen, 1971). ‘’Primary energy’’ is defined as the energy content (measured in joules or watts) of an energy source entering energy supply chains before it is transformed or refined into an economically useful form to be used in the production of final goods and services, such as refined petroleum products (Energy Information Administration). ‘’Primary energy’’ does not measure the inputs of direct energy sources (fossil fuels, electricity, etc.) and the energy embodied in infrastructures, labor and services (indirect energy) required to produce flows of primary energy. It can be thought of as a ‘’non-corrected’’ measure of energy. ‘’Secondary energy’’ is defined as a source of primary energy that has been transformed into a transportable form into supply chains (Institut national de la statistique et des études économiques, 2020).

2.2 Energy and Economics

Since the 1970s, ecological and biophysical economists have developed the methodology of net-energy flows accounting, or Energy Return on Energy Invested (EROI), to estimate the quantity and quality of energy derived from energy carriers (i.e. primary energy that has been transformed into economically useful products for end-users (Giampetro and Mayumi, 2009)) once divided by the energy investments required to produce them. ‘’Quality’’ is defined as the series of physical properties of a resource which determines its potential to produce economic goods and services (Cleveland et. al, 1984). In the context of energy analysis, ‘’quality’’ is defined as the usefulness of a unit of energy to society in terms of the physical work it can perform, the economic output it helps produce, etc. EROI is one amongst several indicators of quality of energy flows and can be used to compare the quantity of work a unit of energy can perform over another unit. Another measure is ‘’useful exergy’’, which corrects for an energy unit’s capacity to perform physical work once subtracted losses in energy-consuming processes (Heun et. al., 2017; Fix, 2015). Owing to their high EROI-ratios (Hall et. al., 2014), ease of transportation, flexibility and non-intermittency (Malm, 2016), it is unlikely capitalism could have become the dominant mode of production globally without fossil fuels (Hall and Klitgaard, 2018: 102; Daly and Farley, 2010) or that Western countries could enjoy their current material standards of living (Lambert et. al., 2014).

It is generally acknowledged that energy played a minor role in neoclassical economic theory until the 1970s (Santos et. al., 2018). Since the Physiocrats, economists have tried to understand the production of economic wealth, or output[5], as a function of inputs. Starting with the Marginalists, several attempts were made to formalize mathematically a theory of output production as a function of labor and land in the form of aggregate production functions (APFs) (Robinson, 1934). APFs have since become one of the main tools of macroeconomics to study the relationships between inputs and output (Heun et. al., 2017), whereby ‘’capital’’ has replaced ‘’land’’ as the (allegedly) most impactful variable of output growth. However, in the late 1800s, the introduction of capital into APFs proved challenging as it involves using a monetary unit of measurement to account for physically distinct capital goods (Robinson, 1970). These difficulties were generally ignored in the mainstream of the economic profession after the introduction by Cobb and Douglas (1928) of their own proposal of an APF (Equation 1) and its alleged empirical accuracy. Indeed, despite acknowledgements of the logical issues surrounding the definition of ‘’capital’’, several economists have argued APFs should be used provided they ‘’work’’, empirically speaking. In Cobb and Douglas’ work, output production can be formalized as:

Equation 1

$Y = b(L^{a}K^{1-a})$

where ‘’Y’’ is ‘’economic output measured in dollars’’, ‘’L’’ is ‘’labor’’, ‘’K’’ is ‘’capital’’, ‘’α’’ is the output elasticity of labor (the change in the quantity of output produced following a change in the quantity of labor used) and ‘’b’’ is a multiplier. Equation 1 shows a homogeneous function of degree one, meaning an increase on one side of the equality must be proportional to an increase on the other side. In economic terms: Equation 1 displays constant returns to scale. Algebraically, it can be shown that the value of α is equal to labor’s share in national income (see Chapter 4, section 4.1.1) in a purely competitive economy. In such an economy, the marginal output brought by an increase in inputs, i. e. its marginal return, is equal to that input’s share of national income (Bumas, 2015). By construction, Equation 1 is true only if a factor receives a share of national income (Santos et. al., 2018) and if it is not created in production processes (Heun et. al. 2017).

Ironically, Cobb and Douglas’s work was harshly criticized upon publication by neoclassical and heterodox economists alike. Some economists emphasized the inability of Equation 1 to

2 To avoid ambiguities, I use the term ‘’output’’ consistently throughout the paper, except when commenting on the concepts used by authors in the literature.

account for technological progress, an indisputable feature of late nineteenth, early twentieth century capitalism. In the 1950s, Robert Solow and Trevor Swan independently proposed one of the most impactful models of economic growth ever produced (Fix, 2015). The Solow-Swan model tried to reconcile the theoretical possibility of economic equilibrium and technological progress into an improved iteration of Equation 1:

Equation 2

$Y = A(t)\, F(L^{a}, K^{1-a})$

where ‘’A’’ is a multiplier representing technological progress. Multiplier A is meant to represent how progress in production techniques account for the historically growing difference between annual changes in output and inputs of labor and capital. Indeed, provided marginal return of inputs is decreasing, observed economic growth could only be explained by the introduction of a ‘’residual’’ equal to the difference between growth in output on the one hand and factors (labor and capital) on the other hand. Investment in capital only would produce a stationary state, at best (Pellegris, 2022). According to Solow, multiplier A represents empirical technological progress in the economy.

Because it earned no income visible in national accounts, energy was absent from Equation 2 upon publication of Solow’s papers in the 1950s. The oil shock of 1973 and the publication of the groundbreaking Meadows Report, *The Limits to Growth*, led some neoclassical economists to reconsider the role of energy in their models. Yet, these new models were developed by economists who vehemently criticized the Meadows report’s purported failure to acknowledge possible substitutions of natural resources by capital goods. For example, Solow proposed to introduce a third factor into his model to account for energy sources:

Equation 3

$Q = A(t)\; F(L^{\alpha}, K^{\beta}, E^{\chi})$

where ‘’E’’ is ‘’energy-use’’, ‘’β’’ is ‘’output elasticity of capital’’ and ‘’χ’’ is ‘’output elasticity of energy-flows’’. Neoclassical modelers do not agree on the nature of energy inputs in the economy. Some scholars (see Denison, 1978, cited in Santos, 2018, et. al) define energy as an intermediate good (a good used to produce other goods) that cannot be incorporated in a standard production function because a) payments to energy are absent from national accounts and b) energy is produced by capital and labor. Another research tradition argues it can: energy is an input substitutable to capital and labor and vice-versa. Investment in capital stock could mitigate the impacts of declining energy inputs to production of economic output (Couix, 2019).

However, the empirical validity of Solow's claims has been warmly debated between neoclassical and various schools of heterodox economists (see Volume 22, Issue 3 of *Ecological Economics* for a particularly insightful review of the debates). As the Meadows report was published, another controversy surrounding neoclassical models was taking place. From the 1950s to the 1970s, post-Keynesian economists, mostly based in Cambridge, United Kingdom, challenged the logical and theoretical validity of APFs. Post-Keynesians argued it is impossible to meaningfully aggregate heterogeneous physical capital goods under a quantitative index using monetary data, whilst others claimed the purported empirical strength of APFs stems from an unacknowledged accounting identity. Post-Keynesians have shown APFs rests on circular reasoning. In a perfectly competitive economy, it is alleged the use of factors of production is equal to the level where their marginal product is equal to their market prices. The price of capital is given by its rate of interest. However, APFs can be computed only if a rate of interest β is given. In other words, production functions fail to empirically predict the price of factors due to a circular reasoning fallacy (Felipe and McCombie, 2013). Furthermore, the coefficient of correlation of APFs found by Solow (over 0.99 for the five mathematical forms tested in Solow's 1957 paper) are, according to Shaikh, the product of an unacknowledged accounting identity, an algebraic relationship between inputs and output, therefore failing to produce any new knowledge of the economy (Shaikh, 1974).

Ecological economics was born in the 1980s out of the rejection of neoclassical economists' response to sustainability challenges laid out in the Meadows report. Specifically, ecological economics seeks to address the purported failures of neoclassical economics to conceptualize 1) the embeddedness of the economy into the biosphere; 2) distributive justice between species, humans and generations (Ament, 2019) and 3) the role of historical time in the evolution of socio-ecological systems (Faber, 2008), the latter defined as complex systems where social institutions and natural ecosystems mutually influence each other. Ecological economists emphasize economic systems are predicated unto the biophysical realm, arguing there are limits to substitutability of natural with man-made capital. Provided there would be no life without biophysical processes, ecological economists argue they must be incorporated into a theory of the economy (Georgescu-Roegen, 1971). Furthermore, they argue path-dependency, positive feedback loops and uncertainties define the evolution of socio-ecological systems. Unlike neoclassical economics' focus on exchanges, ecological economists argue on the need to refocus economic analysis on production (Cleveland et. al., 1984) and how flows of matter and energy enable it (Ament, 2019). In so doing, several ecological economists have rejected the view held by neoclassical economics that energy sources are substitutable with capital. Several arguments were made along this line:

A) the assumption of infinite substitutability of capital and energy means capital can be produced out of an infinitely small quantity of energy, which some argue to be an absurd proposition (Daly, 1997);
B) No substitution can account for the dissipation of the finite stock of low-entropy energy sources on Earth (Daly, 1997). High-entropy cannot be recycled into low-entropy (free energy);
C) APFs rest on a confusion over capital and energy sources being complements rather than substitutes. Increase in output requires an increase in complementary sub-groups of inputs such as capital and energy sources (Daly, 1997);
D) Complementarities between inputs are limited by existing technological constraints (Kümmel et. al., 1985);
E) Although economically useful energy carriers are indeed the product of human labor, free energy is not (Kümmel et. al., 1985). Work and capital are merely economic tools empowered thanks to *exergy* flows, ''exergy'' being defined as the flows of energy performing work, equal to final energy flows minus the flows of exergy destruction (i.e. entropy) generated in energy-consuming processes (Ayres and Warr, 2005). When flows of labor and capital are estimated as sub-functions of the exergy flows empowering them (muscle work for labor and mechanical work and heat[6] for capital) as in Equation 4 (Keen et. al., 2019), a very strong correlation between inputs and output is found, such that the so-called ''Solow residual'' (equal to multiplier ''A'' in Equation 2) is considerably reduced (Ibid.):
Equation 4

$$Q = F((L * E_L * E_X^L) * (K * E_K * E_X^K))$$

where ''E_L'' means ''aggregate energy use by labor'', ''E_X'' means ''aggregate energy use by capital'' and ''E_X^L'', ''E_X^K'' represents the conversion ratios of primary to useful energy (i.e.

[6] When using the concept of ''heat'' in exergy analysis, I use it as defined by Ayres and Warr: ''[...] fuel used to generate heat *as such*, either for industry process heat to do mechanical work or space heat and domestic use [...]''. (2005: 187. Authors' emphasis).

exergy flows) by labor and capital respectively and where ‘’K’’ is measured in physical units. Keen et. al. claim Equation 4 is more realistic than Equations 2-3 since only the former shows that without flows of energy, labor and capital would be inactive. The activation of human-made capital physically requires energy flows.

When finding that using useful exergy as a variable of output growth leads to a quasi-null residual in a production function, Ayres and Warr argue the ‘’technological progress‘’ witnessed across the history of capitalism, understood by Solow to be the growing difference between output and input growth, is actually the history of improvements in exergy conversion into useful work (2005). This kind of ‘’biophysical’’ model corresponds to what Pellegris (2022) terms a ‘’neo-thermodynamic’’ approach, whereby the theoretical and empirical potential of economic modelling is emphasized provided variables are defined in biophysical terms. Pellegris describes the neo-thermodynamic approach as providing an ‘’internal critics’’ of APFs.

If points A)-E) above are true, then declining reserves of conventional fossil fuels and their replacement by lower-EROI unconventional sources means a significant challenge for the future of global capitalism. In my understanding, the ongoing debate on the role of energy in output production involves the issue of the *nature* and *direction* of the empirical interactions between flows of services from man-made and natural capital in the production of output. As summarized elegantly by Santos et. al. (2018), are these linkages:

1) Unidirectional; 1.1) from energy-use to output production (growth hypothesis) or 1.2) from output production to energy use (conservation hypothesis)?
2) Bidirectional: energy-use enabling the production of capital stock and output and vise-versa (feedback hypothesis)?
3) Absent (neutrality hypothesis)?

2.3 Theories of value and prices in neoclassical and ecological economics

This section reviews the literature on the theory of value in neoclassical and ecological economics. More specifically, I examine how the theories explain the connection (if any) between value and monetary indicators. The specific research questions stemming from this review will then be made explicit, as I introduce the four research chapters of the dissertation and the methodologies developed to test my research questions.

A theory of value aims at explaining why commodities are exchangeable, that is how exchange values, or prices, reflect (or not) the value of commodities (Pirgmaier, 2021: 1). The section will show how both schools of thought disagree on the *nature* of value and the role of prices and how they both agree on its *objectivity*. I start with reviewing the neoclassical school, following with the ecological school of economics. With each school, I first identify the school's theory on the origins of value to be followed by how prices emerge and reflect (or not) value according to scholars of these traditions.

There is no unified theory of value in ecological economics. I therefore review a series of theories, starting with historical theories followed by contemporary ones: the reductionist theory of Frederick Soddy, the non-reductionist theory of Georgescu-Roegen, the neophysiocratic and embodied energy schools.

2.3.1 The origin of value in neoclassical economics

According to the marginalist theorists who laid the basis of neoclassical economics, economic value is objective. This statement may come as a surprise, based on neoclassical economists' assumption that value is measured subjectively via agents' utility, or satisfaction of preferences (McShane, in Spash (dir.) 2017). Yet, as shown by Orléan,[7] although the *quantity* of value is subjective as each agents' feelings of utility are her/his own, the fact that commodities have value is objective. Value is ''co-substantive'' with commodities as they carry the ability to satisfy utility (Orléan, 2011). Utility is embedded *into* commodities, not to agents' evaluations. Commodities are objectively valuable (Lancaster, 1966, cited in Ibid: 66) and utility is materialized in consumption (Hornborg, 2014). As paradoxical as it may sound, neoclassical economists share with classical economists the naturalistic and ahistorical assumption that value is essentially objective (labor for the former, utility for the latter). Value is a ''substance'' (Orléan, 2011: 47) that can be perceived and measured by economic agents who are: 1) displaying parametric rationality; 2) displaying transitive, exogenous and satiable (convex) preferences and 3) absolutely isolated from other price-taking agents. Although utility cannot be observed per se, its behavioral effects are, via economic agents' willingness to pay to access

[7] Orléan shows the eminently normative nature of neoclassical theory of value with Walras, for whom prices *must* purely reflect agents' preferences without the slightest social interaction between them on the market, regardless of the method's empirical plausibility (Ibid., p. 73). As such, equilibrium prices are a norm, or what they should be, in the absence of path-dependency, positive feedback loop and social interaction.

a commodity. Thus, willingness to pay (behavior) in general are indirect measures of expected utility (O'Neill, in Spash (dir.), 2017).

The neoclassical theory of value assumes decreasing marginal utility of goods, an analogical assumption to the decreasing marginal returns of factors (Pellegris, 2022). As more goods are consumed by an agent, the extra (i. e. marginal) utility derived from consuming the last unit of good declines. From the perspective of the supplier, whose psychology follows the same logic, production involves an increasing dis-utility of the marginal unit of good produced. As elegantly phrased by Prigmaier, value and price emerge from the intersection of decreasing utility of consumption and increasing marginal dis-utility of production (Prigmaier, 2021: 3). Commodities are ordered along a cardinal (how much) rather than ordinal (ranked) scale according to how much utility, or preference satisfaction, they convey (O'Neill, in Spash (dir.) 2017). Cardinality ensures commodities are substitutable.

But then: how come intermediate goods with no utility in and of themselves (such as crude oil, iron, cement, etc.) for the consumers have value? According to Schumpeter, factors and means of production have an indirect utility whereby their use allows the production of commodities (cited in Prigmaier, 2021: 3). Goods of certain values are used by producers to supply the commodities and meet demand. Thus, economic inputs carry utility indirectly.

2.3.1.1 Value and price in neoclassical economics

In Walras' work, prices ensure commensurability between commodities and the utility they carry in an a-historical marketplace where competition, and competition only, dictates price formation. In the logical (rather than historical) marketplace, the medium of exchange used by market actors to exchange commodities is not money, but numéraire, that is a commodity arbitrarily chosen to express relative prices (Orléan, 2011: 31). Indeed, exchange values are not logically predicated upon a mean of exchange since exchange values are just ratios of commodities (Pirgmaier, 2021: 2).

In Walras' work, prices are introduced in the marketplace by the auctioneer who communicates and changes prices following mismatches between supply and demand. Prices however converge over the long term.[8] As prices express the match between the utility-value of the marginal unit consumed and the value of the marginal factors used in production of the marginal goods, prices reflect marginal utility and thus value (Røpke, 1999; Georgescu-Roegen, 1971). This detail is of paramount importance for the neoclassical edifice: prices do not display the total, but marginal utility of goods, i.e. the prices producers accept in exchange with the extra-cost associated with the production of the last unit of a good produced.

Prices are objective insofar as they are communicated by the auctioneer to market agents alone, and not by market agents interacting with each other. When agents agree to pay in exchange for a good, they express their evaluation of utility. Agents' isolation prevents any positive feedback loop and path-dependency[9] patterns to take prices out-of-equilibrium for long periods of time. The negative feedback loops keep prices oscillating close to equilibrium. Negative feedback occurs as preferences are fixed, meaning agents' preferences do not change with the price of goods, as would be the case should utility display increasing returns. Nor can increasing returns to scale in utility arise from mimetic or strategic behavior between actors (Orléan, 2011, 83). In other words: agents treat prices as given instead of something they can change (Daly and Farley, 2010: 100). The model cannot evolve, i. e. change qualitatively towards another institutional arrangement (Georgescu-Roegen, 1971).

When the idealized conditions for the atomistic and frictionless marketplace designed by Walras are met, the logical outcome is a state of equilibrium whereby the ratio of marginal utility (additional utility derived from the consumption of an additional unit of a good) of two goods is perfectly reflected by the ratio of prices of these goods *and* the marginal physical products of the factors required to produce them. This state of maximum utility, referred to by Daly and Farley as the ''basic market equation'', reflects how unfettered markets allegedly allocates maximum utility between market participants without the interference of planning:
Equation 5

$$\frac{P_x}{P_y} = \frac{Mu_x}{Mu_y} = \frac{MPP_{ax}}{Mpp_{ay}}$$

[8] In the 1950s, K. Arrow and G. Debreu thought they had shown general equilibrium exists in at least one market setting whereby one price vector allows each agent to maximize its utility (Orléan, 2011).
[9] "Path-dependency'' describes a situation whereby minor shocks can shift the evolution of a system in a fundamentally different configuration than the original system (Orléan, 2011: 91).

where ‘‘x’’ and ‘‘y’’ are two goods, ‘‘a’’ is a factor of production (assumed to be the only variable factor in the short term), ‘‘Mu’’ means ‘‘marginal utility’’ and ‘‘MPP’’ means ‘’marginal physical product’’, that is the change in output resulting from the change in one unit of input. Any movement away from Equation 5 produces disutility (Daly and Farley, 2010: 131). Therefore, prices reflect value based on utility in equilibrium. It is this view of money as a medium of exchange of value that led Hotelling to state his rule whereby the future prices of non-renewable resources follow the rate of interest. The rate of interest shows the opportunity cost of holding money instead of resources. Agents are fundamentally indifferent between money and resources whose value are both set by the rate of interest:

Equation 6

$$P_t = P_0 e^{it}$$

where ‘i’ is the rate of interest (Hotelling, 1931).

Money is introduced in the model to facilitate exchanges only, providing a unit of account, a mean of exchange and a store of value, therefore circumventing the double-coincidence of needs arising in barter exchanges. Money, being liquid, has a utility of its own: as such, goods pay for goods (Orléan, 2011: 111; Ament, 2019). Equation 5 shows that in equilibrium, the ratio of marginal utility of two commodities is equal to the ratio of their prices and the ratio of the marginal physical product of the variable input used to produce them. Money is introduced as a good and as such, it has a marginal utility. Choosing ‘’y’’ to denote money, then the price of money is unity (the price of one unit of currency is one unit of currency):

Equation 7

$$\frac{Mu_y}{Py} = 1$$

In equilibrium, the marginal utility of x is equal to its price, itself equal to the ratio of marginal utility to the price of good ‘’n’’, which I define as money:

Equation 8

$$\frac{Mu_x}{P_x} = \frac{Mu_n}{P_n}$$

Simplifying:

Equation 9

$$P_x = \frac{Mu_n}{Mu_x}$$

meaning that prices are nothing but ratios of marginal utility. The price of x is at the point where it is equal to the ratio of marginal utility of holding good x or substituting it with good n, which could be money (Daly and Farley, 2010: 138).

2.3.2 The origin of value in ecological and biophysical economics

Several research programs in ecological economics have tried to show how economic value derives, in fine, from nature. However, the field is by no means united over a definition of value. For ecosystems valuation scholars, several forms of value (use-value, option value, existence value, etc.) are derived from nature. Utility is derived from the direct use value of (un-)priced and (un-)marketed ecosystems. Their values can be estimated using contingent valuation methods such as willingness to pay. Ecosystem valuation scholars do not reject the neoclassical theory of value. For socio-ecological economists (Spash (dir.), 2017) however, values are incommensurable whereby for the Credit Theory of Money, money *is* the foundation of value, since there would be no market exchanges on a large-scale without a unit of account to denominate goods and services (Ament, 2019).

My dissertation focuses on the different schools of ecological economics arguing value derives, in fine, from energy, based on the observation that without matter and energy flows, there would be no wealth on Earth. In contemporary ecological economics, this school is known as ‘’Biophysical Economics’’, which views economic activities as means to exploit nature in order to generate wealth (Hall and Klitgaard, 2018: 83). The current subsection emphasizes the differences between historical and contemporary authors in this tradition. However, all of them are united by a core set of assumptions summarised by Hornborg (2014): energy-value theorists share with the Physiocratic and Classical schools of Economics the following intuitions:

1) there must be a factor of production which produces more value than the fraction of output required to maintain it. Energy sources determine the production of surplus, i.e. the difference between output and the portion of output used to support productive capacities (capital investment, wages, etc.)

2) value derives from production. Monetary transactions make possible the (sometimes unequal) transactions of embedded energy, land and flows of matter between social groups (Hornborg, 2014).

3) The material substratum of value comes from nature: human-made capital and labor only increase the rate of exploitation of the nature-based elements that form the biophysical basis of wealth (Hall and Klitgaard, 2018: 83).
4) The value of money (if any) is subsidiary to the value of energy: ‘’*[…] the services energy provides is far more valuable than its monetary cost*.’’ (Ibid., 300)

Based on Orléan’s typology and on Hornborg’s summary, I argue biophysical economists defend a substantive and objective approach to value whereby energy, as a physical reality, is the true basis of value. Ament argues energy-theories of value are similar to neoclassical theories as they are both single-factor theories of value: value is a function of the supply of an objective quantum (2019). As the subsection below will show, the nature of the interactions between value, money and prices varies with authors.

As my dissertation focuses an empirical examination of these interactions, several theories existing in the literature must be reviewed. This subsection introduces four energy-theories of value and how they purport to explain the relationship between energy-based value and prices. It starts with two of the founders of ecological economics, Frederick Soddy and Nicolas Georgescu-Roegen, followed by two contemporary energy theories of value, the neophysiocratic and embodied energy schools.

2.3.2.1 Frederick Soddy: a reductionist theory

2.3.2.1.1 The biophysical basis of value

Nobel Prize laureate in Chemistry Frederick Soddy’s writings on economic theory stems from a radical critique of 1) a monetary and financial order disembedded from the laws of thermodynamics 2) the economic theories pretending to explain capitalism, both neoclassical and Marxist. Despite the close connection between political economy, the science dealing with production of what human needs, and physical reality, Soddy criticized the absence of an appropriate biophysical foundation of economic theory since Adam Smith. Soddy argues that an examination of how wealth is produced logically precedes how it is distributed. His arguments on the production of wealth rest upon the statement of the two laws of thermodynamics. The first law states the relations between heat and work, the conservation of energy and denies the possibility of perpetual motion. Work cannot be performed without an amount of energy supplied. An economy needs low-entropy inputs, entropy being a measure of the quality of energy in its ability to perform work (Daly and Farley, 2010). The second law of thermodynamics shows that energy tends to dissipate into an unavailable form, i.e. heat of the same temperature as the surrounding environment. These two laws constrain the possibilities of life to develop and to sustain itself. *In fine*, life on Earth depends on flows of energy from the Sun, whose flows reflect debits from its mass (nuclear fusion) that are credited on Earth. Plants capture flows of solar energy to grow via photosynthesis, while animals consume their supply of exosomatic energy feeding from the plants or the animals feeding on plants, themselves feeding from the Sun (Soddy, 1926: 37), as emphasized by Podolinsky in the nineteenth century (Kallis, 2018: 53). Differences in value stems from the quantity of work that can be performed by an energy carrier: human labor and fossil fuels do not have the same value because a meter cube of fossil fuel can perform work several times more than one hour of human labor (Kallis, 2018: 54). The main concern of what Soddy terms ‘’national economics’’ is the provision and direction of values, i.e. energy flows that are the pre-requirements enabling human life (Soddy, 1926),

2.3.2.1.2 Value and prices

Soddy’s work on monetary theory was predicated upon a critique of the disembedness of the monetary and financial markets, conventional by nature, with the laws of physics and the predatory nature of the monetary order of his time. The economy involves exchange of money. Money is not a stock, but a bond between agents allowing the transfer of wealth, provided anyone who owns money can purchase physical wealth in exchange with money. When a monetary system is operational, wealth holders owe wealth to owners of money. As shown by the credit theory of money (Ament, 2019), money is not wealth, but a claim to wealth. Its dual nature as a debit for the creditor and a credit by the debtor fundamentally defines it. Money is at the same time a claim (credit) by its owner on wealth possessed by other agents and a debit, a ‘’[...] *generalized claim upon the totality of the community’s present and future wealth*.’’ (Soddy, 1926: 64) In relation to physical wealth, that is a tangible good with a use-value, money is a claim on a quantity of physical wealth owed to the owner of the claim (Ibid., p. 72).

While holding money, an agent temporarily waives his right to own material wealth. As such, currency is the analogous of an IOU at the national level. Whereas debt is, mathematically speaking, a negative quantity, wealth (in its qualitative, substantive and physical sense) is a positive physical quantity. The process of compound interest reflects this metaphysical mismatch between wealth and debt as it leads to infinity:

Equation 10

$$C_i = Pr * ((1 + i)^n - 1)$$

where ‘‘C_i’’ is the total interest accumulated over a time period and ‘‘Pr’. is the principal. But infinity, ‘’[...] *like minus one* [...]’’ is a mathematical quantity, not a physical one. As such, does money have value? Does it merely reflect it?

Wealth that is not owned by its producers and owed to a creditor is defined as ‘’virtual wealth’’. Virtual wealth is the total quantity of wealth the creditor element inside the community can obtain on demand. It is the quantity the community owes. The money supply, or total quantity of money in an area, is the number of units virtual wealth is worth. Money does not measure virtual wealth, but is measured by it (Ibid., p. 140). Its value is subsidiary to its power to acquire wealth. It has no value in and of itself: rather, it *measures* values that are themselves embodied in goods and services, themselves based on energy flows (Kallis, 2018: 55). Whereby virtual wealth is symmetrical to physical wealth (since virtual wealth is a claim on actual or future wealth), the money supply, i.e. the units of account chosen to denominate wealth, is arbitrary. Hall and Klitgaard aptly summarize Soddy’s view on the nature of money when they define it as a lien, as a mediation to the energy flows of the economy (a view defended by Hornborg (2014) as well). The wealth of an individual or nation is defined as the control the person or group has over flows of energy or embodied energy. Fiat money derives its value from the fact that virtually all agents in an economy accept it as a lien on embodied energy and flows (Hall and Klitgaard, 2018: 83, 92).

The quantity of wealth in an economy cannot be rigorously denominated into money, as both belong to sui generis realities. Only virtual wealth can. Paraphrasing Inge Røpke: biophysical values, unlike prices and utility, are not expressed at the margin (1999). Debt is of the realm of mathematics, wealth of physics. Wealth rots when accumulated. It produces work, not leisure, as wealth (in the form of machines, land, etc.) needs human labor to produce flows of services (Soddy, 1926: 87). The linear nature of wealth is emphasized when analyzing it under the light of the second law of thermodynamics. Wealth is the product of useful energy, whose use generates waste heat which cannot be recycled economically. As such, *a*nergy (a minus) cannot be reintroduced into the economic process as exergy (a plus). Wealth production is a unidirectional flow and economics should be about the control of the flows of exergy. Attacking neoclassical economics, Soddy argues utility cannot stand as an objective standard of value because it changes all the time. More wealth diminishes utility on the marginal unit. However, unlike what should be going on in an objective process, utility (as a variable standard) is superimposed upon the physical quantity of wealth so the ‘’value’’ of wealth is determined according to a changing standard (Ibid., 94) Unlike utility, wealth is not created purely out of human will.

The banking system plays a crucial role in making the monetary system operational. When an agent borrows money, he uses the credit attached to its person to obtain a loan, a debit, while the creditor (the bank) owns the debt. Fractional reserve-banking, a book-keeping convention, allows banks to extend credit to a ratio far superior to their monetary reserves. Bankers create money when lending at interest (Lavoie, 2014). A loan is repaid out of the proceeds of wealth-producing processes. As such, the banking system is not the cause, but the result of wealth production (Soddy, 1926: 148). Yet, out of a social convention, it gives its shareholders the power to acquire wealth. As this description suggests, Soddy rephrases Marxian class conflicts where economic history can be interpreted as how social groups get other groups into debt and prevent its repayment to secure a permanent revenue, something an entire community could not do without provoking the collapse of the banking sector. Under capitalism, creditors actively seek to prevent the repayment of debts to live off interest income (Ibid., 123-124). However, the mismatch between the mathematical conventions of money and finance and the physical boundaries of wealth production will inevitably leads to a point of rupture:

[…] *you cannot permanently pit an absurd human convention, such as the spontaneous increment of debt (compound interest), against the natural law of the spontaneous decrement of wealth (entropy)* (Soddy, cited in Kallis, 2018: 58).

2.3.2.2 Georgescu-Roegen: a non-reductionist theory

2.3.2.2.1 The biophysical basis of value

Nicolas Georgescu-Roegen developed what is arguably the most impactful theoretical foundations for ecological and biophysical economics in his 1971 opus magnum, *The Entropy Law and the Economics Process*. For Georgescu-Roegen, economics, in a biophysical sense, is the application of the laws of thermodynamics to systems of production for the preservation of the human species. This definition reflects the ‘’[...] *connection between low entropy and economic value*.’’ (Georgescu-Roegen, 1971: 277). An economy is a system transforming low-entropy inputs into high-entropy output of waste and psychic fulfillment for consumers (Daly and Farley, 2010). Thus, low entropy is a condition for economic value (Georgescu-Roegen, 1971: 277) and thermodynamics is the physics of scarcity and of processes involved in producing utility to meet human needs.

Energy is the physical basis of value and utility is its economic basis. Energy is the condition of value but is not value itself, as economic value could not exist without utility. In this regard, Georgescu-Roegen does not completely dissent from neoclassical economics. What makes something valuable is psychological gratification, a ‘’psychic flux’’ of utility it provides to consumers (Hornborg, 2014). To focus on energy only as the basis of value is to neglect the demand-side factors influencing supply. For example, the qualitative differences in some goods such as the hardness, conductivity, etc. of construction materials influence its utility to humans irrespective of the quantity of entropy generated in their production (Daly and Farley, 2010). Georgescu-Roegen insists different cultures at different historical times have dealt differently with the need to acquire sources of low-entropy. Thus, institutions should not be independent from the study of Economics (1971).

Wealth has two physical sources: stocks of physical resources whose flows of services depend on the intensities of exploitation and funds, whose flow of services are constant, namely solar radiation (Georgescu-Roegen, 1971: 303). Inserting flows of value into a linear throughput framework of the economic process, Georgescu-Roegen argues an economy produces two output flows: 1) physical (waste) and 2) economic (utility). Here ecological and biophysical economics falls into the same problem neoclassical economics faces, to Georgescu-Roegen’s own admission: the intensity of utility cannot be measured in any meaningful sense.

2.3.2.2.2 Value and price

If value is derived from physical flows, how does price emerge? Price and entropy are logically analogous in relation to value: whereby low entropy is the material condition to value, low entropy may exist without value. Likewise, something must have value to be priceable, although something valuable may have no price (Georgescu-Roegen, 1971: 282), such as when a commodity stems from the non-market value of unpaid work of humans or nature. Value is the sum of what makes life enjoyable, i.e. consumption and leisure, minus what makes it disagreeable, work:

Equation 11

$$V = [(u_1 * 1) + u_2 * (1 - du)] - (ju * du)$$

where ‘’V’’ is ‘’value’’, ‘‘u_1’’ is the intensity of utility derived from consumption, ‘‘u_2’’ is the intensity of utility derived from leisure, ‘‘ju’’ the intensity of the disutility derived from work and ‘’du’’ is the duration of the working day.

For Georgescu-Roegen, whenever an object of value is excludable, it can have a price and be exchanged on the market. As such, prices are a ‘’parochial’’ reflection of value as it relates to market income, itself equal to net product (royalties, rate and interest) plus leisure income minus wages (reflecting the disutility of work).

2.3.2.3 The neophysiocratic school

2.3.2.3.1 The biophysical basis of value

Neophysiocrats are scholars arguing *net*-energy is the basis of output and surplus production (Hornborg, 2014). Because economic surplus is a function of net-energy flows, it can be argued net-energy is the ultimate source of value. For the neophysiocrats, the production of surplus in an economy is a function of the difference between energy produced and energy required to produce it. There can be no economic surplus in any meaningful sense without energy surpluses (Pellegris, 2022). The most well-known methodology used to estimate that surplus is energy return on energy invested (EROI) (Murphy et. al., 2011).

An EROI ratio measures the flows of energy produced by an energy-producing system over the energy flows, both direct and indirect, required to produce energy output. An ‘’energy system’’ is defined by its boundaries, that is the nature of the energy inputs and outputs in and out of the system (King and Hall, 2011). The mathematical intuition of an EROI ratio is straightforward:

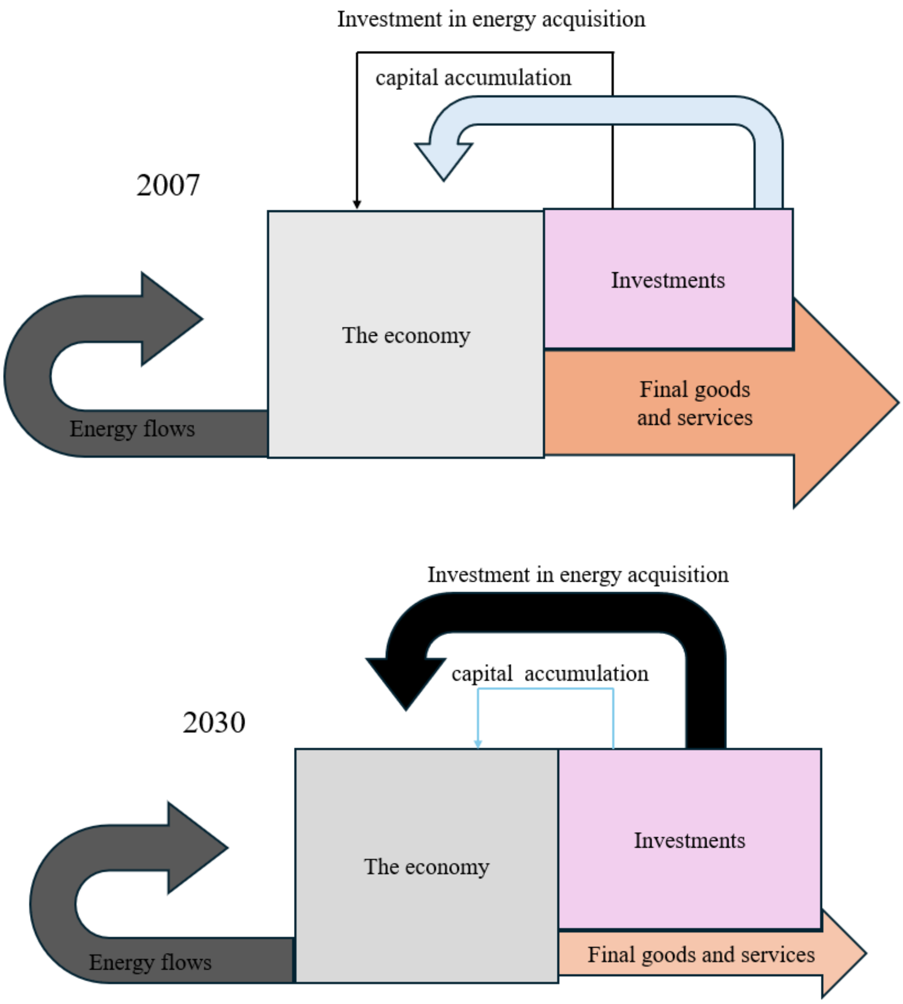
Equation 12

$$EROI = \frac{E_o}{E_i + IND_i}$$

where ‘‘E_o’’ means ‘’flows of energy output’’, ‘’E_i’’ means ‘‘direct flows of energy inputs’’ and ‘’IND_i’’ means ‘‘indirect energy flows’’, corresponding to the energy used in the production of the non-energy goods and services required in the production and maintenance of an energy-production unit. EROI estimations can become quite complex depending on the nature of the boundaries of an energy system. Standard EROI ($EROI_{st}$) measures net energy-flows at the level of extractive facilities (mine's gate), whereas EROI at the point of use ($EROI_{pou}$) estimates the energy costs involved in the production and maintenance of the very infrastructures required to consume energy (roads, airports, etc.) (Murphy et. al., 2011).

The reasoning of the neophysiocrats is that the larger the EROI of energy sources, the larger the flows of net energy to be used by society in discretionary spending (leisure, art, etc.) On the other hand, the lower the EROI, the more energy flows must be diverted into finding and developing new energy sources, maintenance of infrastructures, compensation for capital depreciation, workers' compensation, etc. as illustrated in Figure 1:

Figure 1 Diagrammatic representation of the relationship between net-energy flows and discretionary spending (capital investment and consumption spending)



Source : Hall and Klitgaard, 2018 : 413

2.3.2.3.2 Value and price

Monetary aggregates such as the components of national accounts (consumption, investment, etc.) and economic surplus derive, in fine, from net-energy flows. The relationships can be detected at the aggregate level only. EROI is the ultimate causal factor of output growth as it determines the price of energy and therefore the size of the surplus to be spent on discretionary spending, and thus output (Pellegris, 2022). Therefore, biophysical and monetary indicators are indirectly related via a series of complex interactions, illustrated in Figure 2 should the EROI of common energy sources decline:

Figure 2 Diagrammatic representation of the causal chain from declining EROI to declining monetary output

↓EROI → ↑E$ → ↓ED → ↓I → ↓ GDP

where ‘‘E$’’ is ‘‘energy spending’’, ‘‘ED’’ is ‘‘effective demand’’, ‘‘I’’ is ‘‘investment’’ (see Heun and DeWit, 2011). Declining EROI leads to a rise in the proportion of output spent in energy production therefore lowering the portion of national income available for consumption spending and, in a typically Keynesian fashion, leading business investments to decline. The result of this causal chain is a decline in output (Pellegris, 2022).

For neophysiocrats, money is defined by its function. Energy is the basis of value and money allows the exchange of goods and services produced via energy. Money can be thought simultaneously as an abstraction and a lien, a claim to energy-derived valuable goods (Hall and Klitgaard, 2018; Ament, 2019).

2.3.2.4 The embodied energy school

For the embodied energy school of thought, biophysical and financial indicators are directly related: prices reflect the energy embodied in the production of goods and services. Commodities are ‘’embodied energy’’, the former believed to represent a more objective unit of measure for value provided a joule-measure of energy is invariant with respect to time, does not change with technological breakthrough, etc. (Gilliland, cited in Ament, 2019).

For Odum and Odum, value stems from emergy (embodied energy), that is the energy used to produce a good (Odum, 1976, cited in Hyman, 1980). The relative prices of commodities display the relative quantity of energy embodied in their production. Money flows in a direction opposite from emergy, as payment for emergy-generation. However, as shown by G. Kallis, rent, speculation, the value of artwork and collectibles, etc. fail to be explained by an emergy theory of value (Kallis, 2018: 51).

Using Input-Output tables at the level of the American economy, Costanza (1980) and Costanza and Herendeen (1984) have shown that a strong correlation exists between the dollar value of a sector's output with its direct and indirect energy consumption when including the energy required to sustain labor and government services. The authors regressed dollar output of more than 80 sectors (excluding the primary energy producing sectors) of the economy over the total embodied energy in inputs (in British thermal units/$ of investment), finding the R^2 of their regressions ranging from 0.986 to 0.987 for the years 1963, 1967, 1972, pointing out a strong correlation between energy use and dollar values of goods and services (Costanza, 1980: 1221-1223).

2.3.2.4.1 Energy-deflated price as a feedback mechanism?

Within contemporary biophysical economics, Fix defends an original theory of value where monetary flows act as feedback mechanisms to biophysical flows of energy. This feedback mechanism stems from the circulatory and dynamic nature of money: a sector's monetary output is destined to become another sector's input at a point in the future. Low-entropy natural resources enter the economy and exit as waste, suggesting a linear throughput. However, the circulatory nature of income and expenditures means a circulatory mechanism is involved as well, so that monetary flows in the economy are shown to depend, in fine, from energy flows.

Fix argues that when real monetary output is measured using an energy-based deflator, changes in output are closely related to the productivity of the fossil fuel sector, thus revealing a connection between monetary and biophysical outputs of the economy, the latter embodying flows from the former. A test of this theory first requires estimating the productivity of the fossil fuel production sector f_p. Productivity is estimated by summing the energy value (in joule) of crude oil, natural gas and coal produced annually divided over the sum of hours worked by labor in the fossil-fuel sector:

Equation 13

$$f_p = \frac{\sum_{n=1}^{3} o_j + ng_j + co_j}{L}$$

where ‘o’ denotes flows of crude oil, ‘ng’ denotes flows of natural gas and ‘co’ flows of coal, all in joules. Nominal GDP must then be deflated with a joule-based measure to avoid ambiguities of price indexes (see Section 1.2). Fix argues an appropriate energy deflator is the average price of a joule of energy derived from fossil fuels, which can be found by dividing the flows of joule produced annually by the fossil fuel production sector over its nominal income:

Equation 14

$$AP_j = \frac{\sum_{n=1}^{3} o_\$ + ng_\$ + co_\$}{\sum_{n=1}^{3} o_j + ng_j + co_j}$$

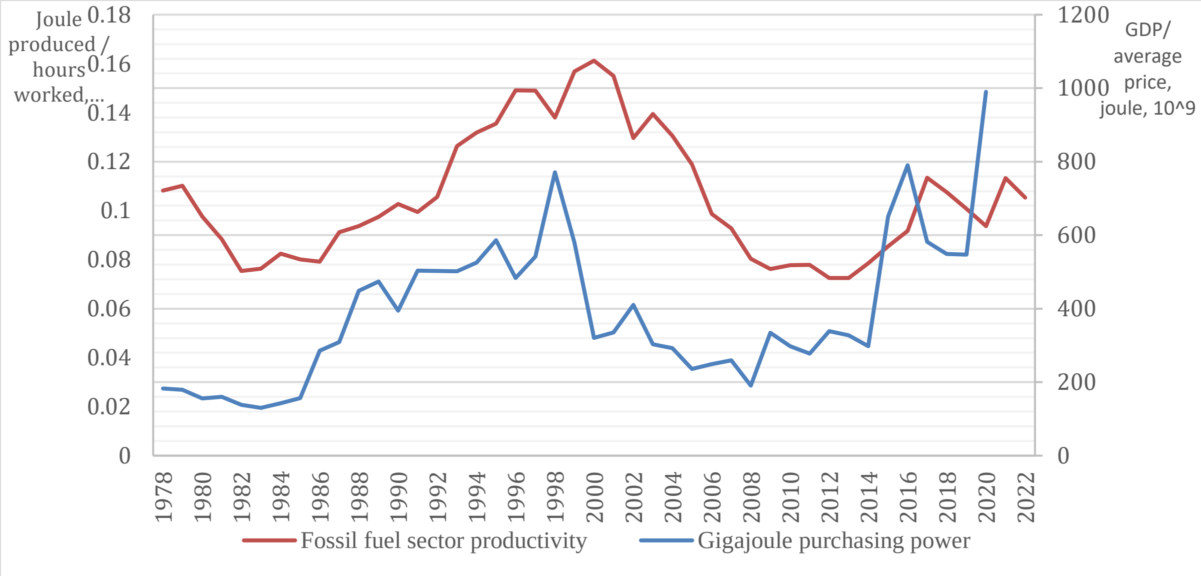
where ‘‘AP_j’’ means ‘’average income per joule’’, found by dividing the sector’s output in units of dollars by the sector’s output in joule. An energy-deflated measure of output can then be found by dividing nominal output over the average price of a joule, providing an energy-deflated measure of output:

Equation 15

$$Y_{jr} = \frac{GDP}{AP_j}$$

where ‘’Y_{jr}’’ means ‘’energy-deflated output’’. An empirical test of Fix’s theory using Canadian data from 1978 to 2022 (a portion of the period covered in the thesis) leads credence to this view. Plotting the energy-deflated output Y_{jr} with the productivity of the fossil fuel sector f_p (measured in joule produced per hours worked) yields two series which seems to suggest a correlation between output production and the productivity of the fossil-fuel sector:

Figure 3 Nominal gross domestic product deflated over energy prices and productivity of the fossil fuel sector



Sources: Statistics Canada, Supply and Demand of primary and secondary energy, in terajoule, Table 25-10-0004-01, Gross Domestic Product at basic prices in current dollars, System of National Accounts by North American Industry Classification, Table 36-10-0394-01, Gross Domestic Product (GDP) at basic prices, by industry, Table 36-10-0401-01

The sudden peak in energy-deflated GDP observed in Figure 3 for the year 2020 is explained by the collapse of the fossil fuel sector's income in 2020 during the world pandemic of Covid-19. Because of the extraordinary circumstances of this period, the observation for 2020 should be considered as an outlier. For 2014, the peak is explained by the collapse of the price of fossil fuel energy in 2014, which shrunk the value of denominator AP_j of Equation 14 for the period 2014-2019 inclusively.

From 1978 to 2019 inclusively, a visual inspection of Figure 3 suggests a correlation between the productivity of the fossil fuel sector and an energy-deflated measure of output. Instead of arguing in favor of a monocausal relationship between energy and monetary output, Fix suggests money acts as a feedback mechanism to fossil fuel production: expanding fossil fuel extraction and refining is predicated upon society's income, itself a function of fossil-fuel energy, a relationship which should be measured and tested using an energy-deflated measure of output.

2.4 Concluding remarks

Based on the literature review on the connections (or lack thereof) between energy and its indicators of quality and monetary indicators, my dissertation will test the correlation and causation between these two sets of indicators. I have found scholars in Ecological Economics to disagree on the nature of the relation between energy, value and monetary indicators, with some scholars finding a direct connection (the Embodied School) between energy-use and monetary indicators, while others believe in a connection between economic output and quality-corrected measures of energy-use (the Neo-physiocratic school). The general, theoretical objective of the dissertation is to determine if quality and non-quality corrected measured of energy provide an explanation for changes in a series of monetary indicators associated with energy sources as such or with output production at the macroeconomic level. The hypotheses discussed in chapter 1 are tested at two different levels. At the level of one specific energy source, I shall examine the correlation between quality corrected measured of energy quality of oil sands production and their prices, costs of production and profitability. At the macroeconomic level, I shall test the same hypothesis but at the macroeconomic level. After the testing is done at these two distinct levels, I will revisit the different theories of value and prices examined in chapter 2 and try to determine whether one of these schools of thought provide a coherent theoretical framework to explain my results. In other words, my dissertation is an empirical contribution to the debates within Ecological Economics on the nature of the relationships between energy and the economy. After testing a series of hypotheses (see chapter 1) on the nature of these relationships, I should be able to address the possibility for the Government of Canada to respect its commitment expressed in the Paris Agreement to reduce its GHG emissions while pursuing the growth of its economy's output. In other words, should I detect a non-trivial, positive correlation between quality and non-quality corrected measures of energy use and monetary indicators such as economic output production, prices, costs of production and profitability of energy sources production, a more factual and critical assessment of the possibility of decoupling (growth of economic output concurrent with a decline in energy use) will be possible.

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PREFACE TO CHAPTER 3

Chapter 2 reviewed the literature in neoclassical and ecological economics on the connections (or lack thereof) between energy-use and monetary (prices, economic output, etc.) With the theoretical context of the discipline now set, chapter 3 starts the empirical section of the dissertation aimed at testing my hypothesis of a statistically significant and positive correlation and causation pathway between quality and non-quality corrected measured of energy and a set of relevant monetary indicators. At first, the hypothesis is tested at the microeconomic level, where the connections (if any) between quality-corrected measured of energy and monetary indicators at the level of one particular energy resource is tested. The first part of the empirical section of my thesis is therefore divided into two, starting in chapter 3 with an estimation of the $EROI_{st}$ ratios of oil sands derived crude extracted via open-pit mining in Alberta from 1997 to 2016. After producing these estimates, I will be able to test the existence of a correlation between these indicators and a set of relevant monetary indicators for oil sands derived crude.

Chapter 3: Estimating the disaggregated standard EROI of Canadian oil sands extracted via open-pit mining, 1997-2016

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Abstract

The Canadian province of Alberta is the main crude oil producer in Canada. Its conventional crude production has declined over the last decades, while production from unconventional sources, i. e. the oil sands, has risen significantly. Two types of crude are produced out of raw oil sands: crude bitumen and synthetic crude. Crude bitumen refers to raw bitumen cleansed from solid particles after extraction on-site which must be diluted with light hydrocarbons (natural gas, condensate, etc.) for shipment via pipelines. 'Diluted bitumen' refers to crude bitumen after blending with light hydrocarbons. Synthetic crude is produced via upgrading (distillation and/or cracking) of crude bitumen, resulting in a crude oil stream nearly identical chemically to conventional crude. Past researchers who estimated the net energy delivered by oil sands-derived crude using the Energy Return on Energy Invested (EROI) as an indicator have either estimated the EROI of one type of crude only or analysed the total EROI of oil sands extracted via both open-pit or in-situ mining. No research has estimated the disaggregated EROI of the two types of crude independently, making a rigorous comparison of the net-energy potentials of the two crude streams difficult. This paper provides disaggregated estimates of the EROI of diluted bitumen and synthetic crude produced via open-pit mining. I find the Standard EROI (EROIST) of diluted bitumen to be 11.6:1 on weighted average from 1997 to 2016 and increasing over time. I find synthetic crude's EROIST to be 4.1:1 on weighted average over the period.

Keywords: EROI, oil sands, net-energy analysis; Biophysical Economics

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3.1 Introduction

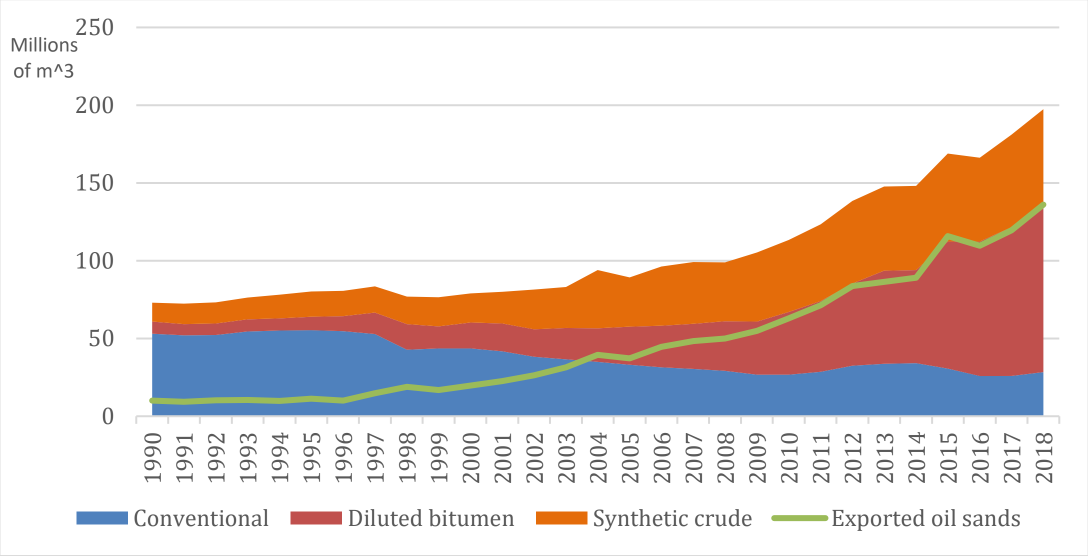
Fossils fuels currently account for 84% of global primary energy consumption (Delannoy et. al., 2021a) with crude oil being the leading source (International Energy Agency, 2020). Energy from crude oil has allowed unprecedented economic growth and improvement in the material standards of living of hundreds of millions of people (Hall and Klitgaard, 2018; Lambert et. al., 2014) during the twentieth century. However, being non-renewable, the future of crude oil extraction is faced with the ongoing depletion of conventional sources[11] (Sorrell, et. al. 2009) and, in theory, their progressive replacement by unconventional sources (shale oil, tar sands, etc.) (Hall et. al., 2009) This shift implies changes in terms of the net quantities of energy societies can expect from crude oil, as unconventional sources tend to deliver less net energy than conventional ones (Delannoy et. al., 2021b).

'Net quantity of energy' means the energy value (in joule) an energy carrier can deliver when the energy costs of producing it are subtracted. Scholars in Biophysical Economics have developed various metrics to estimate net energy production, with the Energy Return on Energy Invested (EROI) now being the most frequently used. Hall et. al. (2009: 2014) argue that a minimum EROI of 3:1 at the level of extraction is the minimum fossil fuels must yield to deliver net energy at the point of use, e. g. to drive a truck: for one unit of energy produced at the point of extraction, about two-thirds is diverted or lost in refining, transport and construction of the infrastructures required to consume it. However, several studies have shown a declining trend in the EROI of crude oil and gas globally and in several countries over the last decades (Cleveland, 2005; Guilford et. al., 2011), meaning the net energy available for non-productive use (education, recreation, etc.) is likely to decline in the future.

The Canadian province of Alberta is an ideal case-study to investigate the net energy potential of unconventional crude oil. Its conventional crude production has declined over the last decades, forcing producers to shift toward unconventional sources, most importantly the oil sands. Located in the Athabasca Valley in Northern Alberta (Canada) (see Figure 4), the oil sands currently are the primary source of crude oil production in the province:

[11] 'Conventional' crude is defined as a source of crude oil or gas flowing to the surface due the reservoir's pressure or with the addition of additional pressures via the injection of water or natural gas into the well. 'Unconventional' crude refers to sources that are mined as solid and converted into liquids at the surface in man-made facilities (Hall and Klitgaard, 2018: 406).

Figure 4 Conventional and disaggregated unconventional crude production and export in Alberta, 1990- 2018



Source: Canadian Association of Petroleum Producers, 2021 and Statistics Canada, 2022b

Two types of crude are produced out of raw oil sands: crude bitumen and synthetic crude (or syncrude) (see Table 1). In nature, bitumen is a solid, asphaltenes-rich hydrocarbon mixed with solid particles of sand and clay. The mining and processing of raw oil sands results in crude bitumen, a heavy, non-marketable crude whose density and sulphur content prohibits transportation via pipeline. Crude bitumen must be diluted with light hydrocarbons (natural gas, condensate, etc.) prior to shipment. After dilution, diluted bitumen can be sold to high-conversion refineries[12] as a sour, heavy crude feedstock. Syncrude is the light sweet crude resulting from the upgrading, i. e. the thermal cracking and hydro-treating of crude bitumen prior to its refining into refined petroleum products (Banerjee, 2012: 22). In the paper, I use the term ‘’crude bitumen’’ to denote bitumen cleansed from solid particles after extraction on-site and prior to shipment. I use ‘‘diluted bitumen’’ to refer to crude bitumen after blending with light hydrocarbons for the purpose of transportation. Table 1 presents a few of the properties of crude and diluted bitumen as well as synthetic crude.

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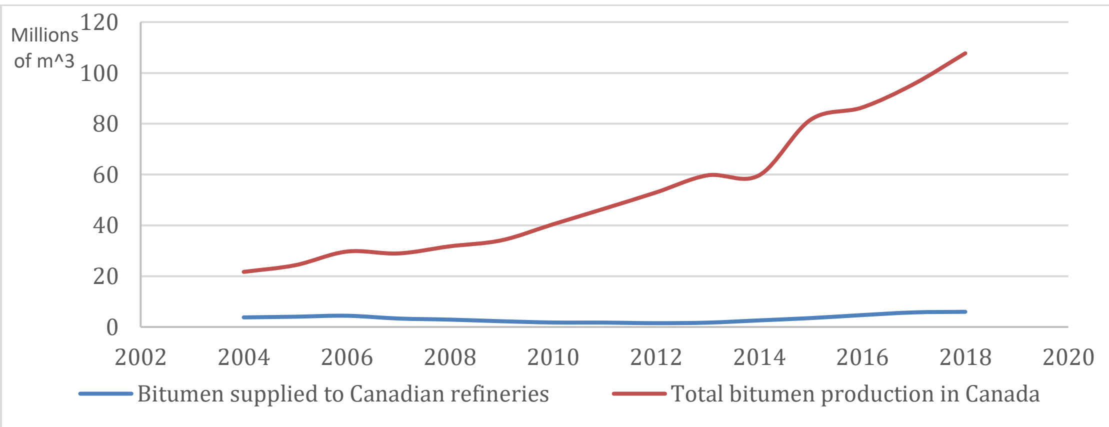
[12] Refineries’ complexities are measured by the ‘’Nelson Complexity Index’’. This index compares refining facilities via a comparison of the costs of their refining equipment. A basic distillation column is given a value of 1. Additional refining facilities (hydrocracking, hydrotreating, etc.) further expands the value of the index (Energy Information Administration, 2012).

Table 1 Raw materials, mode of production and status of oil-sands derived crude in EROI analysis

Crude stream	Raw materials	Mode of extraction/production	Object of EROI estimate
Crude bitumen	Raw oil sands	Open-pit mining (see figure 6)	No
Diluted bitumen	Crude bitumen Diluent (natural gas, condensate, etc.)	Dilution of crude bitumen with light hydrocarbons	Yes
Synthetic crude	Crude bitumen	Bitumen upgrading (see figure 7)	Yes

Whereas the production of diluted bitumen and syncrude were roughly equal until the early 2010s, diluted bitumen's production now dominates. The surge occurred at the same time as the shale oil revolution in the United States. With the growing supply of tight oil from the Midwest, many refineries in the United States Midwest expanded their refining capacity of heavy crude and increased their imports of Canadian heavy oil (Pickren, 2019). In 2018, more than 95% of diluted bitumen produced in Canada was exported to the United States:

Figure 5 Total diluted bitumen production in Canada and diluted bitumen supplied to Canadian refineries (in millions of m^3), 2004-2018



Source: Canadian Association of Petroleum Producers, 2021, Statistics Canada, 2022b.

The literature investigating the net-energy analysis of oil sands is scant. Of the few studies available, the scopes are limited to net-energy of one type of crude only or aggregated estimate of the total (diluted bitumen and syncrude) net-energy produced via both open-pit and in-situ mining. To my knowledge, comparison of the disaggregated net-energy obtained from diluted bitumen and syncrude via the same mining method has not been conducted. Open-pit and in-situ mining involve different levels of capital expenditures, output of crude bitumen per extraction site, etc., all of which influence net-energy ratios. I argue that a rigorous comparison of the two crude streams' net-energy ratios requires a comparison when extracted from the same mining method.

The research question motivating this paper is: how diluted bitumen compares to synthetic crude on a net-energy basis at the mine's gate? My paper focuses on a comparison of the net-energy ratios of the two crude streams produced via one mining method only. Doing so avoids comparing varying levels of inputs (technologies, capital investment, labor, etc.) involved in different mining methods which may influence the estimated EROI of the energy carrier. This methodology ensures the boundaries of analysis of the production of the two crude streams are the same, making the results more directly comparable. Thus, this paper estimates the EROI of diluted bitumen and synthetic crude resulting from the upgrading of crude bitumen extracted via open-pit mining only.

This paper examines the net-energy ratio of diluted, not crude bitumen. Net-energy analysis involves an estimation of the energy value of an energy carrier when delivered to society. The physical and chemical characteristics of crude bitumen makes it non-transportable. Therefore, my research estimates energy output derived from diluted bitumen, the transportable crude stream exported to refining facilities. Because the paper investigates the EROI of syncrude produced from crude bitumen extracted on-site, thus excluding upgrading facilities importing diluted bitumen feedstock from off-site, I am referring to 'crude (non-diluted) bitumen upgraded on-site' when analyzing syncrude production.

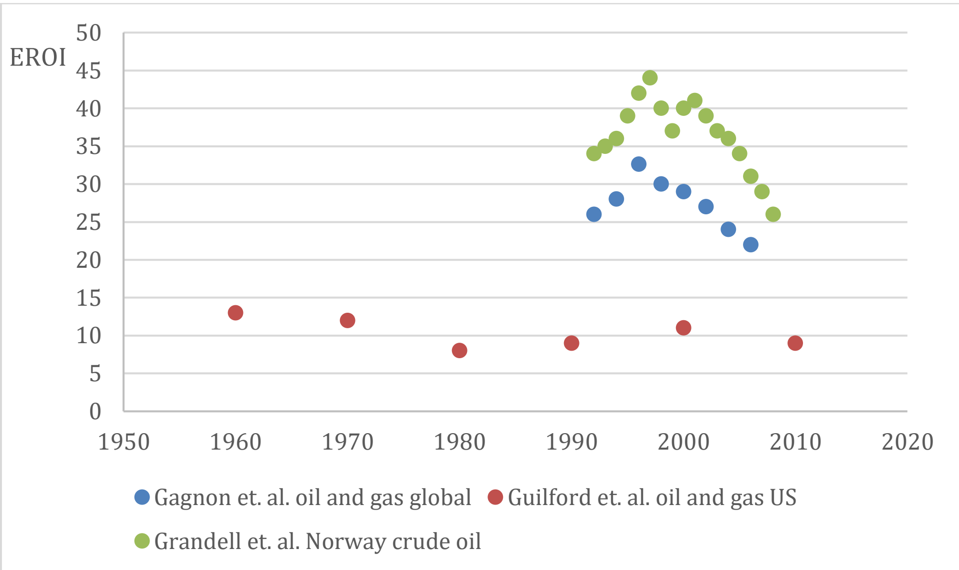
This paper provides an estimation of the EROI of Canadian mined diluted bitumen and synthetic crude extracted via open-pit mining from 1997 to 2016 in Alberta, Canada and is divided as follows. The year range is motivated by data availability. Before 1997, publicly available Supply-and-Use tables (see Section 3.5) of the Canadian economy do not show disaggregated data for the crude oil extraction sector, but for the extractive sector as a whole 'Mining and oil and gas extraction' (2022c). Furthermore, Supply-and-Use tables of the Canadian economy provide disaggregated data for the unconventional oil extraction sector for

2009-2016 only. I first review the literature on EROI in Biophysical Economics followed by a technical background on the different types of crude produced out of the oil sands and mining methods. I introduce the methodology developed to answer my research question as well as the sources of data used. After, the results are presented, followed by a discussion of what I view as my research merits, its limitations, areas of future research and a general discussion on future research avenues.

3.2 Literature review

There is a burgeoning literature in Biophysical Economics on net-energy analysis. Many studies have shown a declining trend in the EROI of oil and gas. Hall et. al. (2014) and Lambert et. al (2014) examine the implications of a declining EROI on the ability for complex economies to maintain themselves or expand. The authors show that with a growing portion of economies' output to be reinvested in energy production, the discretionary energy and monetary expenditures in areas such as leisure, education and arts are likely to contract in the future, implying a simplification of the economy. At the world level, Court and Fizaine (2017) estimate the peak EROI of global crude oil extraction was reached in the 1930s at around 50:1 and has steadily declined ever since.

Figure 6 Estimates of EROI for crude oil produced in the United States, Norway and globally, 1900-2010



Source: Grandell et. al., 2011; Guilford et. al., 2011; Gagnon et. al., 2009

Gagnon et. al. (2009) estimate the worldwide EROI of oil and gas extraction has peaked in 1999 at 35:1 and declined to 20:1 in 2006. Guilford et. al. (2011) estimate the EROI of U.S. domestic oil and gas decreased from 25:1 in the 1970s to 10 :1 in 2007. Cleveland confirms this trend. He estimates the EROI of crude oil discovery and extraction in the United States was at least 100:1 during the 1930s, corresponding to a historical peak in the discovery of large oil fields. In the mid-1970s, the EROI declined at ~25:1 and at ~20:1 in the 2000s (Cleveland, 2005). A similar declining trend in the EROI of fossil fuel extraction was observed in Norway (Grandell et. al., 2011) and China (Hu et. al., 2013). Hall and Klitgaard (2018) report the original work of Guilford et. al. showing the EROI ratio of crude oil and gas discovery in the United Stated decreased to less than 5:1 in the 2010s.

In a study on the difference between primary EROI at the point of extraction (or mine-mouth) and at the point where energy sources enter the economy (point of use), Brockway et. al. show that insufficient data on the EROI of fossil fuels at the point of use lead to overestimates of fossil fuels' net energy potential. Using data from the International Energy Agency from 1995 to 2011, they estimated the EROI of fossil fuels at the point of extraction to be ~30:1 and EROI at the point of use to be ~ 6:1, both declining across the period of study (2019). Their estimates of EROI at the point of use put fossil fuels net-energy ratio close to modern renewables (photovoltaics, wind, etc.) In a study showing the need for EROI estimates at the national level incorporating estimates of energy embodied in the international trade of goods and services, Brand-Correa et. al. develops an input-output based methodology to estimate a national EROI at the level of the United Kingdom from 1997 to 2012. They find the national EROI to have fluctuated from 12.7:1 in 1997 to a peak 13.8:1 in 2000 before falling to 5.6:1 in 2012 (2017: 10).

Studies on the EROI of Canadian fossil fuels are more recent. To my knowledge, the first paper is by Freise, who shows a declining trend in the net-energy of conventional oil and gas in Canada. Whereas the EROI of exploring, drilling, gathering and separating oil and natural gas is estimated to have reached a peak of 80:1 in the 1970s, it dropped precipitously to 22:1 in 1980 and 15:1 in 2006 (Freise, 2011). In terms of oil sands specifically, the first estimate on the EROI of oil sands is Rapier, who estimated the ratio at 3.9:1 in 2008. A more complete estimation, encompassing both diluted bitumen[13] and syncrude extracted via in-situ and open-pit mining was produced by Brandt et. al. (2013). Unlike for conventional crudes, the authors observe an upward trend in the net-energy of oil sands-derived crude, explained by improvements in mining technologies since the early 2000s, such as in froth treatment (separation of raw oil sands into crude bitumen and solid particles). They show the EROI of the two crudes streams to have risen from 4:1 in the 1970s to 7:1 in 2010 at the point of extraction (Brandt et. al., 2013).

Poisson and Hall (2013) estimated the EROI of synthetic crude extraction between 1994 and 2008 to fluctuate around a ratio of 4:1, in comparison with a range from 11:1 to 16:1 for conventional oil and gas during the same period. The authors excluded both diluted bitumen production as well as in-situ mining from their analysis (2013) due to data limitations. Like Brandt. et. al., Wang, et. al., (2017) estimated the EROI of both crude streams disaggregated by the mining method. Their estimates range from 3.2:1 to 5.4:1 for crude produced via in-situ and from 3.9:1 to 8:1 for open-pit mining from 2009 to 2015. Using a firm-based methodology to estimate correlations between EROI and return on equity, Wang et. al. (2019) estimate the EROI of diluted bitumen and syncrude extraction at the mine-mouth by four companies to range from 3.5:1 to 6.5:1 and rising over time between 2010-2016.

The literature reviewed shows the need for the disaggregated estimate of both crude streams potential to deliver net-energy to society when extracted via the same mining method. Such an analysis is required to rigorously compare the crudes' varied energy potentials. The following sections undertake that task.

3.3 The Canadian oil sands: an overview

Oil sands are located in the Western Canadian Sedimentary Basin in Northern Alberta, covering an area of 142,000 km^2 under the boreal forest. Oil sands are currently estimated to represent 166.3 billion barrels of proven reserves, approximately 97% of total crude oil reserves in Canada.

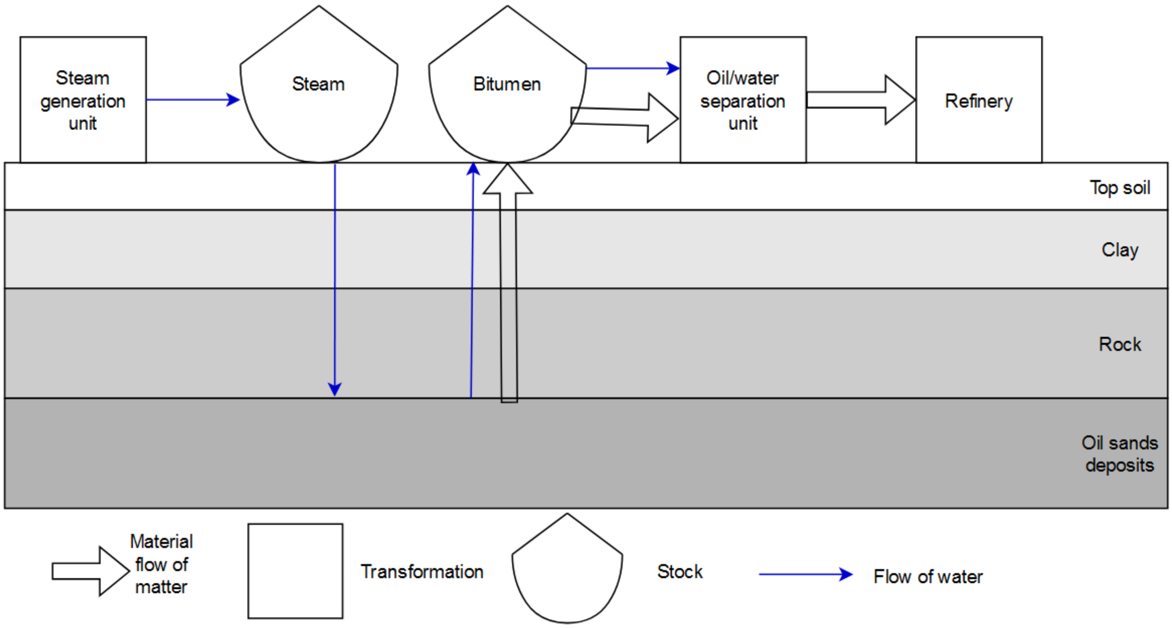
Figure 7 Location of the oil sands deposits in Canada

[13] All the authors reviewed in this section use the unspecified expression 'bitumen' to refer to both crude and diluted bitumen in their work.

Source: Natural Resource Canada, 2016b

Two methods exist to mine the sands: open-pit and in-situ mining. In 2019, they each represented roughly 50% of total raw bitumen extraction. In 2020, there were 10 active open-pit mines in Alberta and 161 in- situ sites (Oil Sands Magazine, 2020a, 2021; Alberta Energy Regulator, 2021a). The share of in-situ mining is expected to rise in the future: it is estimated that 20% of total raw bitumen reserves can be recovered via open-pit mining and 80% via in-situ mining. Open-pit mining is performed when the sands deposits are found at less than 75 meters below the surface (Natural Resource Canada, 2016a). When the overburden is deeper, extraction is executed through in-situ mining, involving the injection of steam at high-pressure in the deep and solid oil sands deposits. As the deposits liquefy, they are pumped to the surface.

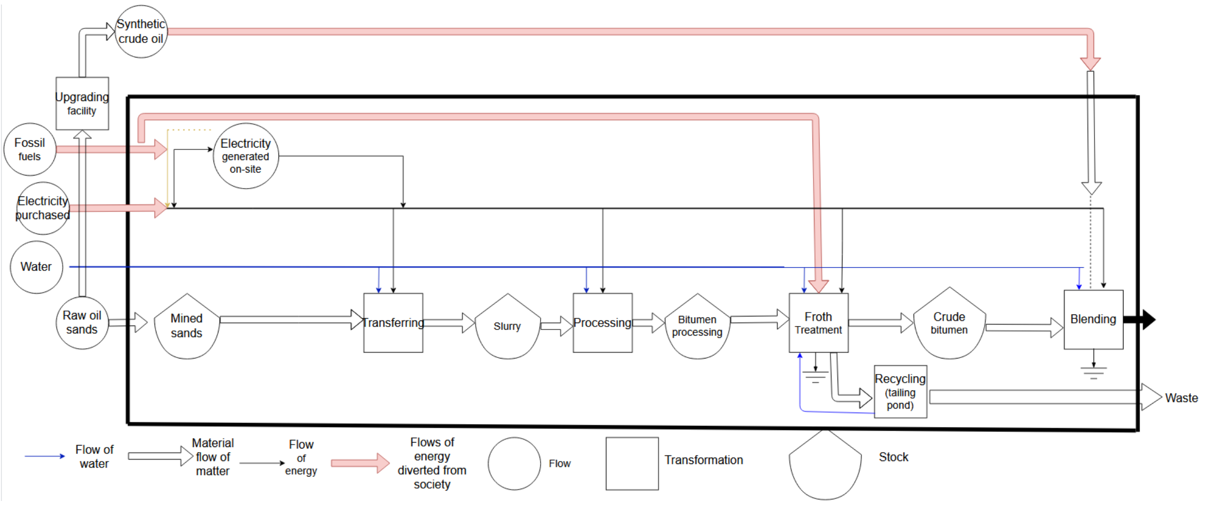
Figure 8 Flow diagram of in-situ mining



Source: Oil Sands Magazine, 2020a

Open-pit mining involves the cleaning of raw bitumen and fluidification of crude bitumen. First, the land covering the raw oil sands is mechanically removed. Then, the raw sand is transferred to installations where the masses of earth, clay, sand, and raw bitumen are crushed and washed with water. After, the sand is pumped to processing units where the solid elements are separated from the raw bitumen by gravity (Oil Sands Magazine, 2021b). The bitumen slurry is transported with water via slurry pipelines into an extraction unit where bitumen is processed into bitumen froth. Crude bitumen is the product of froth treatment.

Figure 9 Flow diagram of a generic open-pit mining facility



Source: Oil Sands Magazine, 2021a

Crude bitumen is too thick to be pumped via pipeline, with an average API[14] of 10 and corrosivity (a function of sulphur content) that can be as high as 5% (Oil Sands Magazine, 2020b). It must be diluted with lighter hydrocarbons (condensate, natural gas or naphtha) to be fluid enough for shipment to refineries through pipelines. After dilution, crude bitumen becomes diluted bitumen. If not transported to a refining facility, crude bitumen can be upgraded into syncrude, whereby it is transformed into a product physically and chemically very close to conventional crude (Oil Sands Magazine, 2020a). Upgrading is performed in two steps. Primary upgrading increases the ratio of hydrogen to carbon of bitumen molecules, either through coking or hydroconversion via distillation and/or cracking, i. e. breaking the chains of hydrocarbon into lighter chains by submitting crude to intense heat. Secondary upgrading is achieved by hydrotreating, a catalytic process performed with the addition of hydrogen to the hydrocarbon in the presence of a catalyst, using natural gas to generate heat and hydrogen. Syncrude can be sold to simple refineries (see note 11). Whilst certain mining facilities upgrade crude bitumen on-site (Suncor, Mildred Lake, etc.) others ship diluted bitumen to upgrading facilities off-site (Alberta energy Regulator, 2021b).

Figure 10 Flow diagram of a generic crude bitumen upgrading facility

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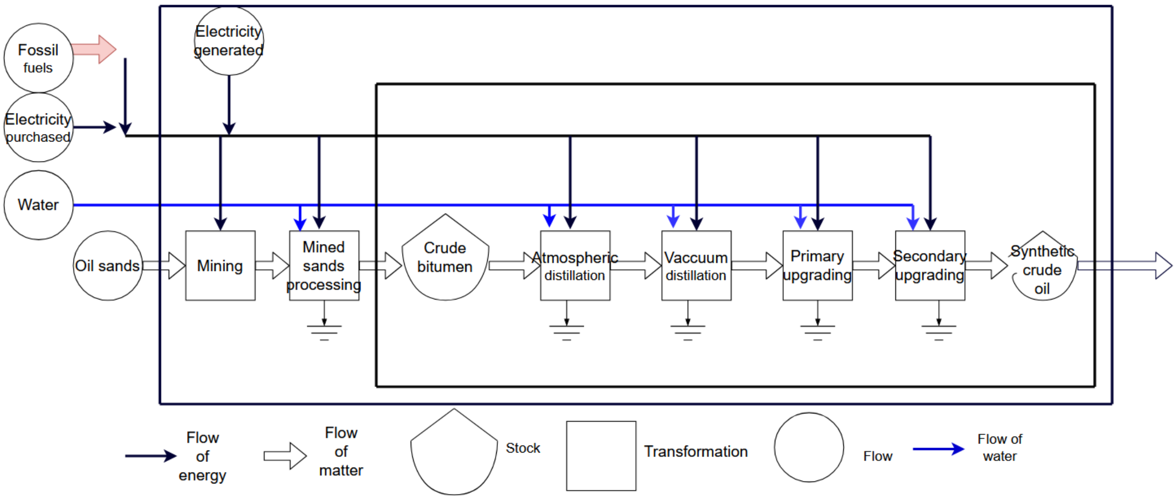
[14] ‘’API gravity’’ is a scale expressing the density of crude and petroleum products. The higher the API gravity, the lighter is the product or source of crude. Conventionally, crudes with an API of 22 or below are defined as ‘’heavy’’ (EIA).



Source: Oil Sands Magazine, 2020c

3.4 Methods and data

3.4.1 Methodology: Protocol to determine standard EROI

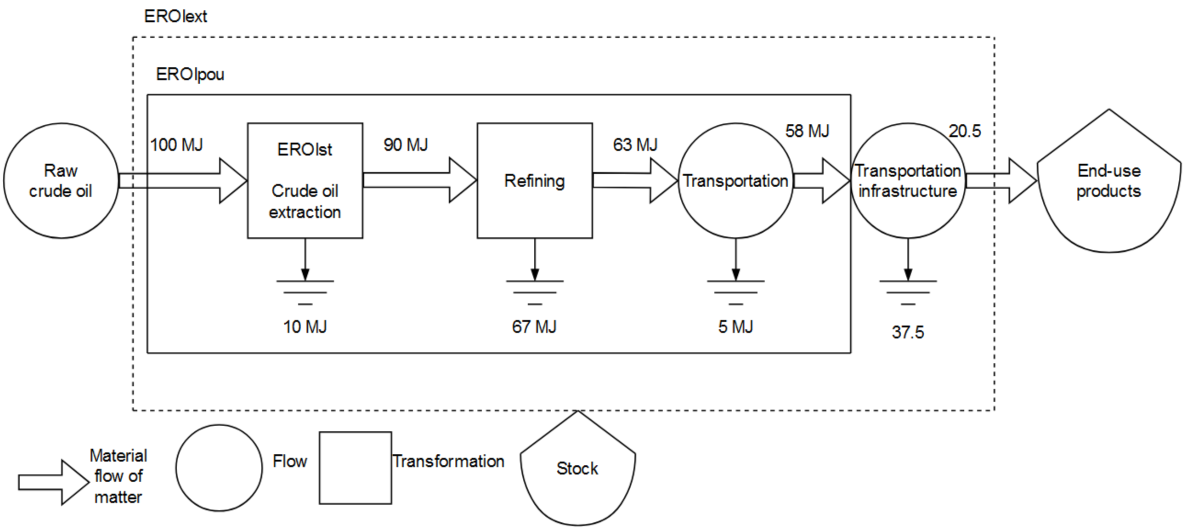
EROI is a ratio between energy produced, or output (numerator) and energy required to produce it, or input (denominator):

Equation 16

$$EROI = \frac{E_o}{E_i}$$

where ''E_o'' stands for ''energy output to society'' and ''E_i'' stands for ''energy input for that process'', both in the same units, normally joule. EROI is a measure of energy quality, that is the ability of a unit (joule) of energy to generate net energy. When energy output is divided by the energy inputs required to produce it, one can speak of net-energy flows. The higher the EROI ratio, the more an energy source produces net-energy flows. When EROI exceeds 1:1, one can speak of an energy source whilst a ratio inferior to 1:1 indicates an energy sink. Because of energy loss in the transport and refining process, the EROI an energy source must yield at the point of extraction must be higher than 1:1 to be an energy source for society (Hall et. al., 2014). Considerable variations exist in the EROI values of fossil fuels depending on quality correction, the intrinsic quality of the fuel in nature (its usefulness, such as electricity being more useful from an economic standpoint than an equivalent quantity of chemical energy (Lambert et. al., 2014)) or the boundaries of analysis adopted (discussed in Murphy et. al. (2011). ''Boundaries'' refer to the choice of the groups of inputs to be accounted for in the denominator of 16, depending on the segments of the supply-chain included (extraction, refining, distribution, etc.) Standard EROI ($EROI_{st}$ in Figure 11 and henceforth) measures the inputs and outputs of energy carriers leaving extraction facilities (well-head or at the ''mine-mouth''), i.e. when directly extracted from nature, as with a coal mine, a crude oil well, etc. It is the measure most appropriate for this paper dealing with oil sands net-energy at the mine's gate.

Figure 11 Boundaries in EROI analysis



Source: Hall et. al., 2014: 142

Two kinds of inputs are considered when estimating $EROI_{st}$: energy (natural gas, electricity, etc.) used directly on site plus the energy required to produce the goods and services (steel and concrete, financial and transportation services enabling production, etc.) used on-site but produced elsewhere in the economy, what I refer to as ''off-site''. In oil sands mining, direct inputs can be used to generate heat or for further processing, such as natural gas used for electricity generation (Canada Energy Regulator, 2021). The heat value of direct inputs must be estimated when entering the boundary of a mining facility.

Two sources of inputs are thus accounted for in the denominator of an EROI ratio:

Equation 17

$$EROI_{st} = \frac{E_o}{E_i + IND_i}$$

Several methods exist to quantify the energy embodied in inputs. Process analysis is akin to a ‘‘bottom- up’’ approach where the energy values of different production stages are first estimated separately and then aggregated. Input-output analysis converts economic input-output tables into sector-specific energy values averages (Murphy et. al., 2011: 1891). Hybrid analysis combine both. Such analysis is useful when data available are incomplete. In hybrid analysis, the energy value of direct inputs can be estimated using process analysis whilst the embodied energy of indirect inputs is estimated by multiplying monetary expenditures in indirect inputs by the average embodied energy per dollar spent in the production of these inputs across the economy, using input-output analysis (Moeller and Murphy, 2016). When data available does not allow for the use of these methodologies, Input-Output based hybrid analysis can be used, where the estimation of the energy content of direct and indirect inputs is done using input-output analysis, although the model can be disaggregated for the parts of the process for which process data are available (Crawford, 2008: 498).

My paper uses hybrid analysis. I use process analysis to convert publicly available data on direct energy input and output from volume into energy units for each open-pit mine in Alberta from 1997 to 2016. I estimate the embodied energy of upstream indirect inputs by converting monetary expenditures into energy values using Supply-and-Use Tables from Statistics Canada. I then estimate total energy inputs by summing the heat value of direct and indirect energy inputs. Supply-and-use tables are aggregation at the level of macroeconomic sectors regrouping heterogeneous sub-sectors, such as different mining methods in oil and gas extraction. Therefore, following Suh et. al. (2004), further disaggregation is required to capture the indirect inputs used in oil sands open-pit mining specifically. Finally, provided the inherent uncertainty in net-energy analysis, the results on the $EROI_{st}$ ratio of oil-sands derived crude extracted via open-pit mining reported below have been rounded to the nearest-tenth.[15]

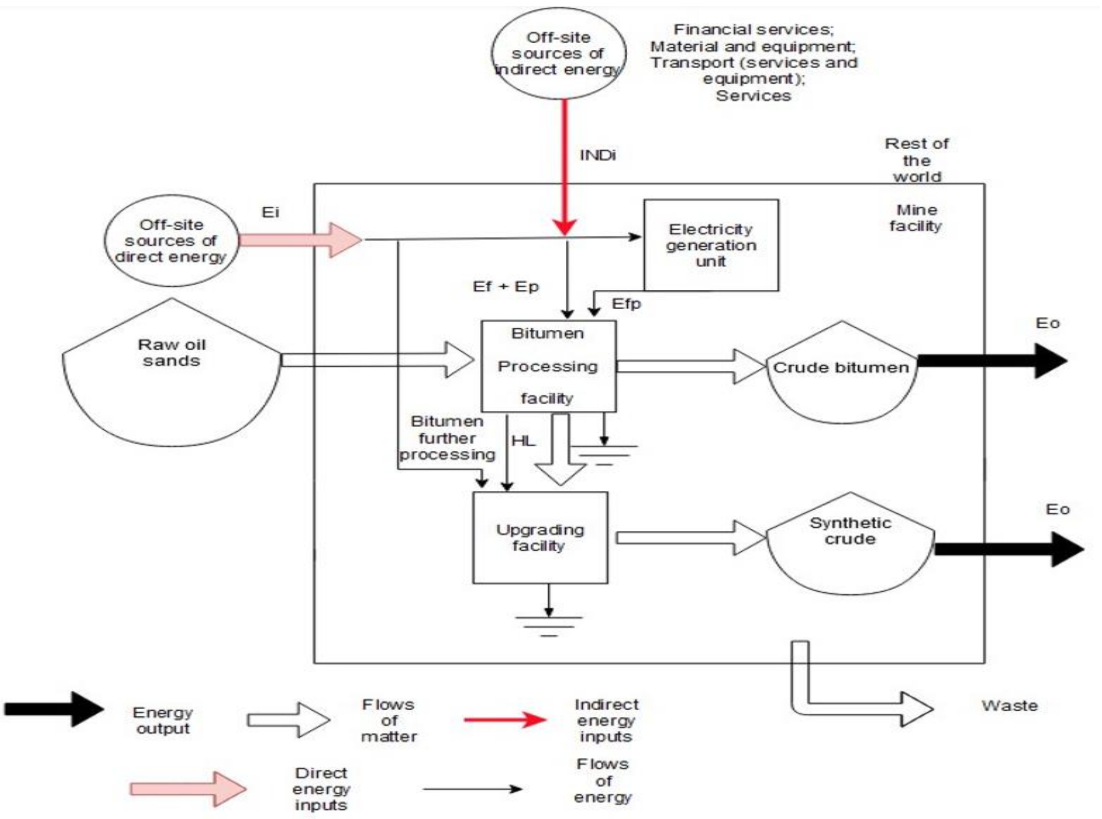
The next section presents the conceptual model developed to determine the boundaries of my analysis of mining facilities, the sources of data and the assumptions used to estimate critical information when unavailable from public datasets.

[15] The author is grateful to the reviewer who advised me to be mindful of uncertainties in EROI analysis.

3.4.2 Boundaries of analysis: a conceptual model of oil sands mines

In this section, I define the boundaries of analysis used to estimate the $EROI_{st}$ of oil sands mining at the mine-mouth. Energy outputs of the systems are defined as the flows of fossil fuels and electricity leaving the mining/upgrading facilities (full back arrows in Figure 12). I define the inputs as the direct energy flows plus the embodied energy of indirect inputs consumed in the mine and upgrading facilities (full pink and thin red arrow respectively in Figure 12). These boundaries reflect the real-world flows of energy involved in 1) raw bitumen mining and 2) mining plus upgrading facilities. I do not include upgrading facilities importing diluted bitumen from off-site. The upgrading facilities analyzed in this paper (Suncor, Syncrude Mildred Lake and CNRL Horizon) all upgrade crude bitumen mined on-site. Figure 15 is a material and energy flow diagram modeling the boundaries defined:

Figure 12 Material and energy flow diagram of an oil sands mining facility



I estimate the aggregate energy values of direct inputs and outputs of all open-pit mines in Alberta by summing their individual values for each mine, resulting in the energy values of the ‘‘open-pit mining’’ sector as whole.[16]

Estimating the energy value of indirect inputs cannot be performed at the mine’s level. No data on purchases of material or financial services per mine (to my knowledge) exist. I conduct an estimation of the energy value of indirect inputs at the scale of the oil sands sector as a whole and then a disaggregation for the share of energy value for indirect inputs used in open-pit mining.

3.5 Data

This sub-section presents the data used to estimate the energy values of the output, direct and indirect inputs in open-pit mining using governmental statistical agencies data only. EROI values are best estimated when analysts can use government data (Hall et. al., 2014) as these data sets tend to be more consistent and vetted by professionals (Peter Victor, personal communication).

3.5.1 Energy output

I used the Alberta Energy regulator (2021b) Statistical Reports #39 (ST-39 hereafter) to estimate the energy values of the mines’ output. These reports contain data on the monthly and annual stocks and flows of fossil fuel in volume units (m^3)[17] and electricity (in MWh) delivered to and out of mines in Alberta. ST-39 uses two categories to report output: ‘’deliveries’’ refers to flows exiting the site and ‘’production’’ refers to fossil fuel produced by mines that can be further used on-site as inputs in production, such as crude bitumen mined and diluted with syncrude before shipping.[18] I use the category ‘’deliveries’’ as the mines’ output. Because mining facilities deliver other fossil fuels used in crude bitumen dilution (natural gas, naphtha, etc.), these deliveries were incorporated into the mines’ outputs (following Wang et. al., 2019).

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[16] Data on direct energy inputs are more ventilated for open-pit mining than for in-situ mining. The Alberta Energy Regulator (AER) provides data on natural gas (in m^3) and electricity (MWh) purchased and generated on-site via natural gas and consumed by each open-pit mine, whereas reports on in-situ facilities provide data on steam production and injection rate (in m^3/day) only (AER, 2020-2021a) for hundreds of facilities.

[17] By convention, in Canada, 1 m^3 is 6.2898 barrels (Canada Energy Regulator, 2016).

[18] The definitions were provided to the authors in a private e-mail from the AER and are available upon request.

The $EROI_{st}$ of diluted bitumen therefore incorporates the energy value of the fossil fuels crude bitumen is blended with in the ‘’output’’ category.

3.5.2 Direct energy input

I use data from ST-39 to estimate the heat value of direct energy inputs. The reports identify three possible uses of energy carriers in open-pit mining: 1) further processing (product undergoing additional processing on-site); 2) delivered (exiting the mine’s gate); 3) fuel and plant use (used on-site for other purpose than fuel, for example synthetic crude used in blending). On the origin of inputs, they are reported as either 4) produced on-site or 5) imported from off-site.

In selecting the categories accounting for energy inputs, I seek to avoid double-counting as, for instance, with a fuel delivered on-site and stored to be used as an energy source later. Following Wang et. al. (2019), I account for direct energy inputs when reported as being used as energy or for processing on site but received from off-site. Three categories of uses for direct inputs were accounted for: inputs used as 1) fuel; 2) plant use and 3) further processing. Following this logic, when a mine reported imported natural gas undergoing further processing such as electricity generation, I used the heat value of natural gas to convert volume units into heat to account for the calorific value of this direct input. Equation 18 represents how I calculate the energy value of direct inputs of mining using the categories of the Alberta Energy Regulator (AER):

Equation 18

$$E_i = E_f + E_p + E_{fp}$$

where ‘’E_f‘’ stands for ‘’energy used as fuel’’, ‘’E_p‘’ stands for ‘’energy used as plant use’’ and ‘’E_{fp}’’ stands for ‘’energy further processed from off site’’, reflecting the categories used in the AER’s reports.

To estimate the chemical energy of direct outputs and inputs, I report the volume of energy carriers identified in Equation 18 and convert them into joules. Table 2 presents the conversion factors used. Following Delannoy et. al. (2021a: 5), I assume the conversion factors to be constant across the period covered in this study.

Table 2 Conversion factors to convert volumetric units of fossil fuel and electricity to energy values

Name of the fuel and unit of measure	Energy density
Crude bitumen (in m^3)	42.80 GJ/m^3
Synthetic crude oil (in m^3)	39.40 GJ/m^3
Natural gas (in 10^3 m^3)	37.39 $GJ/10^3$ m^3
Naphtha (in 10^3 m^3)	35.17$GJ/10^3$ m^3
Coke (in tons)	29 GJ/ton
Electricity (in MWh)	3.6 GJ/MWh

Source: Canada Energy Regulator, 2016; Statistics Canada, 2005 and Alberta Energy Regulator, Statistical Report #98; 2021c

Dealing with electricity as a direct energy input (purchased from the grid) and output (surplus sold) requires adjusting its heat equivalent to account for electricity's superior quality over fossil fuels. Its superior quality stems from the fact that it is cleaner and can produce more economic work per joule than fossil fuels. Thus, a joule of electricity is not perfectly substitutable with a joule generated by fossil fuels (Murphy, et. al., 2011). To obtain an adjustment factor, I follow Turvey and Nobay's (cited in Cleveland et. al., 2000) price-based approach and define the equivalence factor of electricity λ as the ratio of the price of a joule of electricity divided by the price of a joule of an alternative energy carrier:

Equation 19

$$\lambda_i = \frac{P_{it}}{P_{1t}}$$

where ''λ_i'' is the equivalence factor for electricity i, ''P_i'' is the price of electricity in monetary units per joule in time period t and P_{1t} is the price of an alternative source of fuel 1 in time period t. The equivalence is based on the neoclassical assumption that the price per heat equivalent reflects an energy carrier's marginal product (the change in economic output following a change in the use of an energy carrier as an input) and economic usefulness. Because λ_i reflects what buyers of 1 joule of electricity are willing to pay vis-à-vis 1 joule of fuel 1, it is supposed to reflect its enhanced quality. This approach is by no mean perfect as it assumes that the different energy carriers it compares are substitutes whereas in reality, a change in the price of fuel P_i relative to output will probably not result in an equivalent change in the price of fuel P_1 relative to output (Cleveland et. al., 2000).

To construct the factor, I used the price (in $/MWh) charged by ATCO Electric to its oil and gas consumers. I chose Atco Electric because of its extensive network of oil and gas consumers (Alberta Utilities Commission, private communication). Monthly prices are available from 2006 to 2016 via the Alberta Utilities Commission (2022). For years prior to 2006, I multiplied the average price in 2006 by the percentage change in the price index of electricity (year under study and 2006) for non-residential customers (Statistics Canada, 2022a). Finally, the price was divided by its heat equivalent to obtain a price per joule. The factor is 1.80 on average between 1997 and 2016.

3.5.3 Indirect inputs

A thorough analysis of energy embodied in indirect inputs requires data on the energy spent in the production of these inputs. An important issue to address is boundaries, such as whether to include in the estimates the energy required in the construction of the infrastructures to produce inputs. Ideally, such issues are dealt with using Input-Output (I-O) analysis (Miller and Blair, 2009). When energy use estimates are not available, monetary expenditures on inputs can be used when one knows the energy intensity of the sector of the economy these inputs come from. I use a three-steps methodology involving the extensive use of two sources of data: the Supply and Use Tables and Physical-flow accounts, both generated by Statistics Canada.

Supply and Use Tables represent monetary flows among sectors of the economy and are derived from I-O analysis. They differ from standard I-O analysis which is commodities-based. Supply and Use Tables represent the economy as a matrix flows of monetary expenditures by sectors, forming sets of symmetric tables where the ‘’use’’ tables illustrate the purchase of goods and services as inputs by different sectors (Statistics Canada, 2021a; Miller and Blair, 2009). They divide the economy into sectors/columns with rows dividing the economy into sources of inputs (goods and services). Each box represents the monetary expenditure in one sector for the purchase of the input identified in the row.

Over 150 indirect inputs were consumed consistently by the oil sands production sector from 2009 to 2016, i. e. the period during which oil sands extraction is represented in the Tables. I used these recurrent indirect inputs in my estimates and regroup them into four categories of goods and services: 1) Material & Equipment; 2) Transportation: equipment and services; 3) Services and 4) Financial Services.

Finding the monetary value of the inputs in oil sands extraction is straightforward for the years 2009-2016. Starting in 2009, Statistics Canada reports two fossil fuel extraction sectors: ''Conventional oil and gas'' and ''Oil sands Extraction''. The monetary values spent by the oil sands extraction sector prior to 2008 can only be estimated as Statistics Canada reports expenditures for the ''Oil and gas extraction'' sector only. I estimate the monetary values of indirect inputs used by the oil sands extraction sector prior to 2009 by using the ratios of Canadian dollars spent in the purchase of each indirect input by the oil sands sector annually from 2009 to 2016, divided by the total monetary value spent in inputs by the oil sands and the conventional oil and gas sector during the same year:

Equation 20

$$\%IND_{1-OS}^{2016} = \frac{IND_{1-OS}^{2016}}{IND_{1-OS}^{2016} + IND_{1-CON}^{2016}}$$

where ''$\%IND_{1-OS}^{2016}$'' stands for ''share of indirect input 1 in the oil sands in 2016, in percentage'', ''IND_{1-OS}^{2016}'' stands for ''\$CAN spent for indirect input 1 in the oil sands, in dollars'' and ''IND_{1-OS}^{2016}'' stands for ''\$CAN spent for indirect input 1 by the conventional oil and gas sector, in dollars''.

Equation 20 is performed for the 150 inputs consistently purchased by the sector from 2009 to 2016. After, I calculate the mean of the ratios. The annual means are used as coefficients to estimate the monetary value of the inputs used by the oil sands sector. I multiply the coefficients by the total value of every indirect input accounted for by the ''Oil and gas extraction'' sector for years prior to 2009. In Equation 21, the average ratio targeted is for 2009 and based on the average of ratios from 2009 to 2010, for illustrative purposes.

Equation 21

$$IND_{1-OS}^{2009} = \left(\frac{\frac{IND_{1-OS}^{2009}}{IND_{1-OS}^{2009} + IND_{1-CON}^{2009}} + \frac{IND_{1-OS}^{2010}}{IND_{1-OS}^{2010} + IND_{1-CON}^{2010}}}{2}\right) * IND_{1-CON}^{2008}$$

Table 3 provides an example of this methodology for four indirect inputs, providing the share of expenditures in oil sands extraction over total expenditures in the oil and gas sector.

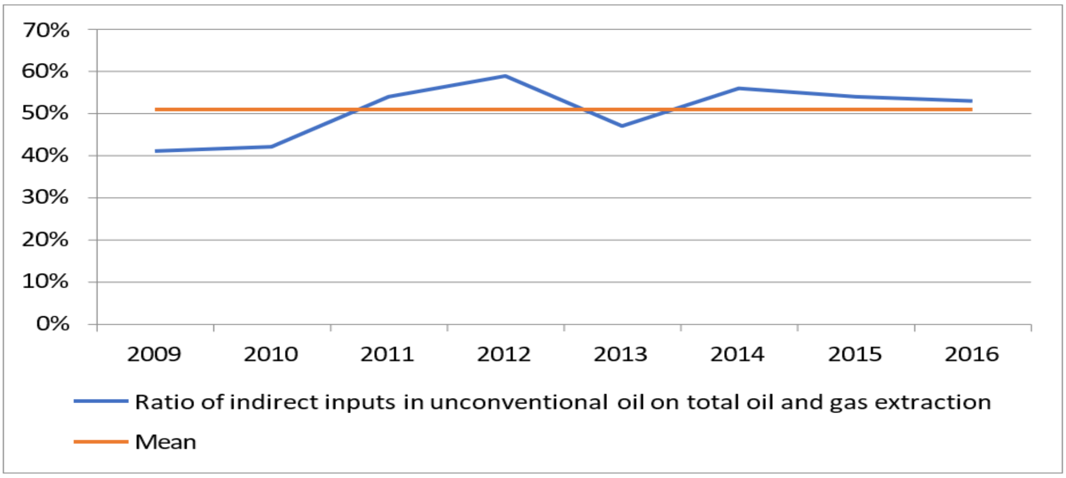
Table 3 Monetary expenditures (in millions of constant 2016 $CAN) by Oil sands extraction (OS) and share (in %) of oil sands expenditures on total oil and gas (conventional oil and gas + oil sands)

	2011		2012		2013		2014		2015		2016	
Input	$OS	%	$OS	%	$OS	%	$OS	%	$OS	%	$OS	%
Gasoline	75	24	73	21	86	18	75	18	65	19	57	17
Tires	11	64	15	78	38	31	43	45	52	49	41	49
Truck transport services	45	47	52	45	64	55	66	65	57	64	51	64
Investment Banking	86	37	77	40	77	38	99	40	55	43	59	55

Sources: Statistics Canada, Supply and Use tables, 2010-2016. Author's calculations

I calculate the mean of the averages of money spent for the 159 indirect inputs. Annual averages range from a minimum of 41% in 2009 to a maximum of 59% in 2012. I assume that the average monetary values of indirect inputs spent by the oil sands extraction sector from 2009 to 2016 for each input are constant across the period under study from 1997 to 2008. This assumption does not closely reflect reality because of the rapid rise in capital expenditures in oil sands extraction from 1997 (1,914.5 million Canadian dollars in 1997 in in-situ, open-pit mining and upgrading to 11,662 million Canadian dollars in 2018, versus 11,670 million Canadian dollars to 15,822 million Canadian dollars for conventional oil and gas (Canadian Association of Petroleum Producers, 2021)). Unfortunately, because of the absence of disaggregated data per category of indirect inputs in each sub-sectors, I know of no better method.

Figure 13 Mean ratio (51%) of indirect inputs in unconventional oil over total oil and gas extraction.



Source: Statistics Canada, (2020). Supply and use tables, 2009-2016. Author's calculations.

The monetary values are adjusted for inflation in 2016 constant Canadian dollars using the most general inflation-index available, the Consumer Price Index for the province of Alberta (Statistics Canada, 2021b). I choose the Alberta-based index as I am assuming that oil sands producers seek their inputs as close as possible to their installations.

Once the monetary values of the inputs are identified, I multiply them by the energy intensity of the sector of the economy from which their production originates for the corresponding year. Statistics Canada's Physical-flow accounts report the energy density of over 100 sectors of the economy (in gigajoules per 1,000 current Canadian dollars of production). Since there are more goods and services reported in the Supply and Use tables than the number of sectors in the Physical-flow accounts, I regroup each indirect input from Supply and Use tables into the sector which is, in my best judgment, the closest in the Physical-flow accounts. Using this last set of data, I estimate the embodied energy of indirect inputs used in the oil sands sector (in joules) such as in Equation 22:

Equation 22

$$IND_{1-OS}^{2016} = I_{1-OS}^{2016} * E_{d1}^{2016}$$

Where ‘‘E_{d1}^{2016}’’ stands for ‘‘energy density in corresponding sector 1 in the Physical-flow accounts in 2016’’ (in GJ/$).

The result of Equation 22 gives the total embodied energy of one category of indirect input in the oil sands extraction sector. To isolate the share used in open-pit mining only, further disaggregation is required.

3.5.3.1 Estimating the share of indirect inputs in mines producing both diluted bitumen and synthetic crude

My research tries to determine the $EROI_{st}$ of diluted bitumen and synthetic crude production separately. Consequently, I need an estimate of the indirect inputs used in the production of each.

To estimate these shares, I first identify the quantities of diluted bitumen and synthetic crude produced annually. I sum them and divide the share of syncrude and diluted bitumen produced in the year under study by the total. I assume the share of the output of diluted bitumen and syncrude to approximate the share of indirect inputs required by their production: if total oil sands production in 2021 was composed of 40% of diluted bitumen and 60% of synthetic crude, I attribute 40% of indirect inputs to the former and 60% to the latter. This assumption most certainly does not closely reflect reality since syncrude production is more capital intensive. However, to my knowledge, there is no way to precisely disaggregate the share of indirect inputs used in syncrude production based on available data.

I estimated the energy value of indirect inputs for the two crude streams by multiplying the total energy value of indirect inputs (see Equation 22) by the share of diluted bitumen and syncrude production mined on total to estimate the share of indirect inputs used in the production of each:

Equation 23

$$IND_{1-OSb}^{2016} = (\,IND_{1-OS}^{2016} * \, ED_{1}^{2016}) \, * \frac{diluted\ bitumen\ produced\ in\ 2016\ (in\ m^3)}{total\ oil\ sands\ produced\ in\ 2016\ \ (in\ m^3)}$$

where ‘‘IND_{1-OSb}^{2016}’’ stands for ‘‘embodied energy in indirect input 1 used in diluted bitumen mining in 2016’’ and ‘’total oil sands’’ refers to the sum of diluted bitumen and syncrude produced in the year under analysis.

The very last step of the methodology involves the attribution of the share of embodied energy of crude bitumen mined through open-pit mining. I first report the total diluted bitumen produced in the year under analysis using data from the Alberta Energy Regulator Statistical reports #3. Then, I divide the quantity of crude bitumen extracted through open-pit mining by the total quantity of crude bitumen produced in the year analyzed as in Equation 24:

Equation 24

$$IND_{1-OS-bop}^{2016} = (IND_{1-OS}^{2016} * ED_{1}^{2016}) * \frac{diluted\ bitumen\ produced\ in\ 2016\ (in\ m^3)}{total\ oil\ sands\ produced\ in\ 2016\ \ (in\ m^3)} * \frac{open{-}pit\ bitumen\ (m^3)}{total\ mined\ bitumen\ (m^3)}$$

Where ‘‘$IND_{1-OS-bop}^{2016}$’’ stands for ‘‘embodied energy in indirect inputs used in open-pit crude bitumen mining’. The $EROI_{st}$ of one crude slate in then calculated using the result of Equation 24 to the 150 inputs under study in the denominator:

Equation 25

$$EROI_{st} = \frac{E_o}{E_i + IND_{1-OS-bop}^{y} + IND_{2-OS-bop}^{y} + IND_{3-OS-bop}^{y} + \cdots + IND_{n-OS-bop}^{y}}$$

Appendix III provides a numerical example of the methodology outlined in this section for Suncor, the largest oil sands mine in the period of study covered in this chapter. Two years of observations are used in the Appendix: 2008 and 2016.

Finally, I estimate the heat loss value of crude bitumen processed into synthetic crude (‘’HL’’ in Figure 12). Syncrude production involves the mining and processing of crude bitumen and its upgrading. The process is akin to an internal energy transfer from bitumen’s thermal inputs to syncrude.[19] I estimate the heat loss represented by this energy transfer by calculating the chemical energy of crude bitumen further processed into syncrude. After, I estimate the energy of syncrude produced in the mines under study. The difference between the chemical energy of crude bitumen processing and synthetic crude produced is roughly equal to the heat loss. Mathematically,

Equation 26

[19] The author thanks an anonymous referee for his suggestion on how to conceptualize the heat loss discussed here.

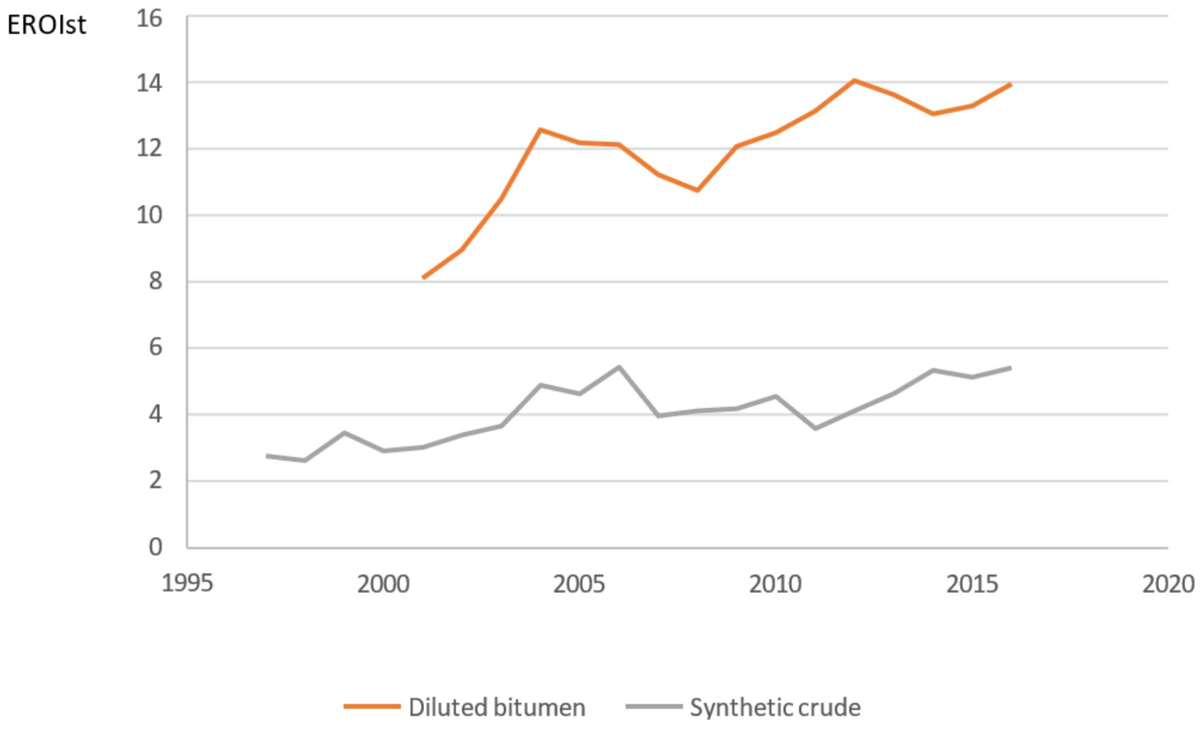
$$HL = b_{fp} \;-\; (1 \;-\; \left(\frac{b_s}{b_{fp}}\right))$$

where ‘‘b_{fp}’’ means ‘’bitumen further processed’’ and ‘’b_s’’ means ‘’barrel of syncrude produced’’. For example: in 2016, I estimate the processing of 46.44 million of m3 of crude bitumen into syncrude resulted in a heat loss of 306,149 TJ.

3.6 Results

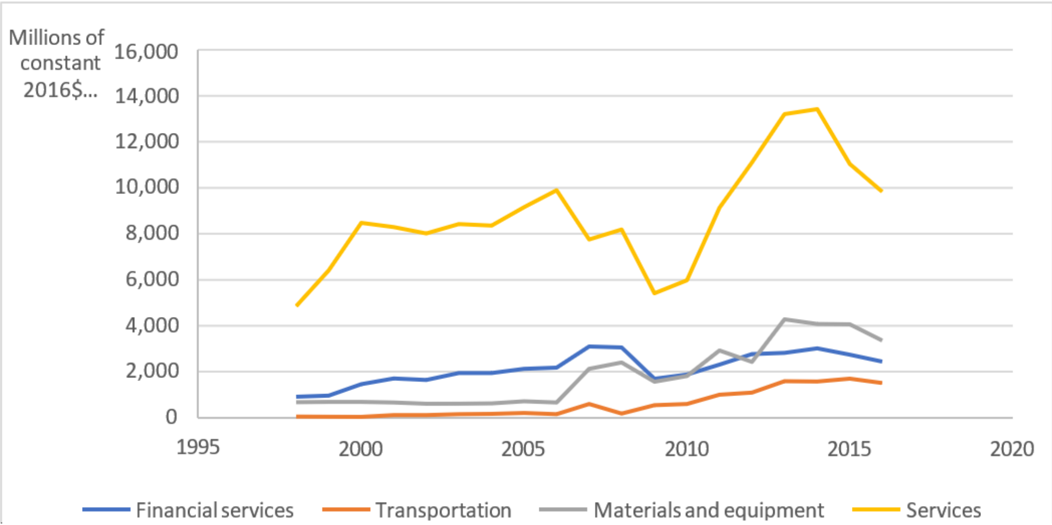
Figure 14 presents the $EROI_{st}$ ratios for synthetic crude and diluted bitumen production produced through open-pit mining in Alberta from 1997-2016:

Figure 14 $EROI_{st}$ of synthetic crude (in orange) and diluted bitumen (in grey) production from 1997 to 2016 (annual measures)



The average $EROI_{st}$ for syncrude across the period is 4.1:1 and 12:1 for diluted bitumen. To reflect the increasing $EROI_{st}$ and output of diluted bitumen across the period, I calculate the weighted average $EROI_{st}$ of diluted bitumen to be 11.6:1. In comparison, the weighted average is 4.1:1 for syncrude (the same as the non-weighted average). Figure 14 shows the difference in the $EROI_{st}$ ratios for diluted bitumen and synthetic crude to be significant and increasing over time. The $EROI_{st}$ of synthetic crude reaches a peak of 5.3:1 in 2014 whereas diluted bitumen's $EROI_{st}$ reaches a peak of 14:1 in 2012 and increases steadily over the period. This result can be understood in relation with total syncrude and diluted bitumen production presented in Figure 4. I believe the increase in the $EROI_{st}$ of diluted bitumen to be a function of increasing production in comparison with relatively constant monetary expenditures (in constant 2016 $CAN) in indirect inputs over the period (Figure 15). Monetary expenditures are constant for three of the four groups of indirect inputs, except for services, the expenditures for which nearly double in the year after the global financial crisis. However, the induced difference in embodied energy does not explain the variations in the value of $EROI_{st}$ observed in Figure 14. The average embodied energy of services is 2.96 GJ/1000 Canadian dollars in comparison with 8.45 GJ/1000 Canadian dollars for material and equipment, 9.16 GJ/1000 Canadian dollars for transportation equipment and services and 1.73 GJ/1000 Canadian dollars for financial services.

Figure 15 Monetary expenditures in inputs in the Oil Sands Extraction sector, 1998-2016, in millions of 2016 constant Canadian dollars



Source: Statistics Canada (2024). Supply and Use Tables. Author's calculations.

Furthermore, the increase is consistent with the tendency for the $EROI_{st}$ of oil and gas to increase during the early years of activity of a mine, due to the resources offering the best energy returns to be exploited first (Hall et. al., 2014; Dale et. al., 2011).

3.7 Discussion

This section concludes with a discussion of how my analysis adds to, or differs from previous research, its limitations, and areas of future research. I found the average $EROI_{st}$ for syncrude to be 4.1:1 from 1997-2016. Across the same time period, the average $EROI_{st}$ for diluted bitumen was found to be 12:1. The weighted average $EROI_{st}$ of diluted bitumen is 11.6:1 and 4.1:1 for syncrude. The $EROI_{st}$ of synthetic crude reaches a peak of 5.3:1 in 2014 whereas diluted bitumen's $EROI_{st}$ reaches a peak of 14:1 in 2012 and increases steadily over the period.

My results do not diverge significantly from those found in the literature. My estimates on the $EROI_{st}$ of syncrude are close to those of Poisson and Hall. They, as well as Wang et. al. and Brandt et. al. identified an upward trend over the period under study. I believe that the recent history of oil sands mining explains this trend. Massive capital investments in the late 1990s and early 2000s have declined since the mid-2000s, with production now benefiting from earlier capital investments. A hypothesis complementing this interpretation is that most open-pit mines being not older than 15 years for the period under study, they might have extracted the resources offering the best output first.

I argue that my results are more robust than those found in previous studies on the $EROI_{st}$ of oil sands. Whereas Poisson and Hall estimate the $EROI_{st}$ of syncrude only, my study includes diluted bitumen. Due to the absence of financial data on the purchase of indirect inputs in the sources used by Brandt et. al. (2013) (AER Statistical Reports #39 and 43), the authors had to estimate the financial value and energy intensity of indirect inputs. I use data from primary sources on the monetary expenditures in indirect inputs. Furthermore, I use the Physical-flow accounts to identify the energy intensity of the sectors of the Canadian economy from which these inputs are produced. Finally, the data I consulted are more recent.[20] I believe my results are more precise than Wang et. al. Indeed, due to data limitations at the moment of writing,[21] they did not use disaggregated expenditures in indirect inputs in the oil sands sector, rather using the energy intensity of the total oil and gas extraction sector as a proxy. I am able to estimate them using primary sources from 2009-2016 via a prorationing method.

The results presented in this paper are limited in several ways. First, whereas synthetic crude production started in Alberta in the late 1960s, the first mine to produce diluted bitumen only,

[20] The latest data available to Brandt et. al. was from 2010.
[21] Authors mention the most recent data available on CANSIM were from 2013 (p. 829).

Syncrude Aurora, became operational in 2001. Consequently, less data is available for interpreting trends in diluted bitumen production, a problem only time can help address. Second, I am not able to estimate the EROI of oil sands- derived crude at the point of use ($EROI_{pou}$) by society. $EROI_{pou}$ is a more comprehensive measure of net energy production that incorporates into the denominator the energy costs associated with producing and delivering end-use products to consumers, such as gasoline for car driving. Further research should include the net-energy of refining and transport of oil sands-derived products further downstream. Such studies would inevitably find a lower $EROI_{pou}$ value than the $EROI_{st}$ estimated in this paper (Hall et. al., 2014). Hall et. al. shows that refining uses approximately 10%-equivalent of energy in a barrel of crude, minus a further 17% of a barrel's output which ends up as non-fuel products. Furthermore, an additional subtraction of 0.52 MJ per-ton mile of crude for pipeline transport must be included in the denominator to account for $EROI_{pou}$ (2009). To engage on this research avenue, high quality data exist for the Canadian refining sector in Supply and Use Tables. Whereas very good data exist on the import of Canadian crude across the various PADD's in the United States (EIA, 2024), no data exist (to my knowledge) on the output generated from Canadian import disaggregated by crude streams (conventional and oil sands), nor are there data available on the indirect inputs used by U.S. refineries. I am therefore skeptical that meaningful research can be produced soon on the $EROI_{pou}$ of heavy source crude-derived end-products in the United States.

An avenue to make the results obtained in this research more precise would be to include the energy required to sustain the labor force engaged in oil sands extraction and upgrading. Following Murphy et. al., (2001) one would need to multiply the dollars paid to labor in oil sands extraction and upgrading by the average energy intensity of the economy (Gross Domestic Product / Total Energy consumption), assuming this intensity reflects the energy to produce the average bundle of goods and services required to sustain labor. If the methodology developed above is strong enough to determine the share of indirect inputs used in open-pit mining and upgrading, then estimating the energy required to sustain labor would be feasible using supply and use as they provide total wages paid in the oil and gas extraction sector.

My results could be improved by using more realistic ratios of indirect inputs used in the oil sands industry vis-à-vis conventional oil and gas across time, thereby allowing the share of indirect inputs used by oil sands extraction from 1997 to 2008 (see Appendix III) to be more realistically estimated. Furthermore, realistic ratios of capital, financial, and services expenditures in in-situ and open-pit mining would allow more precise estimations of the embodied energy of indirect inputs used in these mining methods.

My study assumes energy conversion ratios of energy carriers to be constant (see Table 2). However, concentration of chemical energy in different fossil fuels (natural gas, crude bitumen, etc.) is known to vary across time and place: more precise estimates would use empirically validated energy conversion ratios for direct inputs. Finally, I assume the ratio of expenditures in indirect inputs observed from 2009 to 2016 in the conventional and unconventional oil production sectors to be constant. To my knowledge, no data exists that would allow me to propose a more realistic assumption. For all these reasons, a margin of error certainly exists in my results, although I am unable to quantify it at the present time.

For methodological reasons explained above, my paper has focused on the $EROI_{st}$ of diluted bitumen and synthetic crude upgraded on-site and produced via open-pit mining only. Upgrading facilities importing their diluted bitumen feedstock from off-site were purposefully excluded. To my knowledge, available data do not allow to determine if these facilities use diluted bitumen feedstock extracted via open-pit mining. Should it be found that they do, then a more complete assessment of the net-energy provided by synthetic crude upgraded from crude bitumen extracted via open-pit mining would need to incorporate them.

The Canadian government estimates that 80% of recoverable oil sands reserves can be extracted via in- situ mining only. Crude bitumen extraction from open-pit mining is expected to stagnate in the decades to come (Canada Energy Research Institute, 2018). Consequently, a more complete assessment of oil sands' potential to deliver net energy to society in the future must examine the merits of in-situ vis-à-vis open- pit mining. Such inquiries should help researchers and policymakers alike to address crucial questions such as: does the expected stagnation of open-pit mining mean a decline in the net-energy society can expect from oil sands?

I conclude this paper with a paradox to be further studied in future research. As a lighter source of crude, synthetic crude fetches a higher price on the market than diluted bitumen, raising the issue of the relationship between EROI and profitability. A few authors have studied the relationship between EROI and profitability of fossil fuels. King and Hall (2011) show that all else equal, a theoretical relationship exists whereby at a given EROI, an increase in the energy intensity of investment in fossil fuel production implies that a lower price of energy can prevail on the market for profitable production to occur. Empirically, Wang et. al. compared the return on equity and $EROI_{st}$ of four oil sands companies' output of oil-sands derived crude. They find that no significant relation exists between the two. Because energy production occurs in an economic context where private and public energy-producing companies must generate profit to survive, purely energy-based indicators cannot predict the behavior of actors on the market. Furthermore, despite its lower $EROI_{st}$, syncrude is a more useful type of crude than diluted bitumen, as the former can be sold directly to refineries. More studies are required to shed light on this seeming paradox between EROI, energy quality, price, and profit.

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PREFACE TO CHAPTER 4

In chapter 3, I produced two disaggregated time series of the $EROI_{st}$ ratios of oil sands derived crude, diluted bitumen and synthetic crude, for the period 1997-2016. I identified a modest upward trend in the $EROI_{st}$ of synthetic crude and a significant increase in the $EROI_{st}$ of diluted bitumen. On weighted average, I found the $EROI_{st}$ of syncrude to be 4.1:1 and 11.6:1 for diluted bitumen. Now that two disaggregated time series for each crude stream have been produced, I use these data as indicators of the biophysical quality of oil sands. In the first part of the empirical section of my thesis, I test whether these indicators are correlated with relevant monetary indicators at the level of the resource: prices, cost and of production and profitability. Using the data produced in chapter 3, chapter 4 will directly test the hypothesis at the resource level after identifying or estimating time series for the three monetary indicators selected for each crude stream, using a simple econometric model in first-difference.

Chapter 4 Estimating the relationship between EROI and profitability of oil sands mining, 1997-2016

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Abstract

Biophysical Economics is a school of thought in heterodox economics built on the premise of the primacy of energy in the economic process. Despite significant progress made in the methodology of net-energy analysis, the literature on the relationships (if any) between the biophysical properties of energy sources, such as net-energy ratios, and financial indicators (price, cost, etc.) is scant. Are the biophysical qualities of energy sources reflected by market signals? As such, can the latter guide decision-making in the context of the ongoing depletion of non-renewable energy resources? The paper examines the relationships between the net-energy ratios and price, cost of production and price-to-cost ratios of the Canadian oil sands produced via open-pit mining from 1997 to 2016. A simple econometric model is developed to estimate the correlation between the standard Energy Return on Energy Invested ($EROI_{st}$) with the price, cost of production and price-to-cost ratio of diluted bitumen and synthetic crude over a 20-year period. Preliminary results suggest the absence of correlation between any pair of biophysical and financial variables. No discernable correlation is identified between the $EROI_{st}$ and financial indicators of either crude stream, suggesting biophysical and financial properties to be sui generis realities.

4.1 Introduction[22]

Fossils fuels account for 84% of global primary energy consumption (Delannoy et al., 2021a) with crude oil standing as the first source (International Energy Agency, 2020). The future of crude oil extraction is faced with the ongoing depletion of conventional sources (Sorrell, et al. 2009) and the rise of unconventional sources (shale oil, tar sands, etc.) (Hall et al., 2009). The depletion of conventional sources implies changes in the quantity and quality of energy societies can expect from crude oil, as unconventional sources tend to deliver less net energy (energy returned after accounting for energy used in production) than conventional sources (Delannoy et al., 2021b).

Market-oriented economists suggest market forces could be used to bring about an energy transition. In the context of growing concerns with respect to the reliance of capitalist economies on fossil fuels, one question that arises is whether economic signals, such as market prices or profit rates, are indeed useful guides to orient resources dedicated to energy production towards their most socially desirable uses. If so, it would imply that economic dynamics driving investment choices could be relied upon to effect a rational use of increasingly scarce fossil energy resources, including initiating a transition toward renewable energy sources. Otherwise, a more hands-on approach might be needed.

These questions are of particular interest when considering the Canadian oil sands. Investments required to mine, process, and upgrade the oil sands are notoriously expensive (Reuters, 2017). The oil sands were deemed unworthy of commercial exploitation for decades following their systematic study in the early 1920s (Chastko, 2004). The commercial context changed in the 1960s with the construction of the Great Canadian Oil Sands project in Fort McMurray. After a phase of rapid expansion in the early 2000s, a worldwide collapse in the price of crude oil in 2008 and 2014 brought some activists, researchers, and investment analysts to question the profitability of oil sands extraction (Sanzillo and Lawrence; 2015; Sanzillo and Hipple, 2020; Kirk, 2021). Hussey et. al. (2018) calculated that the five largest oil sands firms in Canada (Suncor, Canadian Natural Resources Limited, Imperial Oil, Husky and Cenovus, today only four after the merger of Cenovus and Husky in 2020 (CTV News, 2020)) paid $CAN 4.16 billion (30.3% of their net profits) to their shareholders in 2018. Profitability is less evident if

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one includes the cost of cleaning mining sites after their closure. These costs (estimated at $CAN 58 billion in 2018) are estimated to exceed the resources set aside for remediation ($CAN 41 billion in accumulated royalties by the provincial government in 2018) (Meyer, 2020: 245).

Along with profitability, changing resource quality is another challenge posed by the rise of oil sands production in Canada. Applied to energy, ‘’resource quality’’ denotes energy cleanliness, density, the net quantity of energy delivered by energy carriers (Hall and Klitgaard, 2018: 476), etc. ‘’Net quantity of energy’’ refers to the energy value (in joule) an energy carrier can deliver once the energy costs of producing it are subtracted. Energy Return on Energy Invested (EROI) is the most well-known indicator to measure net energy production. Net-energy is necessary for an economy to maintain material living standards (Lambert et al., 2014). Provided the lower EROI of unconventional sources on average, one can wonder whether the oil sands represent a good source of energy to maintain the living standards of the Canadian economy.

The problems pertaining to net-energy production and the profitability of fossil fuel resources have largely been dealt with separately in ecological economics, with only a scant literature investigating a possible relationship directly. The connection or lack thereof between biophysical and financial properties of energy sources raises important issues for decision-makers and scholars. To the extent that financial indicators are a fundamental determinant of investment decisions, it is important to know if decision-making based on financial indicators will lead to the development of high-quality energy sources. This paper compares financial indicators and net-energy ratios in Canadian oil sands, using the standard EROI ($EROI_{st}$) ratios of oil sands-derived crude (diluted bitumen and synthetic crude) extracted via open-pit mining from 1997-2016 found by Guay-Boutet (2023). The year range used stems from the availability of the data needed to estimate $EROI_{st}$ ratios, which requires disaggregated data on monetary expenditures per sub-sectors of the economy. Statistics Canada’s Supply and Use Tables start disaggregating the extractive sector into a ‘’Mining’’ and ‘’crude oil extraction’’ sector in 1997 only, whilst disaggregation of the crude oil extraction sector into a conventional and unconventional extraction (i.e. oil sands) sub-sectors start in 2009 and end in 2016 (Statistics Canada, 2022a). We compare the $EROI_{st}$ of crude bitumen and syncrude with the price, production costs, and price-to-cost ratios of the two crude streams. For reasons developed further in Section 4.4, we do not provide an overview of the profitability of oil sands production via in-situ extraction nor do we analyse the profitability of bitumen upgrading when bitumen is imported from off-site upgrading facilities.[23]

Net-energy analysis takes the production system of an energy source as the unit of analysis (King and Hall, 2011: 1813), the system being defined by its boundaries, i.e. the nature of its energy inputs and output. $EROI_{st}$ measures the ratio of energy output over inputs in extractive facilities, at the well-head or ‘’mine-mouth’’, when directly extracted from nature. It can be estimated for one energy production facility or an aggregate of facilities sharing the same boundaries (see Murphy et. al., 2011: 1893). On the other hand, financial indicators such as prices (both spot and future) and costs are intrinsically scale-dependent. Whereas the production costs of one source of crude varies for each well along with biophysical properties, crude oil prices are set in reference to benchmarks which are regional in nature. Benchmarks refer to crude oil streams of specific chemical properties (such as sulfur content) in specific regions, for example the West Texas Intermediate (WTI) sourced from the Permian Basin. In Canada, the Western Canada Select (the heavy sour blend benchmark which determines the pricing of diluted bitumen) is priced at a discount to the WTI (Oil Sands Magazine, 2022). Specifications of the scale of analysis are therefore crucial to the arguments we are making in the paper, as the values of financial and biophysical indicators are not formed at the same scale. We define ‘’local’’ as the scale of the individual crude oil well or mine and ‘’regional’’ as a larger crude-producing area where crude oil sources, sharing similar biophysical properties, are priced under the same benchmark (Energy Information Administration, 2014).[24]

The paper is divided as follows. In section 4.2, we provide a critical literature review of past research on net-energy analysis and its relationships with financial indicators. Section 4.3 presents an overview of the oil sands industry. In section 4.4, we describe the methodological framework used to estimate the price, production costs and price-to-cost ratio of oil sands-derived crude extracted via open-pit mining and upgrading. The estimates are shown in section 4.5 and discussed in section 4.6. Finally, we offer some concluding remarks in section 4.7.

4.2 Literature review and hypotheses

4.2.1 Literature review

[23] Such as the Nexen Long Lake Upgrader. See Alberta Energy Regulator (2021).

[24] ‘’Benchmarks’’ are defined by four characteristics: 1) stability of production; 2) geography, i.e. a free-flowing market in a ‘’[...] geopolitically and financial stable region to encourage market interactions [...] ‘’; 3) adequate storage and 4) delivery points at locations ‘’ suitable for trade ‘’ (Energy Information Administration, 2014). The geographic properties (2 and 4) are particularly relevant for the argument made here.

In this section, we review the literature on net-energy analysis of energy sources with a particular focus on oil sands, followed by a review of the literature exploring the relationship between net-energy and financial indicators. Biophysical Economics is built on the premise of the physical primacy of energy, the input making the production of virtually every other goods and services possible. A common measure of net energy production is EROI, which is defined as the ratio of energy obtained over energy invested at the level of an energy producing unit. The segments of the supply-chains (extraction, refining, etc.) included in EROI analysis depend on the boundaries of analysis (Murphy et. al., 2011):

Equation 27

$$EROI = \frac{E_o}{E_i}$$

where ‘’E_o’’ stands for energy output and ‘’E_i’’ for energy input, both in joules (J). When EROI exceeds 1:1, one can speak of an energy source. A ratio inferior to 1:1 indicates an energy sink. The lower the EROI of an energy carrier, the lower the net energy available to societies producing it. The denominator of Equation 27 can be divided into two categories of inputs: a) direct energy flows of energy carriers (natural gas, electricity, etc.) and b) energy embodied in the goods and services produced elsewhere in the economy and used to produce energy (material, equipment, etc.):

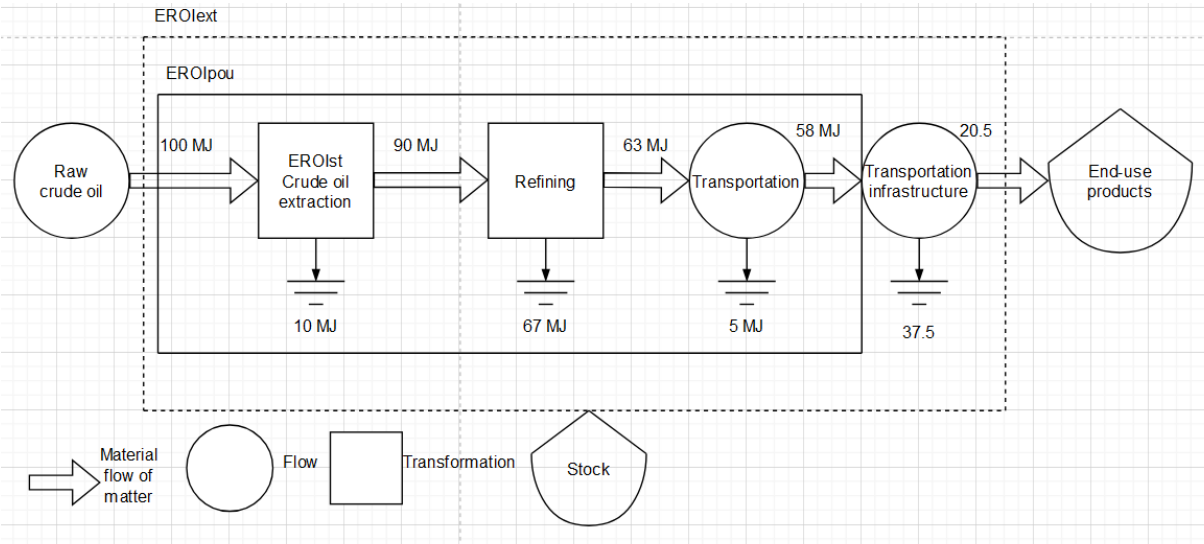
Equation 28

$$EROI = \frac{E_o}{E_{di} + IND_i}$$

where ‘’E_{di}’’ stands for ‘’direct energy inputs’’ and ‘’IND_i’’ stands for ‘’energy embodied in indirect inputs’’. Estimating the embodied energy of direct inputs requires the conversion of the energy used in physical units (in ton, m^3) into its energy content (in J per ton, m^3, etc.). Two ways exist to estimate the energy embodied into indirect inputs: 1) process-analysis and 2) input-output analysis (Murphy et al. 2011). Process analysis is a ‘’bottom-up’’ approach where the energy value of different production stages is first estimated separately and then aggregated. Input-output analysis converts national economic input-output tables into sector-specific energy values. Hybrid analysis combines both. The energy value of direct inputs is estimated using process analysis whilst the embodied energy of indirect inputs is estimated using input-output analysis by multiplying monetary expenditures in indirect inputs by the average embodied energy per dollar spent in their production across the economy (Moeller and Murphy, 2016).

Variations exist in the EROI values of fossil fuels, notably depending on the boundaries of analysis adopted (Murphy et al., 2011), etc. ‘‘Boundaries’’ refer to the groups of inputs accounted for in the denominator of Equation 28, depending on the segments of the supply-chain analyzed (extraction, refining, etc.). Standard EROI ($EROI_{st}$ in Figure 16 and hereafter) measures the inputs and outputs of energy carriers at the ‘‘mine-mouth’’ when derived directly from nature during extraction, as with a crude oil well, etc. In this paper, ‘’$EROI_{st}$’’ is used when referring specifically to net-energy at the mine-mouth and ‘’EROI’’ when the boundaries of analysis are left unspecified, such as in the literature review further below.

Figure 16 Boundaries in EROI analysis



Source: Hall et al., 2014: 142

Scholars have shown a declining trend in the $EROI_{st}$ of crude oil and gas globally (Gagnon et al., 2009) and in the United States over the last decades (Cleveland, 2005; Guilford et al., 2011[25]). In Canada, the EROI of conventional oil and natural gas “[…] exploration, drilling, gathering, and separating […]” (Freise[26], 2011: 2094) is estimated to have reached a peak of 80:1 in the 1970s, dropping to 22:1 in 1980 and 15:1 in 2006. Focusing on the oil sands, Poisson

[25] Guilford et. al.’s study estimates the EROI of oil and gas discovery and extraction, the former not being part of $EROI_{st}$ methodology.
[26] Freise uses the term ‘’ upstream ‘’ to refer to the boundaries of his analysis (2011: 2094).

and Hall (2013) estimated the $EROI_{st}$ of synthetic crude between 1994 and 2008 to fluctuate around a ratio of 4:1, in comparison with a range from 11:1 to 16:1 for conventional oil and gas during the same period. Wang et al. (2017) estimated the $EROI_{st}$ of both oil sands-derived crude disaggregated by the two mining methods used in the industry: open-pit mining and in-situ extraction. They estimated the combined $EROI_{st}$ of crude bitumen and synthetic crude to range from 3.2:1 to 5.4:1 for oil sands produced via in-situ and from 3.9:1 to 8:1 for open-pit mining from 2009 to 2015.

Whereas the net-energy literature is burgeoning, literature relating energy and financial indicators is scant. The nature of the empirical linkages between the two, if any, is subject to debate. On the biophysical-financial linkages of oil sands, Choquette-Levy et. al. uses an integrated partial cost-benefit\life-cycle assessment to determine the relative merits of diluted bitumen production and export to U.S. refineries over oil sands-upgrading into synthetic crude oil and sale to Canadian refiners from the perspective of Canadian stakeholders in the presence of carbon taxes. Whereas bitumen upgrading requires capital investment in upgrading facilities that generate greenhouse gases (GHG) emissions, synthetic crude oil fetches a higher price on the market and is less energy-intensive in refining than diluted bitumen (2013: 79) (see Section 4.3). Assuming a 15% discount rate, the authors find the industry to favor diluted bitumen over synthetic crude production under a 75$\CO2e carbon tax, in contrast with the government and environmentally-concerned citizens (respectively concerned with royalties\job creation and GHG-emissions) preferring upgrading.

At the level of national economies, Costanza (1980) shows a strong correlation between the embodied energy used in production and the market price of several goods and services in the American economy. The author uses input-output analysis to derive the embodied energy of inputs used to generate goods and services. However, at the international level, Illig and Schindler (2017) show that several market prices correspond to the same quantity and quality of crude produced worldwide.

From a theoretical standpoint, some authors argue that the relationship between prices and $EROI_{st}$ could be negative if lower $EROI_{st}$ are reflected in higher production costs. To show this, Heun and De Wit (2012) devise a simple model of global energy prices in which they posit a price for the net energy (assuming away energy imported in the system) available to the economy, which they equate to marked up production costs for total energy output. Their model is formalized as in Equation 29[27]:

Equation 29

$$P_{et} = \frac{m_t + C_e}{1 - (\frac{1}{EROIst})}$$

where ‘’P_{et}’’ is the market price of energy (in $/J) produced by all crude oil producing units globally, ‘’C_e’’ is the production cost of energy (in $/J) sold in the world and ‘’m_t’’ is a markup. From there, they show that for a given m_t and C_e, a lower $EROI_{st}$ implies a higher price, since any level of gross output is associated with a lower quantity of net energy available (so production costs are spread out on less energy units sold). The authors further note that these variables can change at the same time, for example if technological improvement leads to lower energy requirements in extraction and thus a higher $EROI_{st}$, lower production costs, and lower prices or, conversely, if demand leads to the exploitation of lower yielding sources, thus raising production costs, lowering $EROI_{st}$ and raising prices. Either way, there would still be a negative relationship between prices and $EROI_{st}$. Finally, the authors emphasize that although their model uses $EROI_{st}$ data, the biophysical-financial relationships examined through their model should be valid further downstream (2011: 150).

A straight application of this model to the oil sector is problematic. Many factors, from geopolitics to speculative dynamics, can drive oil prices, thus weakening any direct linkage between prices and production costs. Even if we abstract from these, it is likely that a relatively inelastic demand will determine the quantity to be produced, at a price for which it will have to be profitable to exploit the marginal source, giving a rent to all the other ones, in a process akin to what Ricardo described for agriculture (Hall et. al., 1986: 70). In that sense, higher prices could be associated with a lower regional or global $EROI_{st}$ of all energy-production units, not because these prices are driven by higher production costs, but because they enable production in local energy sources with lower $EROI_{st}$ by making them profitable. Moreover, this negative relationship would only apply to the extractive sector at the regional or global scale, not to local energy production units where the biophysical characteristics of the energy

[27] Although Heun and deWit do not use the subscripts ‘’st’’ on the ‘’EROI’’ variable, they define the value of their EROI ratios as ‘’[...] energy accounting at the input to the well or mine [...] ‘’, (2011, p. 150), meaning $EROI_{st}$. The EROI and price times series used by the authors are essentially from the United States.

sources remain unchanged if inputs (direct and indirect) used in production don't change, leaving their $EROI_{st}$ ratios unchanged. Incidentally, Heun and De Wit (2012) recognize the possibility of a relationship driven by changing prices and do provide some historical support for it. Finally, it should be noted that if we start from prices, a negative correlation is not the only possibility. Because fossil fuels are a direct input and enter in the production and transport of indirect inputs such as machinery, higher oil prices could lead to changes in the mix of inputs used towards less energy-intensive inputs, thus leading to an improvement in $EROI_{st}$ for a given oil production unit.

King et al. (2015a; 2015b) also hypothesize a negative relationship between net energy ratios and production costs and market prices. Using historical data from the International Energy Agency to estimate the aggregate energy intensity of economies based on the energy intensities of several energy sources (crude oil, natural gas, and electricity) across 44 countries over a 30-year period, the authors show an inverse relationship between price and both energy intensity and net energy ratios across time. Following King (2010), they define an energy intensity ratio (EIR) for a given energy commodity *n* as EIR_{pn}=(energy units of *n* / price of *n*) / (total energy supply to the economy (in J) / GDP).[28] Thus defined, EIR "[…] *represents how much power one can obtain by spending one dollar relative to how much power it takes to generate an average dollar of output from the economy.*" (King et al. 2015a, 12959). Because the numerator is akin to a system power output and the denominator a system power input, the authors hypothesize that EIR should be largely correlated with power return ratios (PRR, i. e. Power delivered / Power invested) and could thus be used as a proxy for PRR (both indicating more net energy to society per unit of input). This is supported by empirical results from King (2010) for the U.S. By definition, the EIR of a given commodity is inversely related to its price, so to the extent that there is indeed a positive correlation between EIR and PRR (or EROI), then this could herald a negative correlation between EROI and prices.

King et al. (2015a; 2015b) show that EIR and net energy ratios tend to follow each other and are both inversely related to prices from 1978 to 2008. For example, from 2000 to 2008, energy commodities became more expensive, meaning a decline in net output of energy relative to net inputs (King et. al., 2015a: 12963, 12967). Following this, they suggest that net energy ratios and metrics could be used in the forecast of future energy prices and growth.

[28] The units used in EIR make it a dimensionless number, since dollars and megajoules appear both in the numerator and denominator.

King (2010) and King et al. (2015a; 2015b) make an interesting contribution to the study of the linkages between financial and biophysical measures, but we find it hard to transpose their reasoning to the Canadian oil sands. While we agree that EIR could be useful proxies for net energy ratios in some contexts, it is unclear that the relationship with prices would align with that of $EROI_{st}$ for the Canadian oil sands sector. First, if prices are given by global dynamics as is the case of crude oil, unless a producer or a local source is the marginal one, varying prices won't be directly related to its $EROI_{st}$ absent any change technological changes in production methods. Only the level of rent will. As such, for any given energy intensity of GDP (the denominator in the EIR equation) in a country like Canada, a price change would lead to a change in EIR, but not necessarily to $EROI_{st}$. Incidentally, since Canada is a large producer of oil, a change in oil prices would likely produce a change in GDP, all the more so since King et al. (2015a) evaluate GDP at market exchange rates and that oil comprises a large share of Canadian exports. Price changes could thus affect EIR in varying ways, underlying biophysical realities notwithstanding, and we cannot really infer a correlation between prices and a measure like $EROI_{st}$ from EIR. We test this reasoning in section 4.5.

While the relationship between EROI and prices is ambiguous, can anything be said about EROI and profitability? On a theoretical level, Hall et al. suggest the possibility of an ‘’energy theory of value’’ where profitability in the human economy, in an energy-based sense, reflects the difference between the economic work (in J) accomplished by energy carriers and the equivalent economic work accomplished by human effort, measured in dollar terms. In other words, the difference between the chemical energy of a resource and its equivalent energy accomplished by human work, measured in dollars, is profit (Hall et al., 1986: 75)

King and Hall (2011) explore this question using a monetary return on investment (MROI) ratio of energy-producing firms, which they relate to the EROI[29] of energy produced by firms. Assuming no constraint on inputs and a strict definition of the boundaries (see Figure 21) so data all relate to the same well at the field level:

Equation 30

$$EROI = \frac{E_o}{E_i} = \frac{\sum m_i * e_i}{\$_{inv} * e_{inv}}$$

[29] Although the authors do not specify the boundaries of analysis, they use Cleveland (2005) and Guilford et. al. (2011) data on the EROI at the extractive level, meaning the boundaries of analysis belong to the $EROI_{st}$.

where ‘’m_i’’ represents the number of energy output (in volume units) for the *i*th product, ‘’e_i’’ represents the energy intensity of product i (in J/volume unit), ‘’$\$_{inv}$’’ represents money invested in a particular well or firm under analysis and ‘’e_{inv}’’ represents the energy intensity of investment (J/$). The denominator of Equation 30 shows that all else equal, the higher the energy intensity of investment, the lower the EROI ratio. The more energy embodied in the inputs invested to obtain energy on average, the lower the energy return on investment. They then define MROI as:

Equation 31

$$MROI = \frac{\$_{out}}{\$_{inv}} = \frac{\sum m_i * \ p_i}{\$_{inv}}$$

where ‘’p_i’’ is the price of the *i*th unit of energy sold. In Equation 31, each dollar of investment is associated with an energy intensity. For any given energy production unit, an increase in prices of energy will increase both the monetary value of the energy output (numerator) and inputs (direct + indirect energy) but the increase in the value of output (revenues) will dominate, all else equal, since primary energy is only one part of the investment cost. Since energy is involved in the production of virtually all goods and services in the economy, the cost of indirect inputs should rise as well, but less so than primary energy. Thus, a rise in the price of energy should be followed by an increase in profitability. EROI and MROI can be related thus:

Equation 32

$$EROI = \frac{\sum m_i * \ e_i}{\sum m_i * \ p_i} * \ \frac{MROI}{e_{inv}}$$

Assuming a single type of energy production (so M=1), we get:

Equation 33

$$EROI = \frac{e_i}{p_i} * \ \frac{MROI}{e_{inv}}$$

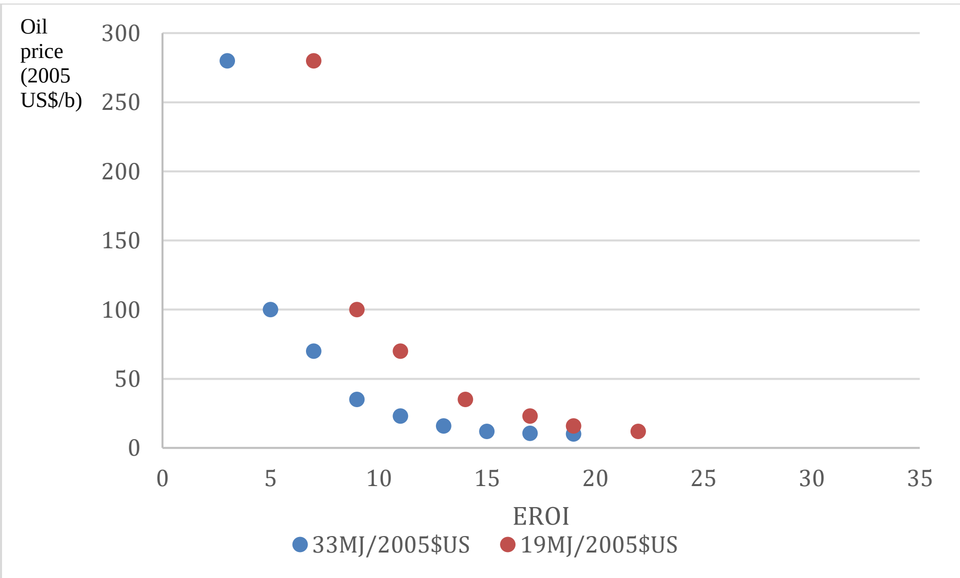
Equation 34

$$P_i = \frac{EROI}{MROI} * \ \frac{e_i}{e_{inv}}$$

Equation 34 shows how EROI and MROI are positively related. If EROI gets lower, all else equal, the price of output p_i must increase for MROI to remain constant or increase, which suggests once again a negative relationship between EROI and prices if firms seek to maintain a given profitability ratio and they have control over prices. King and Hall (2011; 1818) also note that for a given EROI of the output, an increase in the energy intensity of investment implies a lower price of energy to obtain a particular MROI, since a higher energy intensity of inputs implies more energy per dollar invested. That said, they also underline how it is difficult to infer a precise relationship from these equations, since the different variables are not independent from each other. For example, a decline in EROI could raise the energy and monetary value of inputs, thus affecting e_{inv}. Still, for a given price and energy intensity of investment, MROI and EROI are positively related, since a higher EROI implies lower production costs.

Finally, they make some simulations for different values of MROI and e_{inv}, which they compare to existing estimates linking EROI to prices for the U.S. energy sector, using EROI ratios from Cleveland (2005) and Guilford et. al. (2011) and data on prices from the Energy Information Administration and the American Petroleum Institute. We reproduce two of the functions derived from their results below:

Figure 17 Price of oil (in 2005 $US/b) in relation to EROI to produce monetary return on investment



Source: King and Hall,, 2011: 1821.

From this they infer a negative, non-linear relationship between prices and EROI. However, these results seem to depend on a few outliers, as most estimated values are in the flat portion of the curve.

Jackson and Jackson (2021) investigate the macroeconomic impacts of a decline in EROI[30] caused by the depletion of high-EROI conventional sources of fossil fuels. Their model shows that a reduction in EROI leads to a cascading series of effects whose combined impacts ultimately lead to recession. Indeed, assuming the absence of a public sector, a decline in EROI leads to an increase in the price of energy, in the general price level, in the energy sector's capital expenditures, provoking at first an increase in employment and in real wages. Inflation provokes a fall in real consumption and employment. This, in turn, leads to a worsening distribution of income due to the higher propensity to save for shareholders compared with wage-earners. Furthermore, several simulations of the model show that the larger the reduction in EROI, the greater the negative economic effects outlined above.

The literature reviewed so far is largely theoretical. On an empirical level, Wang et. al. (2019) try to detect a co-determination of profitability with the $EROI_{st}$ of unconventional fossil fuels using empirical data. Using a firm-based approach, they use data from public energy regulators as well as corporate reports to determine the $EROI_{st}$ of oil sands produced by four Canadian oil sands producers in relationship with their (declared) return on equity (ROE). The authors estimate the share of firms' equity that can be attributed to their upstream oil sands assets by multiplying the total shareholder equity of each firm by the ratio of the value of their oil sands upstream assets on total assets. Comparing the data between 2010 and 2016, they show that no such co-influence exists as ROE goes down, mostly due to the collapse in crude oil price in 2014, whilst $EROI_{st}$ rises across the period.

4.2.2 Hypotheses

The foregoing literature suggests three types of relationships between financial variables and $EROI_{st}$. We propose the following hypotheses:

(1) First, it is reasonable to expect a negative relationship between $EROI_{st}$ and costs at the local and regional levels. $EROI_{st}$ is not independent from the energy intensity of investments (King and Hall, 2011: 1818), meaning that an energy source with a low

[30] Boundaries unspecified by authors.

$EROI_{st}$ probably reflects high energy-intensity, and thus expensive, investments (King et. al., 2015: 12950) Hypothetically, such a cost-differential should be observed, for example, between a high-$EROI_{st}$ and low-cost (per barrel) conventional crude stream and a low-$EROI_{st}$, high-cost heavy crude streams (King and Hall, 2011: 1816). Although production costs also depend on factors unrelated to biophysical realities, such as the going wage level or the rate of interest, we argue it is reasonable to hypothesize that a decreasing $EROI_{st}$ at the local and regional levels implies more inputs needed to obtain the same quantity of energy output, which will generally translate into higher production costs.

(2) Second, the relationship between $EROI_{st}$ and prices is more complex. If benchmarks move independently of biophysical characteristics (such as an increase linked to a sharp, politically-triggered reduction in supply), higher benchmarks will allow for the exploration and exploitation of more marginal sources with lower $EROI_{st}$ at the regional level. This would not affect the $EROI_{st}$ of any given local crude oil well or oil sands mine already exploited, but could imply a lower $EROI_{st}$ at the regional scale where the $EROI_{st}$ of individual energy production units are aggregated or summed and further downstream as well. In a sense, rising costs due to declining $EROI_{st}$ will imply a rising floor on prices below which exploitation will be unprofitable for marginal sources. If demand is relatively inelastic (King, 2010), gradual depletion translating in lower $EROI_{st}$ at the margin could thus put upward pressure on the value of the benchmark. Still, if the Canadian oil sands are not at the margin for the period studied, such a relationship might not be visible in our study. $EROI_{st}$ will be linked to the extraction setup in the mines themselves while benchmarks (Western Canada Select for crude bitumen and Canadian Edmonton Light for syncrude) will largely be driven by outside factors. This remark is particularly relevant for oil sands. As shown by Wang et al. (2017), oil sands production via in-situ extraction has a lower $EROI_{st}$ than open-pit mining while being less capital-intensive.[31] Thus, changes in the value of benchmark might lead oil sands firms to adjust their production via changes in in-situ extraction, reducing the risks of capital write-offs whilst leaving the individual $EROI_{st}$ of crude produced via open-pit mining unaffected. In any event, oil prices and $EROI_{st}$ for oil sands are likely not directly related.

[31] Capital-wise, bitumen mining is more expensive than in-situ extraction by a factor of 1:1.75 (Alberta Energy Regulator (AER), Statistical Report # 98, 2021), the difference resulting from the superior total capital investment required by the former (Canadian Energy Research Institute, 2017).

(3) Third, $EROI_{st}$ and profitability could be somewhat related through a relationship of $EROI_{st}$ with costs, but price movements probably dominate most times. This is due to benchmarks being formed at the regional and world level whilst the $EROI_{st}$ is estimated at the scale of the energy-producing unit or system when the source of energy is extracted directly from nature. As shown in Table 4 below, the $EROI_{st}$ of oil-sands derived crudes changes less rapidly than the prices of the benchmarks. Moreover, just as other factors than energy returns enter on the cost side, the revenues of oil producing firms will be impacted by the market structure. For example, the fact that diluted bitumen-producing firms in Canada export most of their output to U.S refineries does influence their return as diluted bitumen is sold at a discount to the WTI. Therefore, a change in WTI price will impact the profitability of bitumen production, independently of the oil sands-derived crude' $EROI_{st}$. Furthermore, while a lowering $EROI_{st}$ of an energy source means lower net-energy ratios, it is not clear that it will mean lower profitability for firms themselves. If demand is inelastic, it may simply mean that prices will rise over time and a greater proportion of resources will go to the oil sector. In the interim, for a given energy source like the oil sands, rising prices could imply higher profitability if production costs do not change much. However, as this research focuses on profitability at the mine-mouth, we put aside an examination of profitability at the firms' level to focus on the extractive level. Briefly put, we hypothesize that no relationship between profitability and $EROI_{st}$ will be visible in our data.

4.3 The oil sands as a case-study

This section provides a short introduction of the oil sands extraction industry. Oil sands are located in the Western Canadian Sedimentary Basin in Northern Alberta, covering an area of 142,000 km^2 under the boreal forest (Natural Resource Canada, 2016b).

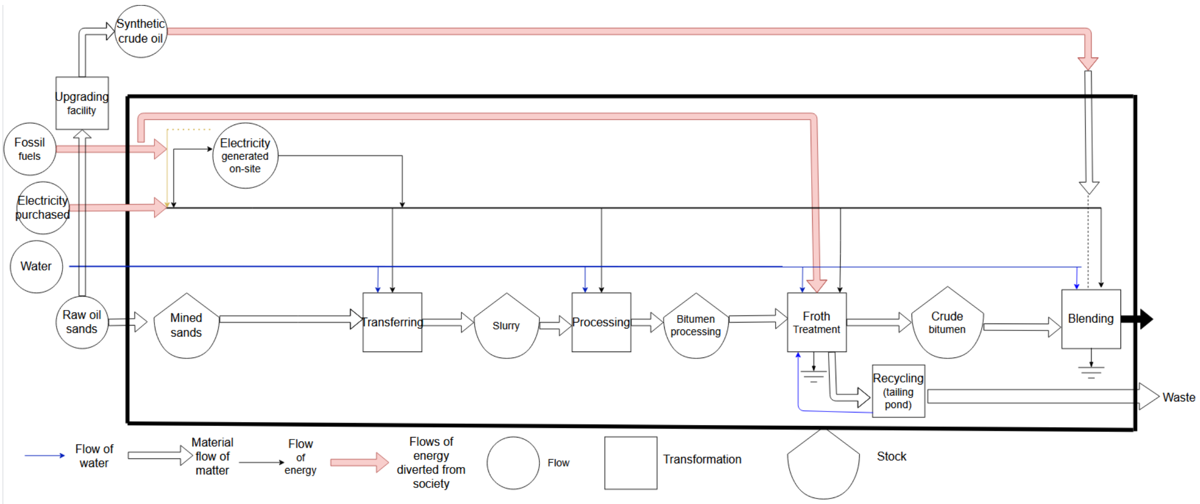
Raw oil sands cannot be transported into pipelines: at room temperature, bitumen is almost solid. In nature, raw oil sands are formed by long chains of hydrocarbon molecules with low API[32] values and high sulphur content. Thus, mined sands must first be transformed into pre-refined products meeting pipeline specifications on weight and sulphur content prior to

[32] ''API gravity'' is a scale expressing the density of crude and petroleum products. The higher the API gravity, the lighter is the product or source of crude. Conventionally, crudes with an API of 22 or below are defined as ''heavy'' (Energy Information Administration).

shipment: synthetic crude oil (syncrude) and diluted bitumen, that is crude blended with light hydrocarbons (condensate, naphtha, etc.)

Two methods exist to mine the sands: open-pit mining and in-situ extraction. Open-pit mining is performed when the sands deposits are found at less than 75 meters below the surface (Natural Resource Canada, 2016a). When the overburden is deeper, extraction is executed through in-situ extraction, involving the injection of steam at high-pressure in the deep oil sands deposits.[33] In 2019, in-situ and open-pit production represented roughly 50% each of total oil sands raw bitumen extraction (Oil Sands Magazine, 2020a, 2021; Alberta Energy Regulator, 2021). Prior to transport, raw oil sands are fluidified into a 'slurry' cleansed from solid particles of sand and clay. The slurry is then hydro-transported into an extraction unit and processed into bitumen froth which, after froth treatment, becomes crude bitumen.

Figure 18 Flow diagram of a generic mining facility



Source: Oil Sands Magazine (2021).

Yet, crude bitumen is still too heavy to meet pipeline companies' specifications on crude fluidity and corrosivity. Bitumen must be blended with lighter hydrocarbons (condensate, natural gas or naphtha) before it can be transported for further upgrading into syncrude or refined into petroleum products in high-conversion refineries (in reference to refineries complexity index (EIA, 2012)),[34] most of them located in the United States.

[33] Orellana et. al. found median emission intensity of in-situ bitumen extraction via cyclic steam stimulation to be more emission-intensive than steam assisted gravity drainage (2018).

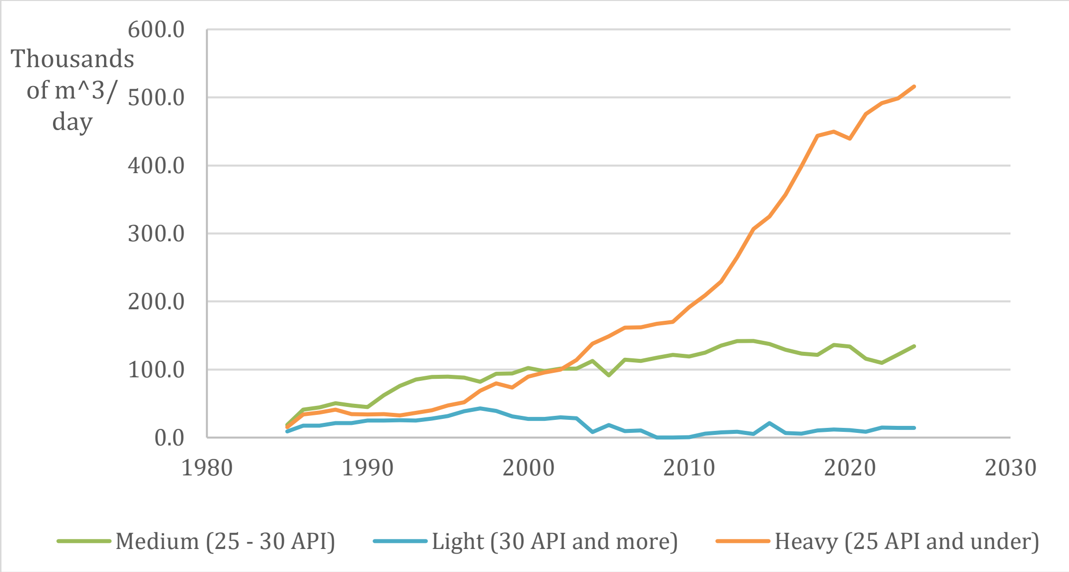
[34] Refineries' complexities are measured by the 'Nelson Complexity Index'. This index compares refineries facilities via a comparison of the costs of their refining equipment. A basic distillation column is given a value of

When upgraded into syncrude, bitumen is transformed into a product physically and chemically very close to conventional crude. Upgrading is performed by lowering the ratio of hydrogen to carbon of bitumen, either through coking or hydroconversion. (Oil Sands Magazine, 2020a). Syncrude can be refined into refined petroleum products and sold to local, simple refiners. A review of the literature on greenhouse gases emissions generated by oil-sands extraction by Charpentier et. al. (2009) found production of synthetic crude oil to be more emission-intensive than conventional crude oil on a kg of carbon dioxide equivalent (co_2-eq)\barrel basis (2009). A comparison of extraction-related emissions between mined bitumen and conventional crude lead to overlapping ranges of emissions between the two (Bergerson et. al. 2012). Using a process-based life-cycle model, Bergerson et. al. found that producing synthetic crude out of bitumen extracted via in-situ extraction was more emission-intensive than bitumen feedstock extracted via surface mining and upgraded on-site. Interestingly for this paper as they consider the same production pathways as we do: bitumen extraction and dilution on-site were found to be less emission-intensive than bitumen extraction and upgrading into synthetic crude oil on-site (Sleep et. al., 2018), the former showing the lowest emissions intensity of the four different oil-sands derived crude production pathways (synthetic crude and diluted bitumen produced out of bitumen extracted via open-pit or in-situ extraction (Bergerson et. al., 2012: 7865)).

Over the last 30 years, synthetic crude production in Alberta has stagnated whilst the production of bitumen has risen rapidly, due to the rising demand of American refiners for heavy crude. Figure 19 shows total export of crude to the United States disaggregated according to the crude's API gravity. Heavy crude (API ≤ 25) represents the largest share of crude export from Canada to the United States and its share on total export has risen dramatically over the last 20 years:

Figure 19 Daily export of crude oil to the United States, in m^3 / day, 1985-2018

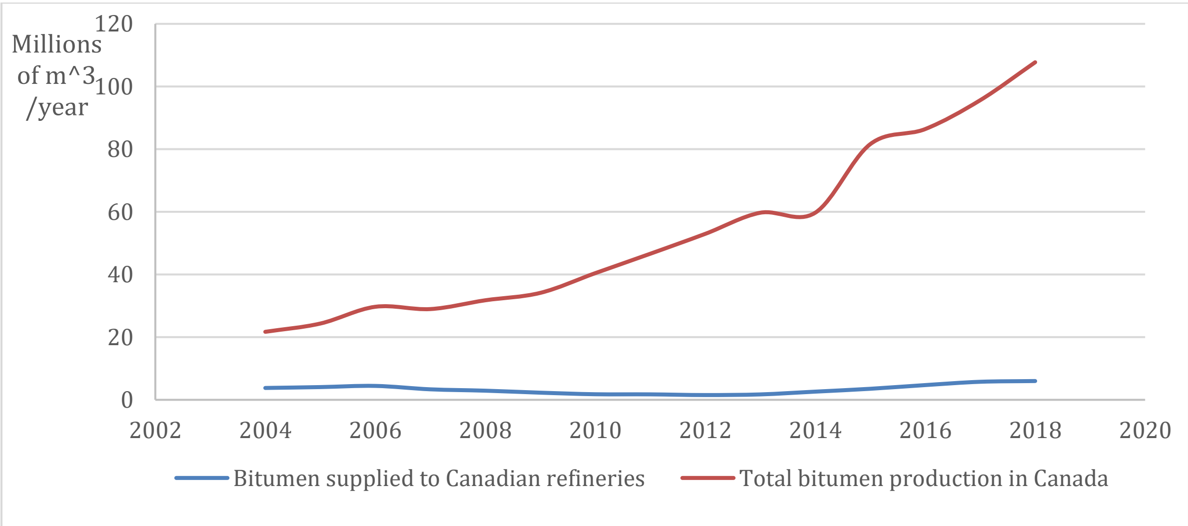
1. Additional refining facilities (hydrocracking, hydrotreating, etc.) further expands the value of the index (Energy Information Administration, 2012).



Source: Canada Energy regulator (2022).

98% of crude exports from Canada go to the United States. Figure 20 shows the quantity of crude bitumen purchased by Canadian refineries in comparison with the total quantity of crude bitumen produced since 2004.

Figure 20 Total bitumen production and supply to Canadian refineries, in m^3/year, 2004-2018



Source: Canadian Association of Petroleum Producers, 2021 and Statistics Canada, 2022b

4.4 Methodology

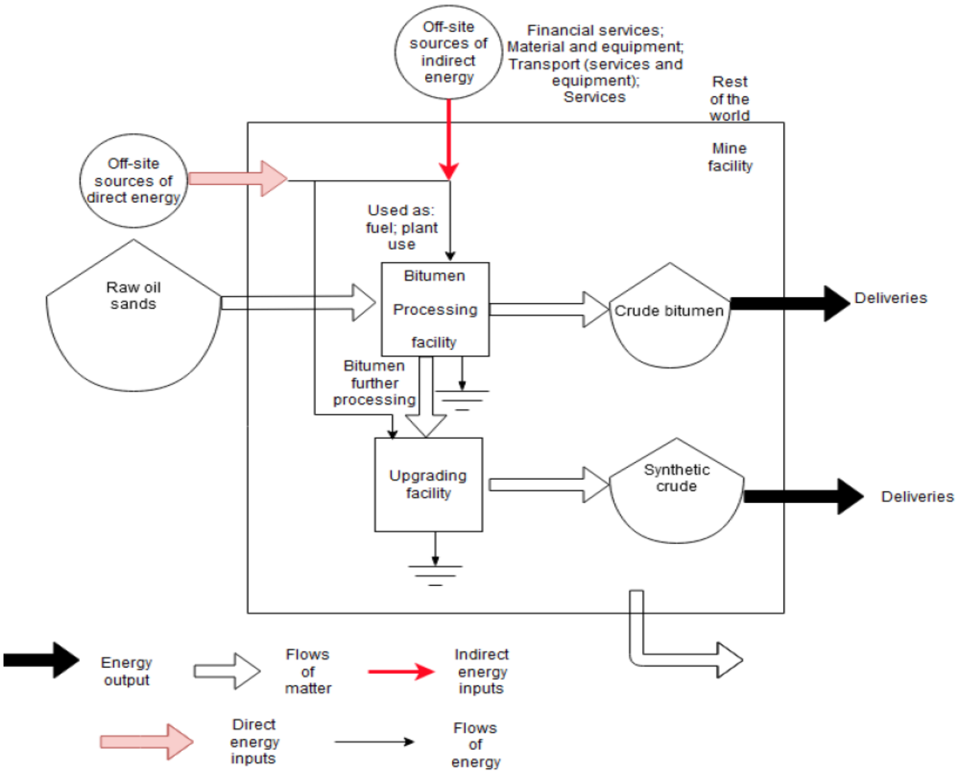
This section presents the methodology used to estimate the profitability of oil sands extraction via open-pit mining and the upgrading of a portion of the bitumen extracted via this mining method. We first define the transactions from which our financial indicators are derived and why these transactions can be compared with our $EROI_{st}$ data. We use Guay-Boutet's (2023) time-series for the $EROI_{st}$ of diluted bitumen extracted via open-pit mining and the portion of bitumen upgraded into syncrude on these sites and shipped at the mine-mouth. Therefore, our financial indicators must reflect the location from which the net-energy estimates were built:

A) Mined crude bitumen sold at the mine-mouth;
B) Diluted bitumen upgraded into synthetic crude on the site of extraction and sold at the mine-mouth.

Publicly available data allow us to disaggregate production costs into capital expenditures and operation expenditures. For syncrude, the cost of bitumen used as feedstock in upgrading must be considered in production costs. For profitability, we use a price to cost ratio as a measure of profitability, i.e. the return per barrel divided by the cost per barrel. Because EROI is a ratio, a comparison of a biophysical with a financial ratio such as price-to-cost is more coherent. Our data on oil sands-derived crude cover crude bitumen extracted via open-pit mining only and bitumen upgraded into syncrude on-site from 1997 to 2016. Whereas syncrude was produced all along the period under study, diluted bitumen produced via open-pit mining started to be sold on the market in 2001 only. Before 2001, bitumen produced via open-pit mining was used as feedstock in bitumen upgrading only. It is impossible to estimate the $EROI_{st}$ of bitumen used as feedstock in the absence of bitumen sold as output. Consequently, our data on the $EROI_{st}$ and price, production cost, and price-to-cost of diluted bitumen starts in 2001. The financial data on bitumen mining prior to 2001 below are to be understood as the portion of the production cost of syncrude corresponding to bitumen as feedstock.

Figure 21 is a material-flow diagram representing the boundaries of our analysis. From 1997 to 2016, various oil sands facilities extracted bitumen, processed it into bitumen to be sold on the market and diverted a portion of the bitumen extracted to be upgraded into synthetic crude and sold. Our analysis focuses on these mines only.

Figure 21 Material and energy flow diagram of an oil sands mining facility



4.4.1 Measure of profit

To measure profitability, we compute the ratio of the price of output to the price of the *technically required inputs* per barrel produced by the mines under analysis. We focus on the costs of diluted bitumen and syncrude directly linked to production, that is the *capital and operation costs*, as they are the most relevant basis of comparison with a biophysical ratio. By contrast, costs like sales and income taxes or royalties, which are imposed by governments on firms, depend on political decisions rather than the technical requirements of production. Similarly, financing costs depend on financial market conditions that are not directly linked to the production process and should thus not be expected to vary in sync with biophysical realities. We do not account for carbon taxes either as the social cost of carbon involves ethical assumptions on the weight of future monetary values (Fleurbaey et. al., 2019). Furthermore, an estimation of the respective GHG emissions for diluted bitumen and synthetic crude production would be required to estimate this type of cost (see Choquette-Levy et. al., 2013)

Our metric is built by first identifying the total annual amount for capital expenditures[35] (capex) and operation expenditures (opex). These are disaggregated for both bitumen and syncrude production annually, and then divided by the number of barrels of bitumen or syncrude produced during the year (b) by the facilities under analysis. The components are estimated using data in current $CAN and then summed up to obtain a total production cost per barrel, such as for bitumen in equation 35:

Equation 35

$$PC_{cb} = \frac{CAPEX_{op} + OPEX_{op}}{b_b}$$

where 'PC_{cb}' stands for 'Production costs for bitumen, '$CAPEX_{op}$' stands for 'capital expenditures incurred in open-pit mining' and '$OPEX_{op}$' stands for 'operation expenditures in open-pit mining' and 'b_b' stands for 'barrel of bitumen'.

We then use this as the denominator with the price of the crude stream's benchmark as the numerator of the price-to-cost ratios. We use the Western Canada Select at Hardisty as a proxy for the cost bitumen and the Canadian Light at Edmonton for the price of syncrude to obtain a profitability ratio per barrel:

Equation 36

$$PtC = \frac{PR_b}{PC_{cb}}$$

where 'PR_b' stands for 'price of a barrel of bitumen'. The data on the market price of bitumen and syncrude are annual averages (Canadian Association of Petroleum Producers, 2021). A more precise estimation of profitability would necessitate the knowledge of the price of futures traded by energy and financial companies to predetermine the price of crude. Unfortunately, we do not have access to these data. Prices and total production costs are converted into constant 2016 $CAN, using implicit price indexes disaggregated for the province of Alberta (Statistics Canada, 2022c). The next two subsections indicate the method used to estimate each cost component.

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[35] The first author acknowledges the assistance of Clark Williams-Derry in calculating depreciated capital expenditures.

4.4.2 Capital and operation expenditures

We use the Canadian Association of Petroleum Producers's *Statistical Handbook for* data on capital and operation expenditures as it provides data on annual operation and capital expenditures per segment of the oil sands industry: in-situ extraction, open-pit mining, and upgrading. The last two fall under the purview of our study. 'Operation expenditures' includes field, well, and plant expenditure including the cost of fuel and electricity on mining facilities and some taxes paid by producers to federal, provincial, and municipal governments (Statistics Canada, 2020). Estimating the per barrel cost of operation expenditures required the division of annual operation expenditures per segment of the industry (open-pit mining or upgrading) by the number of barrels (bitumen for open-pit and syncrude for upgrading) produced into these segments.

Unlike other costs, annual capital expenditures cannot simply be divided by annual output since capital investment lasts many years. We therefore elect to impute these expenditures to a stream of years after they are made, following firms' depreciation practices. Unfortunately, firms active in the oil sands sector don't use the same depreciation methods. For example, in 2019, Suncor (the largest firm oil sands production firm by market capitalization level in 2017 (Hussey et al., 2018: 7)) indicated that its depreciation time frame spawned across the ''*expected useful lives*'' of the assets, which for ''*Oil sands upgraders, extraction plants and mine facilities*'', was from 20 to 40 years and 5 to 15 years for mine equipment (Suncor Energy Inc, 2019: 93). Meanwhile, Imperial Oil, the third firm in importance in oil sands extraction by market capitalization in 2017, disclosed a depreciation of 15 years for its equipment on mining sites and 50 years for its mining properties per se (Imperial Oil, 2019: 72). Since there is no consensus and no way to know what exact time frame is used by the firms, we use the median value from Suncor of 30 years for the remainder of the analysis.[36]

A second issue is that there is no consensus for the depreciation method either. Imperial Oil uses a unit of production method whereby ''*Depreciation is calculated by taking the ratio of asset cost to total proved reserves* […] *applied to the actual cost of production*.'' (Imperial Oil, 2019: 57). Suncor (2019: 55) uses the straight-line method, whereby the cost of an asset in year 1 is divided by its useful life. We adopt Suncor's practice, given that it is the largest actor in

[36] Different time frames were tried but they did not influence statistical results in a fundamental way.

the sector. This gives the following equation for capital expenditures imputed on year t, assuming an average useful life of n years:

Equation 37

$$\frac{CAPEXimp_t}{b_t} = (\sum_{i=t-n+1}^{t} \frac{CAPEX_i}{n})/b_t$$

The *Statistical Handbook* provides disaggregated data on capital expenditures by the two segments of the industry of interest for our study from 1997 to 2016. For years prior to 1997, capital expenditures are not disaggregated. Because the depreciation of capital costs meant that in 1997, capital expenditures for the last 30 or 40 years were being paid, we estimated the share of total capital expenditures in the entire oil sands industry pertaining to crude bitumen (open-pit mining) and syncrude (upgrading) production via the following: we calculated the average proportion of capital expenditures attributable to open-pit mining over the total oil sands sector (open-pit mining, in-situ extraction, and upgrading) from 1997 to 2016 and extrapolated it on the aggregate capital expenditures for each year from 1980 to 1997 (commercial in-situ extraction started in 1980 (Oil Sansa Magazine, 2022)). For the years prior, we divided the capital expenditures attributable to open-pit-mining over the total of open-pit and upgrading and extrapolated the proportions over the total capital expenditures from 1958 (first year with capital expenditures reported) to 1979.

4.4.3 Bitumen as feedstock

An additional cost applies for syncrude; the production costs of bitumen processed into syncrude. We estimated the amount of bitumen processed into syncrude using the *Alberta Mineable Oil Sands Plant Statistical Reports #39* on open-pit mining activities (Alberta Energy Regulator, 2022), identifying the quantity of bitumen further processed into synthetic crude in every facility under study and then dividing it by the quantity of syncrude produced for each year under study.[37] We then multiplied this number by the estimated cost of bitumen.

Equation 38

[37] Bitumen used as feedstock in syncrude processing is reported in ST-39 under the rubric ''further processing'' (AER, private communication).

$$C_{BF} = \frac{b_{fp}}{b_s}$$

where ‘‘b_{fp}’’stands for ‘bitumen further processed’ and ‘b_s’ stands for ‘barrel of syncrude produced’. Thus, the production costs for syncrude are equal to:

Equation 39

$$PC_s = \frac{CAPEX_U + OPEX_U + (P_b * C_{BF})}{b_s}$$

where the subscript ‘u’ stands for ‘incurred in the upgrading segment of the industry’.

4.5 Results

This section presents the results of our analysis. Using a simple econometric model, we investigate the existence of a correlation between prices, costs, or profitability and $EROI_{st}$, as well as between prices and costs. As we explain below, since the time series used were not stationary, the estimation was made in first differences for every variable. In none of these cases do we find any evidence that a correlation exists between any given pair of variables.

Table 4 shows data for prices, production costs, cash flows (price – total cost) and price-to-cost ratios in 2016 Canadian dollars for the 2 crude streams. Prices have generally trended upward throughout the period in both cases, with a decrease at the very end, while costs peak mid way and trend down afterwards. Regardless, measures of cash-flow suggest the production is profitable throughout. Accordingly, price-to-cost ratios also remain above 1 for the whole period, but there is less of a discernible trend. Still, ratios tend to be higher later in the period in both cases, though this is less pronounced for syncrude. Finally, $EROI_{st}$ has generally trended up throughout the period in both cases.

Table 4 Prices, costs, and profitability per barrel and $EROI_{st}$ for diluted bitumen and syncrude (1997-2016) in constant 2016 $CAN

	Diluted bitumen					Syncrude				
	Price	Total cost	Cash-flow	Price to cost	$EROI_{st}$	Price	Total cost	Cash-flow	Price to cost	$EROI_{st}$
1997	35.18	25.48	9.70	1.38		45.82	33.67	12.15	1.36	2.78
1998	25.43	21.50	3.93	1.18		34.90	30.38	4.52	1.15	2.64

1999	37.71	25.39	12.32	1.49		44.17	37.50	6.67	1.18	3.47
2000	47.72	24.83	22.90	1.92		61.59	36.48	25.10	1.69	2.93
2001	33.73	27.75	5.97	1.22	8.12	52.71	39.26	13.45	1.34	3.04
2002	43.74	28.38	15.36	1.54	8.97	55.16	43.48	11.68	1.27	3.40
2003	41.18	33.37	7.81	1.23	10.50	54.51	52.12	2.39	1.05	3.67
2004	44.84	32.12	12.73	1.40	12.58	62.66	40.95	21.71	1.53	4.90
2005	47.09	31.78	15.31	1.48	12.18	73.85	42.35	31.50	1.74	4.64
2006	53.48	36.06	17.42	1.48	12.13	76.28	48.40	27.88	1.58	5.44
2007	53.07	32.09	20.98	1.65	11.23	76.68	46.34	30.34	1.65	3.98
2008	74.53	28.80	45.73	2.59	10,76	91.85	43,55	48.30	2.11	4.13
2009	60.07	41.32	18.75	1.45	12.08	67.49	59.45	8.04	1.14	4.19
2010	65.75	30.97	34.78	2.12	12.49	75.80	50.09	25.71	1.51	4.56
2011	72.38	27.40	44.98	2.64	13.14	89.21	51.31	37.90	1.74	3.60
2012	68.89	25.35	43.54	2.72	14.05	80.52	48.39	32.14	1.66	4.13
2013	67.66	26.40	41.27	2.56	13.62	83.54	50.98	32.56	1.64	4.65
2014	68.50	27.11	41.39	2.53	13.05	80.84	48.91	31.94	1.65	5.34
2015	48.47	24.05	24.42	2.02	13.29	56.20	44.34	11.86	1.27	5.14
2016	39.13	23.83	15.30	1.64	13.95	53.95	42.70	11.25	1.26	5.42

First we test for the stationarity of time series. Using a 1% critical value threshold, in all cases we cannot reject the null hypothesis of non-stationarity and all of them turn out to be integrated of order 1. We thus take the first difference of all the variables and use this transformed data for the rest of the exercise.

We then devise a simple econometric model to investigate the existence of a correlation between changes in EROIst and changes in prices, costs, and price-to-cost ratios. Basically, we estimate the following equation to capture first-differences for each of price, costs, and price-to-cost ratios as the left-hand-side variable, for both diluted bitumen and syncrude:

Equation 40

$$(Y_{it} - Y_{it-1}) = \beta_o + \beta_1(EROI_{it} - EROI_{it-1})$$

where the subscript *t* denotes time and i is either syncrude or diluted bitumen. The models are thus kept as parsimonious as possible. In particular, we don't include any lagged variables since such variables did not prove statistically significant in any of the regressions tested with first difference data and their inclusion did not impact the statistical significance of the coefficient on $EROI_{st}$ first differences.

Equation 40 is meant to test the hypothesis of a relationship between financial (Y_{it}) and biophysical ($EROI_{it}$) indicators. The results of the regressions can be seen in Tables 5 for diluted bitumen and 6 for syncrude:

Table 5 Regression results for changes in diluted bitumen $EROI_{st}$ ratios on: changes in market prices, costs of production, and price-to-cost (PtC) ratio (all variables in first differences)

Bitumen	ΔPrices	ΔCosts	ΔPtC ratio
$\Delta EROI_{st}$	-2.612	1.765	-0.167
	(3.138)	(1.556)	(0.156)
Number of observations	15	15	15
Adjusted R-squared	-0.022	0.020	0.010
Standard errors are in parentheses. The coefficient for the constant term is not reported.			
*statistical significance at 10%			
**statistical significance at 5%			
***statistical significance at 1%			

Table 5: values of the coefficients β_1 (first row), the standard errors (second row), and adjusted R-squared (third row) of the regressions of changes (Δ) in diluted bitumen EROIst on changes in market prices, costs of production, and price-to-cost ratio (all variables in first differences).

Table 6 Regression results for changes in syncrude $EROI_{st}$ ratios on: changes in market prices, costs of production, and price-to-cost (PtC) ratios (all variables in first differences)

Syncrude	ΔPrices	ΔCosts	ΔPtC ratio

$\Delta EROI_{st}$	-0.363	-0.229	-0.009
	(4,505)	(2.385)	(0.134)
number of observations	19	19	19
Adjusted R-squares	-0.058	-0.058	-0.059
Standard errors are in parentheses. The coefficient for the constant term is not reported.			
*statistical significance at 10%			
**statistical significance at 5%			
***statistical significance at 1%			

Table 6: values of the coefficients β_1 (first row), the standard errors (second row), and adjusted R-squared (third row) of the regressions of changes (Δ) in syncrude EROIst on changes in market prices, costs of production, and price-to-cost ratio (all variables in first difference).

In both cases, and for all three variables, the coefficients are not statistically significant. That is to say, there does not seem to be a correlation between changes in $EROI_{st}$ and changes in prices, total costs, and profitability.

A related question arising from the literature was the relationship between prices and costs. In other words, do prices move largely in response to costs or are they largely tributary to other factors? To investigate this, we ran a similar model as before, replacing ‘’changes in $EROI_{st}$’’ by ‘’changes in costs’’ and once again, using variables in first differences:

Equation 41

$$(Price_{it} - Price_{it-1}) = \beta_0 + \beta_1 (Cost_{it} - Cost_{it-1})$$

The results are laid out in Table 7. In both cases, there is no discernible correlation between changes in prices and changes in total costs. This suggests that changes in costs may not be the dominant factor in movements in the price level for bitumen and syncrude.

Table 7 Regressions results for changes in diluted bitumen and syncrude prices on changes in the costs of production

LHS variable: Δprice		
	Bitumen	Syncrude
ΔCosts	-0.512	-0.47
	(0.519)	(0.444)
Adjusted R-squared	-0.002	0.007
number of observations	19	19
Standard errors are in parentheses. The coefficient for the constant term is not reported.		
*statistical significance at 10%		
**statistical significance at 5%		
***statistical significance at 1%		

Table 7: values of the coefficients β_1 (first row), the standard errors (second row), and adjusted R-squared (third row) of the regressions of changes (Δ) in diluted bitumen and syncrude market prices on changes in costs of production.

Briefly put, our data suggests no statistically significant correlation between changes in the $EROI_{st}$ of bitumen and syncrude and changes in their price, costs, or price-to-cost ratio, as well as between changes in prices and changes in costs of production. This is broadly in line with our hypothesis that prices likely move independently of $EROI_{st}$, implying a disconnect between the two variables, as well as between $EROI_{st}$ and profitability, which is heavily influenced by price levels. Indeed, changes in prices don't even seem to be related to changes in production costs, which suggests other factors outside the production process are in play. Regarding costs, our hypothesis was that there could be a relationship between them and $EROI_{st}$. However, the statistical results suggest that other factors dominate in the determination of the costs of bitumen and syncrude.

4.6 Discussion

Three main results emerge from the statistical analysis. First, the price of bitumen or syncrude is consistently above the cost of the inputs required to produce them. A full analysis of the profitability of oil sand extraction would require the inclusion of other costs such as financing, carbon taxes or royalties, but this sheds doubts on the claims reported in the introduction that the sector is largely unprofitable. Second, there is no discernible correlation between changes in prices, total costs, or profitability and changes in $EROI_{st}$ for either bitumen or syncrude, which goes against much of the existing literature on the topic but is broadly in line with our hypotheses. Third, changes in prices and changes in costs don't seem to be correlated either for bitumen or syncrude.

These last two sets of results put into question some of the common conceptions regarding the relationship between costs, price, and profitability found in the literature, where it is typically asserted that $EROI_{st}$ and prices or profitability would be linked through costs. Since a lower $EROI_{st}$ is expected to imply a higher cost, if prices reflect those costs, say through a markup structure, a lower $EROI_{st}$ will imply higher prices. Profitability could go either way, depending on which of costs or prices dominate, but lower net-energy returns suggest that profitability should eventually decrease. However, our results suggest that changes in prices and costs are not correlated, which breaks the purported link between $EROI_{st}$ and prices and also profitability, given the impact prices likely have on the latter.

Our analysis suggests biophysical properties such as $EROI_{st}$ ratios are not significantly correlated with monetary indicators such as prices, costs, and profitability. Provided oil-producing firms are profit-driven and make decisions based on production costs and market prices to adjust production, our results suggest their decisions are independent from biophysical qualities. This in turn implies that financial variables are likely poor guides for the management of energy sources, be it with an eventual ecological transition in mind or simply a preoccupation for the durability of the level of complexity of human societies. As such, there may be scope for greater planning and intervention in these sectors by governments or other actors that have a broader horizon than individual firms.

4.7 Concluding remarks

Our study contributes to the literature on the relationship between financial and biophysical indicators in at least two ways. First, we document financial data on the oil sands sector in Canada and estimate its profitability using publicly available data. Along with the fact that our study encompasses a longer time frame, we feel that this approach allows for a closer comparison between financial and biophysical realities than that of Wang et al. (2017), who employed firms' financial statements to estimate the firms' activities in the oil sands. Second, we investigate the relationship between biophysical ($EROI_{st}$) and financial (costs, prices, profitability) indicators. We show that in the case of the oil sands, there is no discernible correlation between any pair of variables estimated in first differences. This stands in contrast to much of the literature on the topic, in which it is commonly argued that there is a negative linkage between $EROI_{st}$ and prices and suggests that the issue should at the very least be investigated further, at different levels and with more case studies, as it bears some importance with respect to policy in the energy sector.

There are also some limitations to our analysis which motivate further study. Data availability forced us to select the spot price to estimate oil sands-derived crude market price at the mine's gate. However, a large portion of energy products are exchanged via futures whereby the price of the product is predetermined. A more realistic profit-estimation approach would necessitate incorporating futures prices. Moreover, our data on the $EROI_{st}$ of oil sands production start in 1997, which makes for a relatively short timespan and forces us to use very parsimonious models. Lengthening the period under study or adding data on comparable cases would allow for a more detailed analysis. Similarly, using annual data prevents the study of intra-year variations, which could notably be relevant if production decisions are not consistently made annually. For example, because of the high volatility of crude oil prices, monthly data could indeed reveal interesting patterns, such as the price of energy in mining facilities increasing in the winter due to the cold temperatures in Northern Alberta.

A final limitation of the study is the boundaries of our $EROI_{st}$ ratios, which were collected at the mine's mouth. It could be interesting to investigate possible relationships between biophysical and financial indicators further downstream. King observes lower EIR of fossil fuels as they progress in the supply chain (higher EIR at extraction than at refining) (King, 2010: 4). Further research might thus include the net-energy of refining processes and transport further downstream. Such studies would inevitably find a lower EROI value than those estimated in this paper. Indeed, Hall et al. (2009) shows that refining uses approximately 10%-equivalent of energy in a barrel of crude, minus a further 17% of a barrel's output which ends up as non-fuel products. Furthermore, an additional subtraction of 0.52 MJ per-ton mile of crude for pipeline transport must be included in the denominator to account for EROI at the point of use (2009).

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PREFACE TO CHAPTER 5

In chapter 4, after finding data on the spot prices of diluted bitumen and synthetic crude as well as estimating costs of production and profitability for both crude streams for the period 1997-2016, I used a first-difference econometric model to test my hypothesis of a significant, positive correlation between spot prices and profitability with annual changes in $EROI_{st}$ for both crude streams as well as a significant, negative correlation between costs of production and $EROI_{st}$. The results of the six regressions were unexpected as I failed to identify any statistically significant correlation. At the resource level, I was unable to reject the null hypothesis of no correlation between any set of biophysical and monetary indicators.

The second section of the empirical part of my dissertation involves a reiteration of the hypothesis testing conducted in chapter 3 and 4 but at the macroeconomic level. In this second section, I endeavor to test if changes in quality and non-quality corrected measures of energy-use are correlated with changes in economic output at the national level. Furthermore, the existence of causal feedback between monetary and biophysical indicators will be performed as well.

As reviewed in chapter 2, the method used by several neoclassical and ecological economists alike to examine questions of this nature is via Aggregate and Biophysical Production Functions (BFPs), despite the severe logical weaknesses supporting Aggregate Production Functions (APFs) raised during the Cambridge Capital Controversy. As such, the second section of the thesis starts with a review of the history of APFs, their critique by post-Keynesian and ecological economists and the proposal by the latter to correct for the alleged theoretical inconsistencies of APFs. After this historical review, I will be able to conduct a testing of my hypothesis. Knowing what the alleged weaknesses of these modelling techniques are, I might be able to correct for those and strengthen the empirical relevance of my results.

Chapter 5: From aggregate to biophysical production functions: On the history of aggregate production functions, their critique and reappraisals in ecological economics

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Aggregate production functions (APFs) model the production of economic wealth (or ‘’output’’) by means of technical relationships between labor and capital services inputs at the micro and macroeconomic level. The empirical strength (or lack thereof) of APFs at the macroeconomic level has been warmly debated between neoclassical and heterodox economists (Lavoie, 2014: 53), despite the generally acknowledged theoretical and logical weaknesses supporting them, following the Cambridge capital controversy. Amongst the issues debated during the controversy was how to rigorously define ‘’capital’’, a notion conventionally defined as a stock of something that yields flows of goods and services across time (Blanco and Costanza, in Cramer et. al. (dir.) 2019). From the 1950s to the mid-1970s, neoclassical and post-Keynesian economists (respectively from Cambridge, Massachusetts and Cambridge, United Kingdom) debated the merits of APFs in meaningfully measuring ‘’capital’’ stocks and flows and their predictive power on the distribution of national income between capital (profit) and labor (wages).

In our view, a problem arising from both sides of the debate is the absence of biophysical factors (natural resources, energy flows, etc.) as a meaningful variable in the production of output (see, for example: Robinson, 1954, 86; Cobb-Douglas, 1928: 165) in standard, two-inputs APFs or in their critique by the post-Keynesians. The role of energy in output production has been the hallmark of Ecological and Biophysical Economics.[38] Some ecological economists have tried to incorporate different measures of energy flows into production functions. However, a question remains: are production functions useful to analyse production of economic output even if energy is accounted for as a full-fledged input? If energy-use and production of output are causally related, how can this causality be characterized? Santos et. al. identify four possible chains of causation (or lack thereof): unidirectional causality from 1) energy use to output; 2) from growth in output to energy consumption; 3) bidirectional causality

[38] The distinction between the biophysical and ecological schools of economics stems from the biophysical economists’ critique of ecological economics’ alleged focus on the quantification of the market value of ecosystem services and disregard for energy (see Hall and Klitgaard, 2018). However, based on their common theoretical lineage and agreement on the biophysical basis of the economic process, this paper does not address the differences between the two schools.

(or feedback) and 4) no causality (Santos et. al., 2018: 107). Can an empirical study of the relationship between output production and energy, capital and labor shed light on what causal chain (if any) is the most plausible between biophysical and human-made inputs and output production?

The aim of this section of the thesis is twofold. First, I wish to revisit the debate surrounding production functions and their critical incorporation in ecological economics. Second, I aim to test the merits of these theoretical options by testing the statistical relationship between economic growth and various indicators of energy-use in Canada from 1961 to 2022. I use three distinct measures of energy to estimate its role in output growth according to corrections (or lack thereof) in the quality of energy flows: a) primary and secondary energy flows; b) net-energy ratios and c) exergy flows. My objective is to estimate the share of energy along other standard factors in output growth and to investigate the impact of changes in the correction for energy quality in production functions.

The discussion is divided into a theoretical and empirical chapter. In this chapter, I revisit the history of production functions from early marginalist theory to Robert Solow's models based on static equilibrium. The critique of production functions by post-Keynesian economists is reviewed. I underscore the absence of biophysical inputs in both research traditions and move on with the presentation of models of production function including energy developed in ecological economics where economic aggregates are measured partially in biophysical units. The theoretical discussion is followed by Chapter 5, where several models of production functions are tested.

The chapter is divided as follows. Section 5.1 reviews the concept of aggregate production functions (APFs) in contemporary microeconomics. In section 5.2 I review the history of production functions from the early marginalists to the 1928 Cobb and Douglas's seminal paper and review Robert Solow's model of growth, one of the most influential neoclassical models of economic growth based on APFs. A review of the post-Keynesian critique of neoclassical production functions is presented in section 5.3 followed by models of economic growth from ecological economics explicitly accounting for energy-use in section 5.4.

5.1 Production functions: a theoretical review of microeconomic production functions

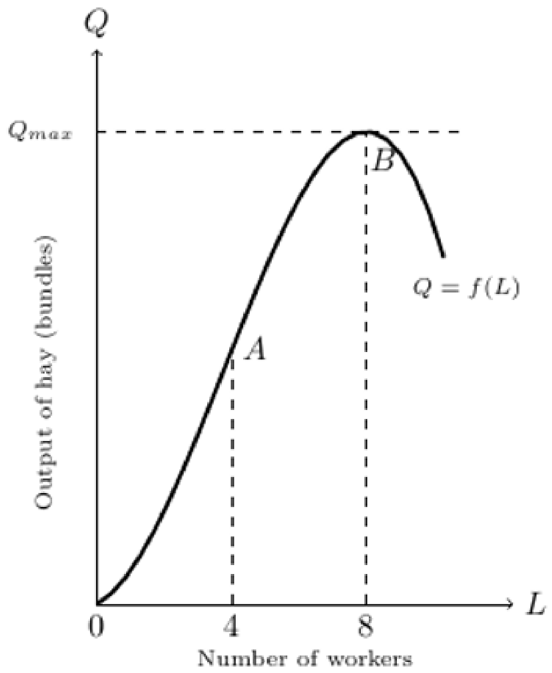
In this section, I review the history of production functions. Because APFs were formulated in analogical terms with microeconomic production functions (Shaikh, 1974: 115), the discussion starts with a presentation of micro-economic production functions. Contemporary neoclassical microeconomics is built upon the concept of marginal physical product (MPP), defined as the change in output (measured in physical units) associated with the change of one unit of input:

Equation 42

$$MPP = \frac{\Delta Q}{\Delta L}$$

where ‘‘Q’’ refers to output measured in physical units. Over the short term, marginal productivity, that is the additional output resulting from the addition of one unit of input, is assumed to increase from no to a few units of input (over the short-term, labor) used. As more units of labor are added, the marginal quantity of output produced from increasing inputs declines. Once a threshold is met, adding more units of inputs brings total output to decline. Graphically:

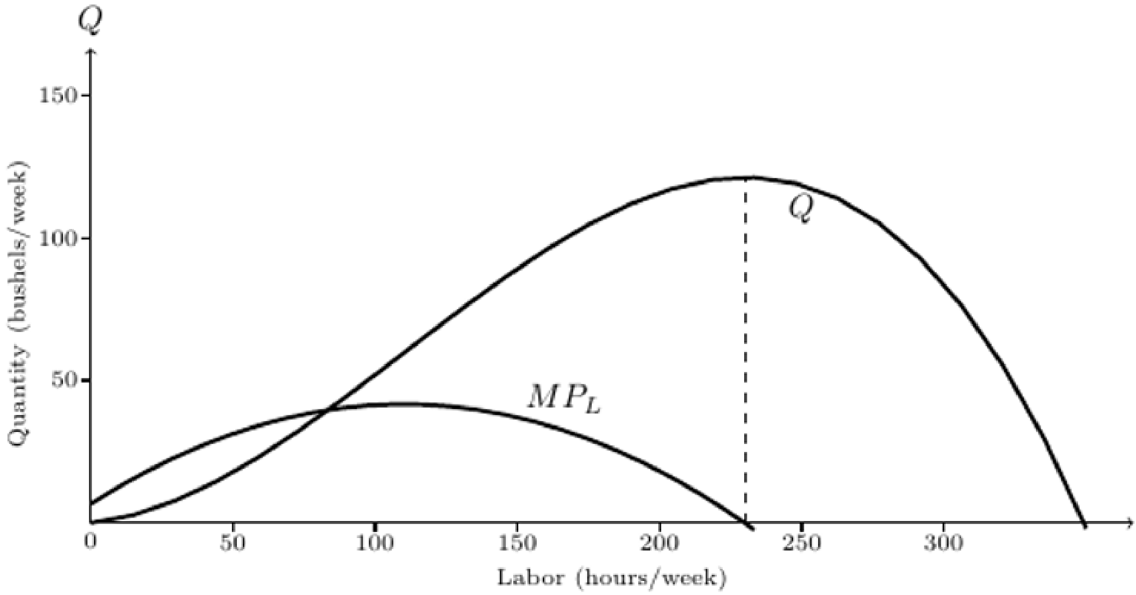
Figure 22 Production function with one variable input



Source: Mahanty, 1980: 148

In Figure 22, from 0 to 4 workers L, marginal physical product increases, with the curve Q = f(L) displaying increasing returns. From 4 to 8 units of labor, total returns increase but marginal returns decrease, as suggested by the flattening of the curve, i.e. decreasing returns. After 8 units of input, total output declines. In theory, rational profit-maximizers will produce up to the equimarginal point, that is until the MPP of input L is equal to the price of the commodity-output. Beyond this point, the costs associated with increasing inputs surpass the income generated from the sales of additional output. Figures 23 and 24 illustrate the relationship between production, marginal and average productivity:

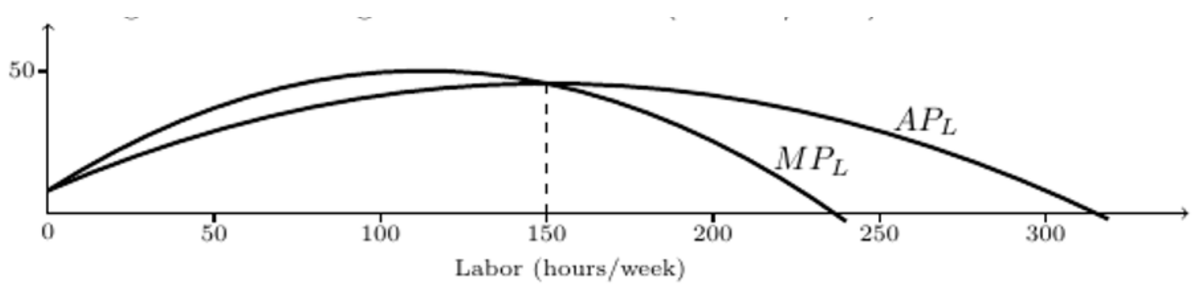
Figure 23 Production function and marginal productivity



Source: Bumas, 2015: 120

In Figure 23, marginal productivity displays increasing returns to scale from 0 to 100 units of labor and decreasing returns to scale from 100 to 230 units. Profit-maximizing capitalists will keep on increasing inputs employed up until 230 units, where marginal physical product is equal to 0.

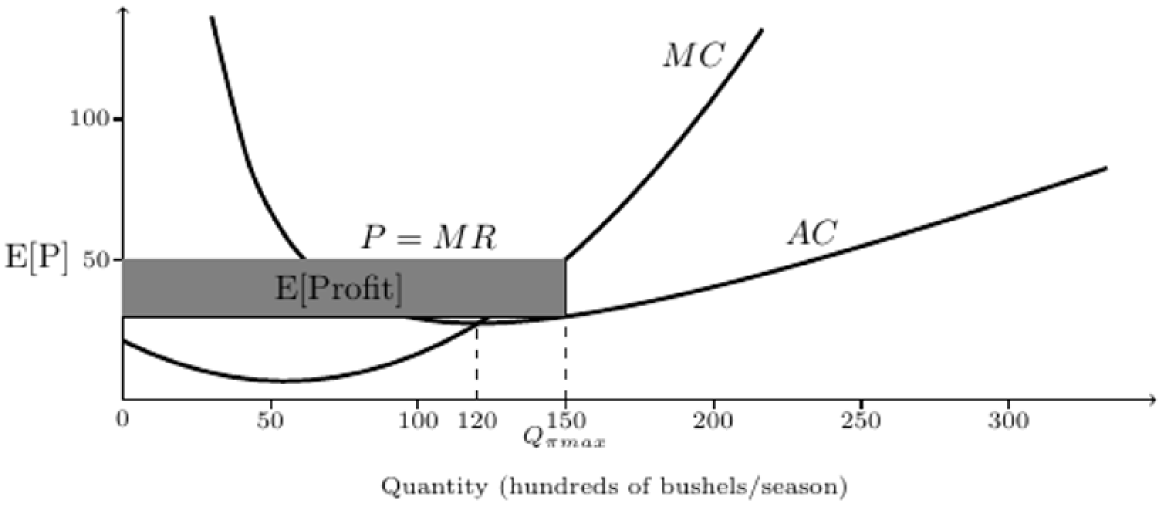
Figure 24 Marginal and average product of labor



Source: Bumas, 2015: 120

Figure 24 shows the relationship between the average and marginal production functions, intersecting where the average product is at its maximum at x = 150. Average production is defined as the total output divided by the number of units of inputs. Figure 25 shows the relationship between the quantity of goods produced and profitability (assuming perfect competition and price stability):

Figure 25 Average, marginal cost and profit



Source: Bumas, 2015

At 150 units produced, the capitalist maximizes its profits (revenue minus cost), equal to the rectangle representing the product of the number of units produced on the x-axis and the difference between the market price/marginal cost and average cost on the y-axis. Revenue is equal to price on the 150th unit. Assuming prices remain constant, marginal revenue is equal to prices. Marginal costs (changes in variable costs associated with producing an additional unit of output), after reaching a minimum at 50 units produced, increase from 50 to 150 units produced, where they are equal to price. The marginal cost of the 151st unit exceeds its price, generating a loss.

The maximum value of the marginal productivity curve (at x = 100 units) corresponds to the point where the scale of returns of the production function turns from increasing (greater than 1) to decreasing (less than 1 but greater than 0). At 150 units, the value of the average production function starts declining and intersects with the marginal production function:

Equation 43

$$\frac{AP_{150}}{MP_{150}} = 1$$

It can be shown that at this point, output elasticity of the variable factor labor α is equal to 1, implying that output elasticity is equal to the marginal and average productivity:

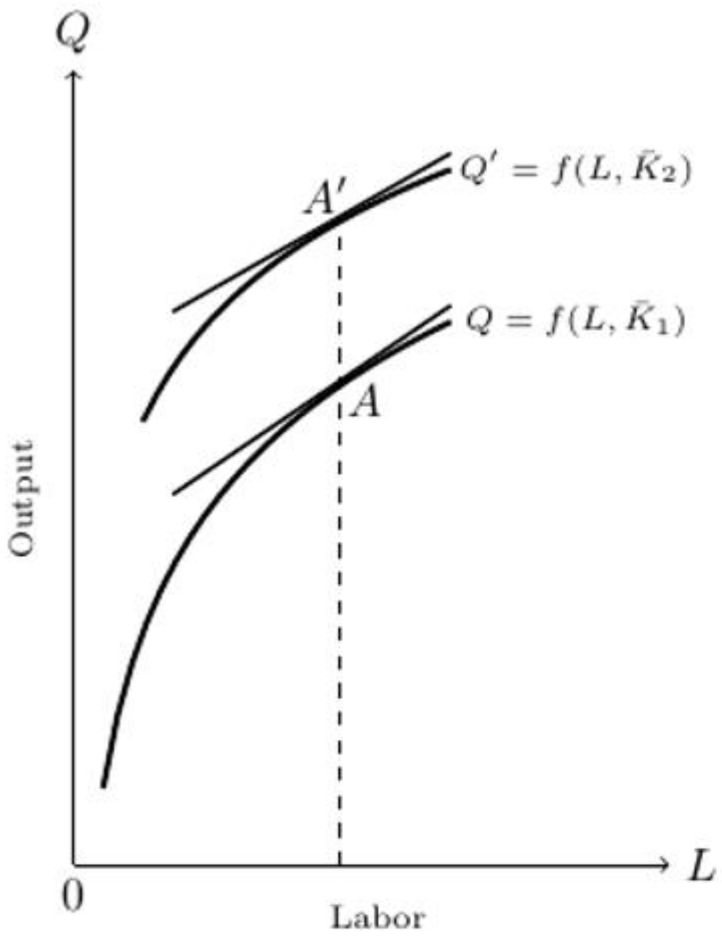
Equation 44

$$a = \frac{\Delta Q}{\Delta L}$$
$$= \frac{\frac{\Delta Q}{L}}{\frac{\Delta L}{Q}}$$
$$= \frac{\Delta Q}{Q} * \frac{L}{\Delta L}$$
$$= \frac{\Delta Q}{\Delta L} * \frac{L}{Q}$$
$$= \frac{\frac{dQ}{dL}}{\frac{Q}{L}} = a$$

Equation 44 shows that in theory, output elasticity of labor can be equal to the ratio of marginal to average productivity. When that ratio is equal to 1, then output elasticity of labor is equal to 1 as well. At this point, the income of the last unit of labor hired is equal to the market value of the output it produces. At the margin, labor income is strictly equal to its marginal productivity.

Increasing productivity over the long-term necessitate changes in the quantity of capital, the second factor of production, as illustrated in Figure 26:

Figure 26 Increasing productivity with changes in capital and labor



Source: Mahanty, 1980: 156

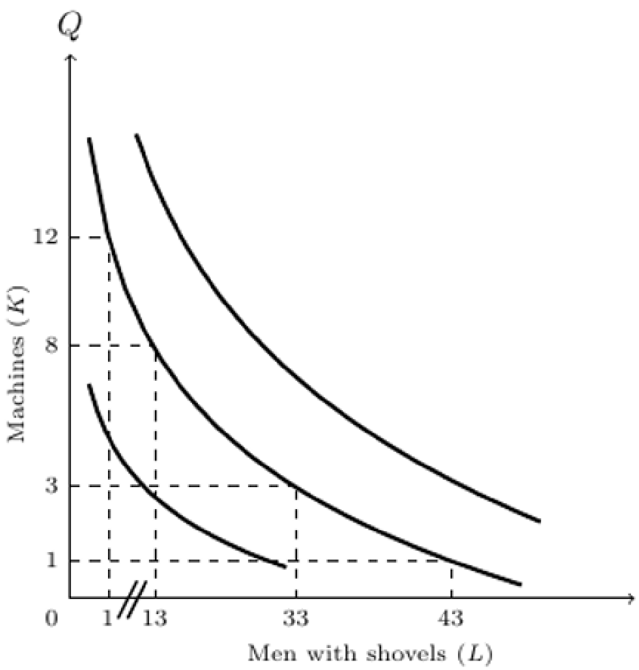
Productivity (measured in terms of output per unit of input) increases with the quantity of capital used, from K_1 to K_2. MPP of labor remains unchanged, as suggested by the slopes of the tangents at points A and A' being equal. Because any point along Q and Q' is now a function of two factors, the production function is restated as:

Equation 45

$Q = f(K, L)$

Every possible value of Q can be represented by a point along a function showing every possible combination of inputs yielding this output: the isoquant. Several isoquants represent a production function, such as in Figure 27 where each isoquant represents one quantity of output:

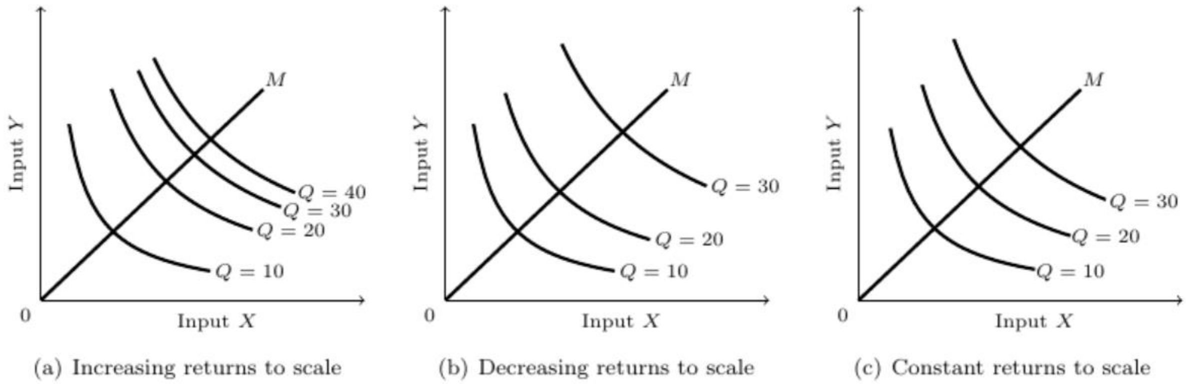
Figure 27 Three isoquants representing three production functions



Source: Mahanty, 1980: 165

Land and natural resources are excluded as a third factor of production because once labor is used to work the land, the latter is no more in its ‘’natural state’’, therefore becoming capital (Bumas, 2015: 119-120). Isoquants can be used to represent returns to scale, as in Figure 28:

Figure 28 Increasing, constant and decreasing returns to scale



Source: Mahanty, 1980: 172.

Figure 28 shows the three possible returns to scale, i.e. proportional increases in output when inputs are increased simultaneously. For example, when a 11% increase in inputs X and Y induces a 33% increase in output (left-most graph in Figure 28 focusing on isoquants Q = 30 and Q = 40), the firm is experiencing increasing returns to scale: increase in output is superior to increases in inputs. The shifts of the isoquants to the right on each diagram illustrates the ‘’expansion path’’: each isoquant represents one coordinate along a production function (Mahanty, 1980: 165, 172).

In Figure 27, it is assumed inputs are substitutable, i.e. 12 units of machines can be changed to 8 if 1 unit of labor is increased to 13. Marginal rates of technical substitution (MRTS) are defined as how many inputs must be added/subtracted when the second input changes to produce the same quantity of output. The value of MRTS is equal to the slope of the isoquant at a particular point of the curve. The convexity of the isoquants illustrates that the quantity of one input that must be substituted with one unit of the other input to yield the same output increases further down and up the slope. Isoquants can be used to estimate the optimal value of output, which occurs when the price of inputs K and L is equal to the ratio of their marginal products:

Equation 46

$$MRTS = \frac{\Delta L}{\Delta K} = \frac{MPP_K}{MPP_L} = \frac{P_K}{P_L}$$

A production function can be represented along with output elasticities of each factor. ‘‘Output elasticity’’ refers to the percentage change in output following a percentage change in the input of interest. Restating Equation 45 with output elasticities of factors yields:

Equation 47

$$Q = f(T) * (L^{\alpha}, K^{\alpha-1})$$

where ‘’T’’ is a constant. Equation 47 means that a α% increase in input L is required to induce a 1% change in output Q (Mahanty, 1980: 176). For example, let’s assume a firm uses 16 units of labor and 64 units of capital, each of them displaying a 50% elasticity of output, to produce 32 units of output. It then increases its inputs of labor by 10%:

Equation 48

$$16^{0.5} * 64^{0.5} = 32$$
$$(16 * 1.1)^{0.5} * 64^{0.5} = 33.56$$

The increase in output is 5%. Dividing the 5% increase in output by the 10% increase in input gives 0.5, the value of α (Mahanty, 1980: 457). Elasticity of output is better illustrated by taking the derivative of Equation 47:

Equation 49

$$lnQ = (a * lnK) + ((a - 1) * lnL)$$

which is tantamount to expressing the percentage change of Q with respect to percentage changes in inputs (Mahanty, 1980: 457).

Production functions show that in theory, output elasticity of factors can be equal to the factor's share in total income. Expenditures in production necessarily being an agent's income, then the sum of labor and capital income is necessarily 100% of output in a perfectly competitive economy. The wage rate is set by the marginal unit of labor employed to produce output as capitalists are assumed to produce up to the point where the marginal costs of inputs are equal to the marginal benefits of an additional unit produced. Thus:

Equation 50

$$W = MPP_L = \frac{\partial Q}{\partial L}$$

where ''W'' means ''wages''. Taking the first derivative of the marginal product of labor yields the wage rate:

Equation 51

$$\frac{\partial Q}{\partial L} = a * T * L^{1-a} = a\frac{Q}{L}$$

where ''T'' is a constant used to harmonize the units on both sides of the equation. Simplifying, we obtain the share of wage in national income:

Equation 52

$$W * L = a * Q$$

The marginal product of labor times the output is therefore equal to the share of wages in national income. A similar method is used to show the share of capital in national income, r, is equal to output times the MPP of capital β:

Equation 53

$$r * K = \beta * Q$$

Substituting, we find:

Equation 54

$$Q = (W * L) + (R * K)$$

Equation 54 shows the equality between output, the income shares of factors and their marginal productivity (Bumas, 2015) in a perfectly competitive economy.

Production functions are at the core of neoclassical microeconomics. Can they be aggregated at the macro-economic level? The next section reviews theories of production at the macroeconomic level from early marginalists to modern neoclassical economics.

5.2 Macroeconomic production function: from Wicksell to Robert Solow

5.2.1 Early production functions

For marginalist economic theory, production is over-determined by a theory of exchange, where the former is strictly symmetrical with the analysis of marginal utility (Pasinetti, 1977: 25). Knut Wicksell is probably the first marginalist economist (to our knowledge) to have developed a mathematical theory of production:

Equation 55

$$Y = f(L, T)$$

where output ‘’Y’’ is a function of labor (L) and land (T). Defining ‘’r’’ as payment to landowners, it follows:

Equation 56

$$Y = wL + rT$$

Should Equation 56 be continuous and convex, then the marginal product of labor will be equal to wages. If the same holds for the marginal product of land, then:

Equation 57

$$Y = \frac{\partial Y}{\partial L} L + \frac{\partial Y}{\partial T} T$$

As pointed out by Wicksteed, owing to Euler’s theorem, Equation 57 is true if it is homogeneous to the first degree, i.e. if it displays constant returns to scale. This functional form implies: 1) factors L and T are paid their marginal products; 2) net output is distributed among the two factors completely, without residue (Robinson, 1934). Equation 57 is a homogeneous function of the first degree if both sides of the equality can be multiplied by factor m such that:

Equation 58

$$mP = m(a, b, c \dots n)$$

If the economy follows Equation 58, then payments to factors are completely distributed between workers and landowners. Solutions are impossible unless increases in output are strictly proportional to increases in inputs (Robinson, 1934).

4.2.2 Introducing capital in early production functions

Wicksell's theory stumbled across conceptual difficulties as soon as marginalist thinkers tried to introduce capital as a factor into Equation 57. Doing so implies knowing capital share in output (profit, i.e. percentage of national income paid to capital). However, knowing the rate of profit is predicated upon knowing the value of the capital stock. According to Robinson, the difficulties associated with introducing capital into production functions stem from two distinct definitions of ‘’capital’’ in marginalist Economics. In Walras' work, capital is defined as a list of machines denominated in physical terms.[39] The price of capital is its rental price, denominated in the same physical units used to denominate the goods they help produce. A second line of thought defines capital as a fund of savings where the price of capital is a rate of profit, i.e. the long-term rate of return on capital under long-term, competitive equilibrium. Confusion of the two definitions leads to conceptual challenges: changes in technical relationships can be performed by ‘’squeezing’’ or ‘’spreading’’ a constant quantity of capital onto an infinitely differentiable quantity of labor. If 9 workers use 9 units of capital (or ‘’leets’’), adding a tenth laborer is possible by squeezing the units of capital into a tenth and sharing one-tenth of the output with him (Robinson, 1970: 311-312).

4.2.3 The Cobb-Douglas production function

The empirical foundations of production functions took a giant leap in 1928, when Cobb and Douglas attempted to quantify how relative changes in units of capital and labor-use causes relative changes in the production of output and the shares of inputs in national income, using empirical data from the American economy. Cobb and Douglas provided empirical grounds for production functions, whose logical problems had only been dealt with theoretically

[39] ‘’ ‘’Capital’’ is not what capital is called, it is what its name is called. ‘’ (Robinson, 1954: 83).

(Biddle, 2012). The objective of Cobb and Douglas was to prove the marginalist theory of distribution (see Equation 54) which posits that output elasticity of labor and capital in APFs accurately predicts their share of income in the economy, so that the partial derivative of capital would be equal to the rate of profit (Pasinetti, 1977: 30).

Cobb and Douglas proceeded by building indexes of the changes in output, labor (wages) and capital (defined as machinery, tools, equipment and factory buildings in constant $US) from 1899 to 1928 using publicly available data from U.S. federal and state agencies. The authors chose to emulate the Euler formula to propose a production function, explicitly citing Wicksteed (Cobb and Douglas, 1928: 151) as a reference to their own model (see Equation 57):

Equation 59

$$Y = b(L^{a} * K^{1-a})$$

Using Douglas' historical time-series on the index value of capital and labor, Cobb and Douglas plugged these values into Equation 59, estimated the value of coefficient α by the method of least squares and predicted the values of Y yielded by the model (Biddle, 2012: 225). To estimate α, the authors investigated the changes in the index of capital, labor and output on a logarithmic scale, finding the values of b, K and 1-K to be 1.01, .75 and .25 respectively, using the method of least squares. Therefore:

Equation 60

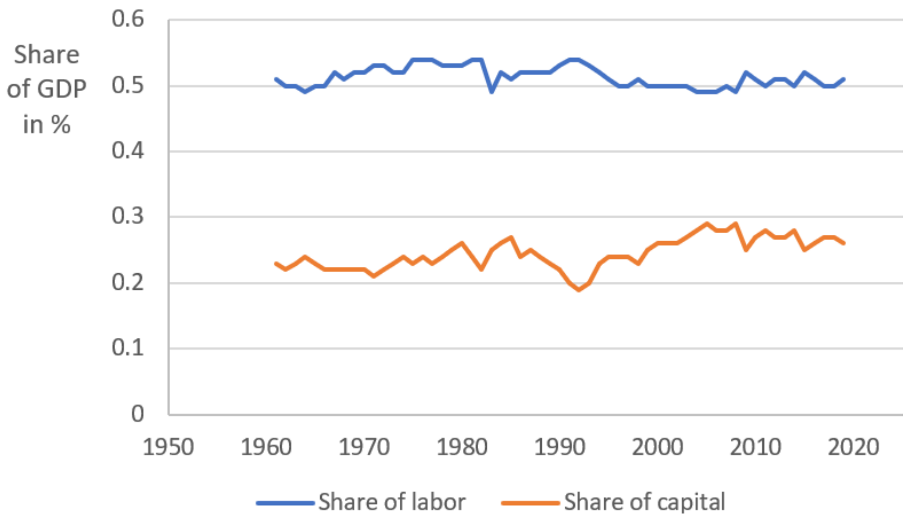
$$Y = 1.01(L^{0.75} * K^{0.25})$$

The authors found a correlation coefficient of 0.97 for Equation 60 over their time-series, thus concluding the value of α to be empirically and theoretically valid: not only is there an intrinsic relationship between labor, capital and economic output, but the predicted (Y') and observed value (Y) of output and their three-years moving average move ''closely together'', thereby excluding the possibility of a fortuitous secular trend upward between the indexes (Cobb and Douglas, 1928: 160).

Taking Canada as an example, the share of wages and capital income in output seems to confirm Cobb and Douglas' theory. From 1961 to 2020, their respective share in total GDP has been remarkably constant[40] and close to the value predicted by Cobb and Douglas:

[40] The difference between '1' and the sum of the two factors in the table are to be attributed to the consumption of capital by government and non-profits plus the income of unincorporated businesses.

Figure 29 Share of payments to capital and labor in Canadian GDP, in constant 2018 Canadian dollars, 1961-2019



Source: Statistics Canada, Table 36-10-0103-01, Gross Domestic Product, Income-Based. Author's calculations.

To test whether the model closely follows distribution of income between laborers and capitalists, Cobb and Douglas compare the relative exchange value of a composite unit of manufactured goods to obtain a proxy of the relative value of product per laborer compared with the relative movements in real wages across the period studied. They find a correlation of 0.69 between the two, rising to 0.89 when the correlation of the 7-years averages is estimated, therefore suggesting that distribution follows production with a slight lag. Interestingly, the authors conclude the paper emphasizing the need of pursuing research further by including natural resources as a third factor as well as the impacts of doing so on the law of rent (Ibid: 165).

However, the very hostile reception of their results at the 1927 meeting of the American Economic Association might explain why this line of research was not pursued by the authors. It was not before Solow's papers in the 1950s that the work of Cobb and Douglas became widely accepted by neoclassical economists. Interestingly, the hostility stemmed equally from heterodox institutionalists, hostile to econometrics, to neoclassical theorists, who scorned at attempts to quantify the value of intrinsically theoretical parameters and econometricians alike, who disputed Cobb and Douglas' statistical interpretation (Felipe and McCombie, 2013: 137-

139). Econometricians emphasized the need to estimate the empirical value of output elasticities instead of assuming their sum to be equal to unity, while others underscored the multicollinearity between the variables. The issue of multicollinearity was addressed by Douglas in the 1940s in papers estimating the values of the coefficients including cross-industry regression, showing the value of α to be close to the value found in 1928. However, Felipe and McCombie (2013) emphasize the lack of empirical grounds for inter-industry regression, arguing how unlikely different industries display similar production functions. Others criticized the absence of technological progress from the production function, in which growth is explained by the growth in labor and capital only, which is at odds with the empirical development of technologies in industry in the early twentieth century.[41]

5.2.4 The Solow-Swan production model

With his 1956 and 1957 papers, Robert Solow laid the ground for one of the most influential models of economic growth, the Solow-Swan model, in which economic growth is a function of capital accumulation, changes in labor force and total factor productivity, itself a function of technological progress (Santos et. al., 2018: 103). The Solow-Swan model of economic growth was developed independently by Robert Solow and Trevor Swan. For simplicity, this paper focuses on Solow's work. Solow's basic argument is to emphasize the difference between shifts in production functions due to technical change increasing the output/input ratio while leaving MRTS unchanged and shifts along the function due to changes in capital/labor ratios (Shaikh, 1974: 117). Whereas Keynesian economists Harrod and Domar believed labor and capital were complements, Solow wishes to demonstrate factors are substitutes (Pellegris, 2022).

Solow's model of the economy is formed by aggregate households and firms where households own the factors of production and rent them to firms. A single product forms the output of the economy, defined as Y(t). The fraction of output that is not consumed is saved and invested:

Equation 61

$$\delta K = sY = sF(K, L)$$

The labor force grows at a constant rate n (equal to δL):

[41] Re-estimating the value of output elasticities using Cobb and Douglas data for 1899-1928 using more modern econometric techniques such as rolling regressions, Felipe and McCombie find the output elasticity of capital to be negative (-0.449) (Felipe and McCombie, 2013: 149).

Equation 62

$$L(t) = L_0 e^{nt}$$

Assuming L_0 to represent fully employed labor and substituting 62 into 61 yields:

Equation 63

$$\partial K = sF(K, L_0 e^{nt})$$

which represents the changes in capital that must happen for full employment to occur. Dividing L out of F in Equation 63 yields:

Equation 64

$$\frac{L}{K} = \frac{1}{\frac{K}{L}}$$

Substituting Equation 64 in 63 yields:

Equation 65

$$\partial \frac{K}{L} = \frac{K}{L} * \frac{sF(K, L)}{K} - n * \frac{K}{L}$$

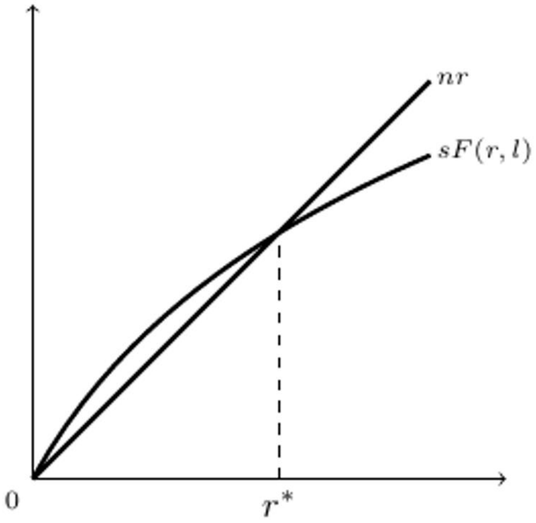
where $\frac{K}{L}$ is equal to the capital ratio r. Thus, Equation 65 can be rewritten as:

Equation 66

$$\delta r = sF(r, 1) - nr$$

Equation 66 states the fundamental relationships of the capital-labor ratio. When Equation 66 is equal to $(\frac{K}{L})$ ('r' in Figure 30) the growth path is respecting a Harrod-type balanced growth: the economy is stable. Figure 30 illustrates:

Figure 30 Rate of change of the labor force and capital stock



Source: Solow, 1956: 70

In Figure 30, the rate of change in capital (sF(r,1)) displays diminishing marginal returns and the rate of growth of the labor force nr is constant. Growth is balanced whenever the rate of change in capital is equal to the rate of change in the labor force. When r is to the right of r*, there is a surplus of capital over labor and the value of the capital/labor ratio declines following declining investments. The capital-to-labor ratio tends toward equilibrium where its relative change is optimal. If the ratio is inferior to its equilibrium point, there is a scarcity of capital: new investment, and thus output, increases faster than the labor force to take advantage of productivity gains (capital has, to the left of r*, a higher marginal physical product) and vice-versa (1956: 70), which will bring the capital per capita back on its long-run growth path (Michaelides and Papadakis, 2023: 111). Saving is positively correlated with the interest rate and, logically, negatively correlated with the capital/labor ratio. If the ratio is too high and there is a surplus of capital savings go down and the growth of the labor force reduces the ratio.

Thus, changing ratios allows for balanced growth where output growth and full employment can coexist. The economy can steer toward equilibrium by the interplay of the growth of the labor force and in capital, provided steady investment (Solow, 1956: 73). In and of itself, this model follows the Cobb-Douglas function. Capital investments display decreasing marginal returns. In the absence of an exogenous factor, capital investments make the economy move towards a stationary state illustrated by the flattening of sF(r,1) (Pellegris, 2022). As Solow shows, only technological change can shift sF(r,1) upwards and steers the economy away from a stationary state.

Solow’s model addresses how production functions are complexified by technological breakthroughs, something Cobb and Douglas did not address. Solow tries to disaggregate the share of variations in output per capita to be attributed to capital versus technological change. To do so, Solow rewrites the Cobb-Douglas production function:

Equation 67

$$Q = F(K, L)(t)$$

where Q is in units of ‘’ commodity ‘’-output (i.e., in physical units), ‘’t’’ stands for time and ‘’F’’ for technical change, (i. e. ‘’[…] *any kind of shift in the production function* […]’’ (1957: 312)) and assuming away ‘’scarce nonaugmentable’’ resource like land (1956: 67). Changes in the quantity of capital stem from a portion of output being saved, that is:

Equation 68

$$\Delta \mathrm{K} = \mathrm{sQ}$$

Substituting Equation 68 into 67 yields:

Equation 69

$$\Delta \mathrm{K} = \mathrm{sF}(\mathrm{K}, \mathrm{L})(\mathrm{t})$$

The right-hand side of Equation 69 measures the flow (unit of output per unit of time) of services from labor and capital. Wages measure the flow of labor services while the rental cost of capital measures profits (Hoover, 2012: 313). Conceptual problems inevitably arise when attempting to measure the flow of capital services. Solow proposes to use a proxy of ‘’capital in use’’ in the United States, estimated by subtracting from the stock of capital the fraction of the labour force unemployed in a year (1957: 314). Then Solow introduces of a multiplicative factor supposed to measure the cumulative effects of technical changes:

Equation 70

$$Q = A(t)F(K^{a}, L^{1-a})$$

where ‘’A’’ is a dimensionless multiplier known as ‘’total factor productivity’’ which represents the cumulated effects of shifts F(t) (see Equation 67) in the production function (the ‘’shift effect’’), or an increasing scale factor (Solow, 1956: 85). The coefficients of capital and labor of Equation 70 sums to one so constant return to scale prevail, following the Euler theorem. Changes in the production function are Hickes-neutral if they operate whilst leaving marginal rates of substitution of inputs unscathed (Solow, 1957: 312). Provided technological changes are completely captured by changes in coefficient A, technological changes are Hicks-neutral.

The function can be expressed in monetary values if one assumes prices can be derived from physical magnitudes. Assuming a circulatory-flow framework of the economy and knowing money does not leave nor enter the economy exogenously, then it is a fair assumption that constant prices somehow reflect physical magnitudes (Felipe and McCombie, 2013: 49). The circular-flow view of the economy assumes the value of output must necessarily be equal to the value of inputs. Then the value of output Q can be defined in terms of payments in units of currency p to factor L and K:

Equation 71

$$pQ = p\big(F(L,K)\big) = Y = (W * L) + (\mathrm{r} * \mathrm{K})$$

From this identity, the production function denominated in monetary units can be derived. Dividing the equality on the right of Equation 71 by p yields:

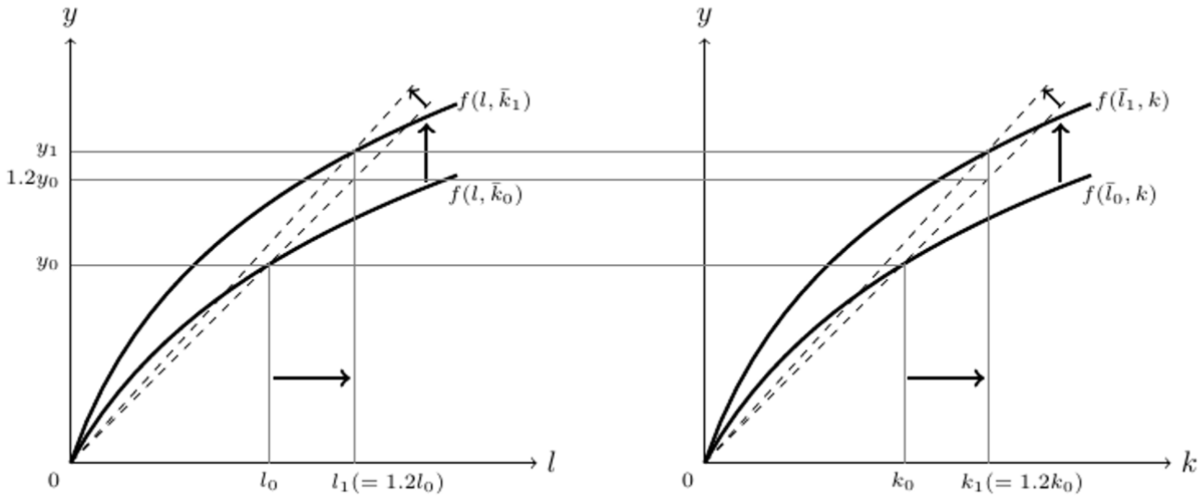
Equation 72

$$Y = \frac{w}{p} * L + \frac{\mathrm{r}}{p} * K$$

as shown by Felipe and McCombie (2013). Output is equal to the units of factors employed time their marginal productivity, assumed equal to their share of national income.

From Equation 72, one can infer: 1) a rise in the quantity of capital causes lower marginal product of the additional units of capital and, consequently, a lower rate of interest all else equal; 2) the share of labor (wage) and capital (interest) out of national income is the result of their relative scarcity and marginal productivity (Cohen and Harcourt, 2003). However, thanks to coefficient A, the increase in output can be greater than the increase in inputs. Figure 31 illustrates:

Figure 31 Increases in output following changes in inputs: increasing marginal returns



Source: Hoover, K. (2012: 318)

Figure 31 illustrates increasing returns to scale: whereby both factors k and l were increased by 20% from l_o to l_1 and k_o to k_1, increase in output ($y_1 - y_o$) is superior to 20%. This result is possible due to coefficient A, which multiplies the productivity of inputs and causes the curve to shift upward and the slope of the second production function to be steeper than the first production function, thus suggesting higher marginal product over the interval (l_o to l_1). Producers will increase production up to the point where their marginal revenues equal their marginal costs. This point occurs when the marginal physical product of labor is equal to the real wage rate:

Equation 73

$$MPP_L = \frac{\alpha Y}{L}$$

The share of labor in GDP is equal to wages in national income, i.e. labor's marginal physical product times the units of labor hired:

Equation 74

$$\alpha = MPP_L * \frac{L}{Y}$$

To sum up, Solow argues there are three possibles sources of output growth in a market economy:

1) via increases in labor employed. If the labor force increases by five percent and its share of income in the technical relationships the economy is into is equal to ⅔, then:

Equation 75

$$1.05L^{\frac{2}{3}} = 1.033$$

meaning there will be a 3.3% increase in GDP;

2) without changes in the capital stock, increases in labor alone faces the prospects of decreasing marginal returns, illustrated by the flattening of the curve sF(r,1) in Figure 30. Rise in output per capita with constant labor requires a rise in the capital labor ratio:

Equation 76

$$\Delta \frac{K}{L} = s * f(k) - (n + \partial) * \mathrm{k}$$

where ‘‘s’’ is the marginal propensity to save, ‘‘n’’ is the rate of population growth and ‘’∂” is the rate of capital depreciation (Nikolaos and Tsaliki, 2021). Rise in output is positively related to savings and technology, whereas population growth and depreciation tends to lower per capita income, *ceteris paribus.* In this model, a steady-state economy is possible whereby s*f(k) offsets the effects of the growth in population and the depreciation of the capital stock. Avoiding a steady state therefore requires a third component to growth;

3) technological changes can cause an increase in the total productivity of factors. Solow argues that the value of total factor productivity can be estimated by subtracting the share of capital in output from year-to-year changes in output (see Solow, 1957, 313):

Equation 77

$$\frac{\delta A}{\delta t} = \left(\frac{\frac{\delta Q}{\delta t}}{Q} - \frac{\frac{\delta L}{\delta t}}{L} \right) - (wK * \frac{\frac{\delta K}{\delta t}}{K})$$

meaning changes in the multiplicative factor A is equal to the relative change in output Q minus the relative change in labor minus the share of capital in total income ‘wk’ times the relative share of capital on output over the period. ‘wk’, the share of capital in output, is equal to the relative changes of capital in changes in output times the capital/output ratio, or:

Equation 78

$$wK = \frac{\delta Q}{\delta K} * \frac{K}{Q}$$

Another way to estimate it is by considering that changes in output can be estimated by taking the first derivative of Equation 70. Considering that any expenditures in a circular-flow representation of the economy is equal to income, changes in expenditures is necessarily equal to the sum of changes in factor's income:

Equation 79

$$\frac{\partial Q}{Q} = \frac{\partial A}{A} + W_K * \frac{\partial K}{K} + W_L * \frac{\partial L}{L}$$

With the sum of ''wk'' and ''wl'' being equal to 1, we find constant return to scale. Defining 'q' as output per capita (Q/L), Equation 79 can be simplified as:

Equation 80

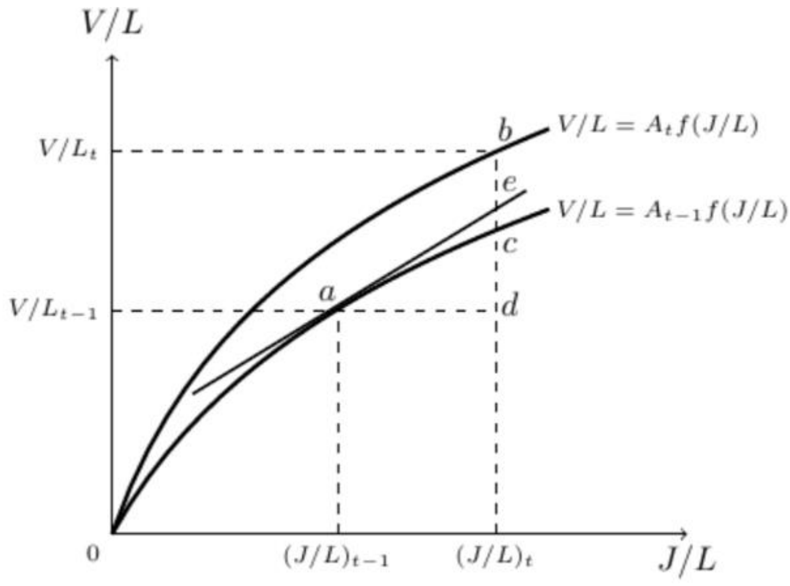
$$\frac{\partial q}{q} = \frac{\partial Q}{Q} - W_L \frac{\partial L}{L}$$

$$\frac{\partial Q}{Q} = \frac{\partial A}{A} + W_K * \frac{\partial K}{K}$$

$$\frac{\partial A}{A} = \frac{\partial q}{q} - W_K * \frac{\partial K}{K}$$

Therefore, the Solow residual is equal to the difference of changes in output with changes in the capital/output ratio. It is equal to the share of output growth resulting from total factor productivity, that is how technology over-determines the productivity of capital and labor. It is ''neutral'' as it leaves the marginal rate of substitution, expressed by the slope of the production function unchanged at any particular point. Graphically:

Figure 32 Upward shift in the production function

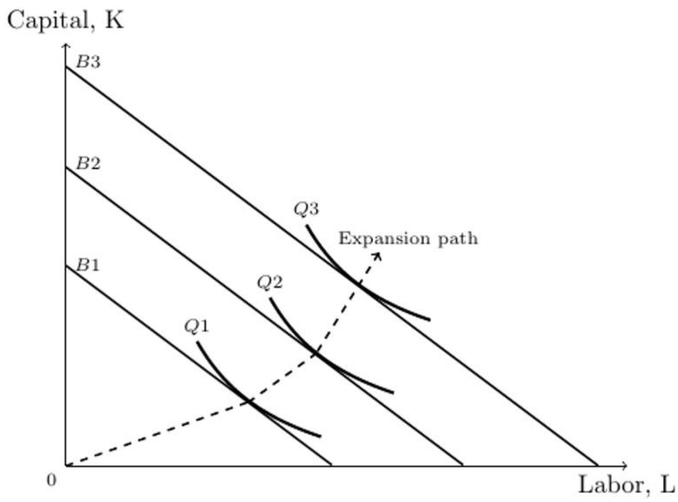


Source: Felipe and McCombie, 2013: 163

In Figure 32, output is expressed as value-added V and capital as J. Each point along the production functions is expressed in intensive forms, i.e. per unit of labor. For the capital-labor ratio $\frac{J}{L_{t-1}}$, output per man-hour is $\frac{V}{L_{t-1}}$ for the first production function with technology $A(t)_{t-1}$. When multiplied by the multiplicative factor A(t), the production function shifts upwards and reaches the level of output per man-hour $\frac{V}{L_t}$. With the second production function, the capital per labor required to produce the same quantity of output per capita as with the first production function is reduced by about half, as shown by the horizontal distance between the two functions along the horizontal d.

Output growth ($\frac{V}{L_t} - \frac{V}{L_{t-1}}$) is the result of increase in factor inputs $\frac{c-d}{a}$ and increase in factors' productivities $\frac{b-c}{a}$ = A(t) (Felipe and McCombie, 2013). Shifts caused by multiplying the function by A(t) leave the capital/labor ratio unchanged from points c and b, despite changes in output (Hicks-neutral change). The new function can still be represented as isoquants intersecting with their budget lines. In Figure 33, the coordinates c and b of Figure 32 would correspond to the isoquants Q1 and Q2:

Figure 33 Three isoquants and their respective budget lines



Bumas, 2015: 131

As mentioned above, Solow argues it is possible to estimate the share of increased output pertaining to capital intensity vis-à-vis productivity, i.e. movements along production functions vs shifts in the production functions. Empirically, he estimates the value of A(t) using data from 1909-1949 from the United States on the real output per man-hour, which nearly doubled from 1909 to 1949. Setting the value of A(t) in 1909 at 1 and assuming changes in A(t) are equal to At_0*(1 + ($\Delta At_0/\Delta At_n$)), Solow divides output per man-hour in 1949 by the value of the multiplicative factor A(t) in 1949, yielding a ''corrected'' output per man hour net of technical change, equal to a 13% increase from 1909 to 1949. Thus, 13% of the increase in output per man hour from 1909 to 1949 can be attributed to increase in capital per man-hour (or capital intensity) and the difference (87.5%) to technological change (1957: 316). The difference (87.5%) is the Solow residual, the total factor productivity or measure of technical progress. To confirm the results, Solow shows a near perfect correlation between the index of output per capita corrected for coefficient A(t) and capital formation.

5.2.4 The Solow model and the role of energy

By definition, energy cannot be a factor in Solow's model. Only factors a) whose income can equal their marginal productivity and b) that enable production, yet are not part of the final products, can stand in the model (Santos, et. al., 2018: 104). Energy therefore plays a role as an intermediate product, i.e. produced by a combination of capital, labor and technology. Energy use is the *consequence* of output production, not its cause; accumulation of capital, technical progress, etc. causes energy consumption to rise (Ayres and Warr, 2005). In Solow's models, output elasticities are equal to the share of the inputs' payments in national income.

Since ‘‘energy’’ does not receive a share of national income per se, it cannot be incorporated as a genuine factor of production (Denison, 1978, cited in Santos et. al., 2018.: 288).

With the oil shock of the 1970s and the rising costs of energy, neoclassical energy economists started a research program on how energy and natural resources could be substituted with capital. Empirically, if Equation 70 was correct, then the oil shock of the 1970s would have produced a much lower decline in output vis-à-vis observed declines (Santos et. al., 2018: 104). In his late work, Solow attempted to address the problems over the limits to growth emphasized in the Meadows Report to the Club of Rome known as *The Limits to Growth*. In Solow’s view, natural resources do not necessarily represent an absolute limit to output production provided natural resources are substitutable to capital and that the output elasticity of capital is greater than the output elasticity of natural resources (Couix, 2019: 1345). To do so, he changed his model and incorporated a variable for non-renewable natural resources:

Equation 81

$$Y = f(K^{\beta}, L^{\alpha}, R^{c})$$

where ‘‘R’’ is the stock of non-renewable resources, which can be measured in different units depending on the theoretical or empirical problem at hand (Couix, 2019). Solow argues that the substitutability of R and K is possible. Dividing the right-and side with the left of Equation 81 yields:

Equation 82

$$R^{C} = \frac{Y}{K^{\beta} * L^{\alpha}}$$

where the marginal product of R can be expressed as:

Equation 83

$$\lim_{R \to 0} \frac{\partial Q}{\partial R} = \infty$$

meaning that a limited stock of natural resources does not prohibit economic growth (Dzhumashev, 2023) provided the marginal productivity of capital β is superior to the marginal productivity of natural resources *C,* so that increasing K increases the productivity of R, regardless of the absolute value of R. In other words: the absolute value of R can decline and yet its productivity can increase provided capital investment increases the marginal productivity of natural resources (Pellegris, 2022). With a constant labor force, an output Y of virtually any value can be produced with a constant quantity of natural resources provided the capital stock is large enough (Daly, 1997).

5.3 Post-Keynesian critiques of neoclassical production functions

From the 1950s to the mid 1970s, a major debate took place between post-Keynesian and neoclassical economists from Cambridge, U.K. and Cambridge, Massachusetts. At the core of the controversy was the contention by post-Keynesians that 1) production functions suffered from fallacy of composition and were self-referential, stemming from the difficulties of defining ‘’capital’’; 2) micro-founded production functions could not be aggregated at the macroeconomic level. Furthermore: 3) the direction of causation between profitability of capital and its productivity and 4) the role of time in economic analysis both led to contradictions (Cohen and Harcourt, 2003). This section reviews the post-Keynesian critique of APFs, starting with the problem of the measure of capital, itself sub-divided into two sub-problems, following with a review of the identity problem. These critiques purport to demonstrate APFs are irremediable flawed and cannot be used as theoretically and empirically valid modelling devices. As such, these critiques can be described as ‘’external’’ to the APF framework by opposition to ‘’internal critiques’’ which will be examined in section 5.4.

5.3.1 Measure of capital

For the sake of clarity, the post-Keynesian critique on the neoclassical definition of ‘’capital’’ can be summarized into two specific critiques: the aggregation problem and the measure of capital.

5.3.1.1 The aggregation problem

The post-Keynesian critique of production functions focuses on their realism at the aggregate level. It does not challenge the validity of production functions at the microeconomic level, but rather on aggregating microeconomic functions in a given functional form into production functions at the macroeconomic level in the same functional form (typically, the Cobb-Douglas (Felipe and McCombie, 2013)). A major epistemological issue is how heterogeneous goods (such as capital stock and output) can be aggregated by a simple index. For example, how can labour (endosomatic energy use by humans) be aggregated into a single index with capital stock (exosomatic energy use), provided they both are ontologically distinct entities? How can different capital goods be compared, provided each of them are produced using their own microeconomic production functions? Standard APFs define ‘’capital goods’’ as homogeneous and theorize changes in capital goods by the mere addition or subtraction of units of capital. However, as Robinson aptly puts it: ‘*’The difference between a more or less mechanised technique is not produced by adding some spoonfuls of investment to a pot-au-feu of ‘’ capital ‘’.* ‘’ (Robinson, 1954: 92).

Using monetary figures to define and measure capital inevitably falls into self-referential and circular arguments. In standard microeconomics, a profit-maximizing capitalist is assumed to adjust the production of output along an isoquant at the tangent point with an isocost curve, where the marginal products of factors are equal to their prices. To perform this adjustment, the capitalist needs not only to know about the physical rate of marginal substitution, but also the cost of the arrangement of factors he envisages. To know the costs, the capitalist needs to know the price of these factors. Where is he to find information on average prices? Not from official statistics, which do not reflect an economy in equilibrium (Robinson, 1970). Using monetary figures to measure capital presupposes a given rate of interest, whereby the purpose of production function is precisely to explain the causation of the rate of interest (Felipe and McCombie, 2013: 33).

Neoclassical modelers claim their model can help find the rate of profit in the economy. Post-Keynesians show the circularity in this position. Indeed, as a capitalist examines the different input combinations possible along the isocost curve to produce a given level of output at a minimum cost, surely the capitalist examines the market price of goods and services. However, at any given point in time, provided the capitalist is in a competitive capitalist economy, market prices are equal to the marginal cost of the last unit produced. At this point, profitability reflects the product of the difference between the market price and the marginal costs on the last unit produced and the number of units produced. The producer of the last unit makes no profit, as the marginal cost is equal to the price of that unit. Thus, market prices incorporate a difference between marginal revenue and average cost for every unit produced to the left of the point where price is equal to marginal cost, allowing profit on these units. The problem is particularly salient with the price of capital goods. On a market, capital has a price which, at time t_0, reflects its production cost plus gross margin. The difference between the price and production cost on the goods determines profits. Therefore, at time t_0 market prices are determined by a rate of profit. The existence and knowledge of the rate of profit is therefore required to find prices.

In conditions of perfect competition, aggregating labor is not problem-free either. As shown by Fisher (cited in Felipe and McCombie, 2013: 27), aggregating labor under a different index requires that microeconomic functions (at the level of the firm) are identical except for their capital\labor coefficient, in other words that firms are hiring undifferentiated labor. Specialization of labor is absent. Firms must produce the same bundle of goods. The only difference between firms' output is a difference of quantity. Such conditions are unlikely to materialize in any real economy.

5.3.1.2 Measure of capital

Several problems arise with the very definition of the concept of ‘'capital'’, many of them summarized by J. Robinson. The basis of Robisnon's critique of neoclassical capital theory is that it rests upon the assumption of equilibrium, which itself rests upon the assumption of a smooth analogy between space and time. Robinsons argues neoclassical economists think of economic models as systems that can move from A to B and back from B to A. However, historical time defines the very essence of the economy at time A and B. Thus, as soon as an event unexpected by the economist occurs at time A, it changes to, say, A'. Any recursive return to A is impossible. Considering the iron necessity of historical time destroys the conceptual apparatus of equilibrium in neoclassical economics upon which the theory of capital rests. Using the concepts of physics, I argue that thermodynamics prohibits a return to state A after it transitioned to state B, thus following Robinson's critique:

> [...] in time the distance from to-day to to-morrow is twenty-four hours, while the distance from to-day to yesterday is infinite, as the poets have often remarked. Therefore a space metaphor applied to time is a very tricky knife to handle. (Robinson, 1954: 84)

To attack neoclassical economics' definition of capital, Robison examines several possibilities and the difficulties associated with each. She suggests capital can be defined in terms of cost (units of purchasing power spent in producing it) or productivity (stock of goods it can generate). In a two-inputs, non-monetary economy, capital is a function of saving (foregone consumption) that must be quantified in terms of units of labor, that is a sum of value in terms of product. But the existence of a ‘'labor unit'’ quantum presupposes some knowledge of the product-wage ratio. However, this rate changes with changes in the ratio of labor to capital. To sum up, measuring capital in terms of labor means capital measures the quantity of output and of labor.

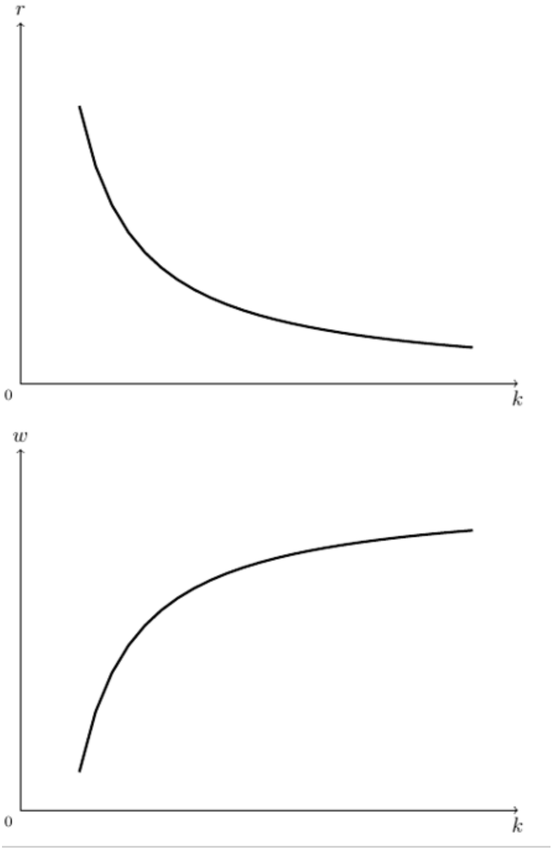
Several other avenues exist to define ‘’capital’’ in a hypothetical, two-inputs economy. As argued by Robinson, one theoretical avenue would be to define ‘’capital’’ as all goods existing at a moment t_0. This definition would be empirically valid over the short-term only, provided changes in capital\labor ratios lead to fundamental changes in the technical relationships between labor and capital and between capital goods over the long-term. Likewise, the relative value of capital cannot be measured in units of labour, provided ‘’labor’’ abstracted from capital does not exist in the real-world. Finally, costs offer no better options. If money cost is used as the metric to measure capital, provided a given rate of interest, then the value of money changes over time (Robinson, 1954: 84). If replacement cost is the metric, then the ‘’man of deeds’’ will measure the value of capital to be invested as a ratio of capital already existing. But because capital exists in relation to a future stream of output, replacement costs inevitably bring in future earnings into the ratiocination of the man of deeds. Furthermore, the supply price of equipment capital is a function of its initial costs (on which interest is paid) minus gross earnings, i.e. expected future profits. From the point of view of the capitalist who sold replacement capital to the investor capitalist, the value of capital is therefore a function of cost and earnings of the current investor-capitalist. Therefore, the value of capital depends on future earnings. Provided these expected earnings and costs were made in equilibrium, the value of capital must remain equal across time, i.e. the stock of capital must not change. It seems unlikely for such conditions to ever arise in any existing economy.

As mentioned above, neoclassical economists argue that the formation of interest rates take place under conditions of equilibrium. Doing so forbids the introduction of historical time. Indeed, equilibrium requires that investments made today are made with an expected rate of profit. If interest rates are expected to fall in the future, a rational capitalist would refrain from investing today, borrowing at rate t = a, provided the rate at which he can borrow in the future, t = a - b, will be lower (Robinson, 1954: 100). If they rise, some indebted capitalists find themselves unable to honor their obligations. The uncertainty of historical time precludes the use of equilibrium in analyzing production functions. In other words, the possibility for the rate of profit to change thanks to changes in capital/labor ratios precludes the assumption of a single interest rate. When using historical time, the economist must acknowledge there is more than one rate of interest. Rates of interest change across time, lengths and across different lines of production involving heterogeneous capital goods. However, neoclassical economists assume an exogenous, uniform rate of interest corresponding to a given ratio of capital to labor (Robinson, 1954: 92, 98).

In the neoclassical theory of capital, the accumulation of capital stops when its marginal productivity is equal to the rate of interest, that is when capital's MPP is equal to its marginal return. According to Champerowne, a diversity of production techniques formed by heterogeneous capital goods is related to a downward sloping interest-rate curve on a so-called ‘‘technological frontier’’ (Pasinetti, 1978: 185). This approach, however, is problematic. An illustration of these problems is the re-switching problem, which arises when certain capital\labor ratios are preferred at two discontinuous rates of interest, whilst another ratio is preferred at an intermediate rate of interest, which contradicts Solow's model of a downward sloping rate of interest in relation to capital.

Neoclassical Economics defends the existence of an inverse monotonic relationship between profitability and the capital/labor ratio, based on the assumption of an infinite substitutability of capital and labor. As more capital is required over the quantity of labor, the rate of profit declines, as illustrated in Figure 34. The ‘’reswitching debate’’ arose precisely around that claim, whereby the post-Keynesians argued infinite and continuous substitutability does not make sense empirically.

Figure 34 Inverse monotonic relationship between profitability r, capital/labor ratio k and wage rate w



Source: Felipe and McCombie, 2013: 36

Figure 34 illustrates the relationships between capital/labor ratio, capital, wage and profit. It was originally thought by neoclassical economists to illustrate the inverse relationship between wage and labor in the market for one capital good/sector. Post-Keynesians did not challenge the validity of the model for one sector but its aggregation for several sectors. Samuelson, assuming perfect competition (so wage and profit are the same across several capital goods markets) and the same capital intensities across consumption and industrial goods production functions, argued the technological frontier should be concave down. As the wage rate w falls, the value of the capital/labor ratio k decreases and profitability r increases. The sum of wage and profit is equal to national income. Thus, as the rate of profit falls in the economy, the share of wages in national income increases.

Post-Keynesians challenged the aggregation of these relations at the macroeconomic level. An example of ‘’reswitching’’ is the production of wine using two different capital/labor ratios (Cohen and Harcourt, 2003) which aims to show capital goods are not homogeneous and cannot be ‘’smoothly’’ aggregated .This example purports to demonstrate the existence of ‘’Wicksell effects’’, where changes in the value of the stock of capital is associated with changes in the interest rates (Fix, 2015: 10). Assuming the rate of interest to reflect the cost of capital, wine production requires labor and capital over 4 time periods (t = 0, 1, 2, 3). Scenario A involves the uses of 7 units of labor at t = 2 and scenario B involves 2 units of labor at t=3 and 6 units at t=1. The total costs of each scenario can be estimated with the following:

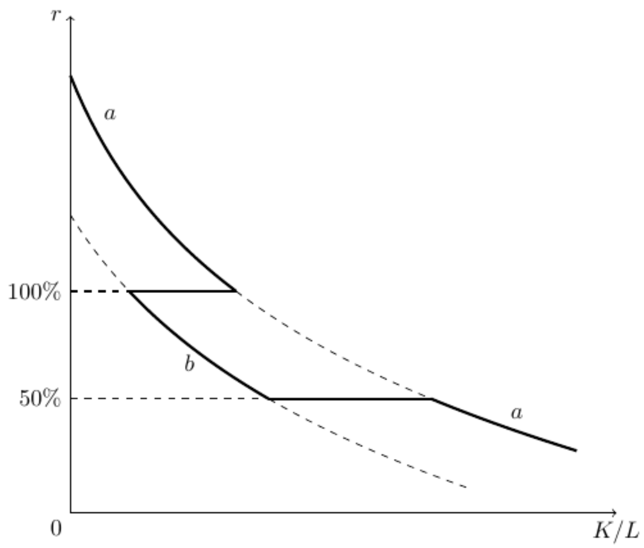
Equation 84

Total costs, scenario A: $7L(1+r)^2$

Total costs, scenario B: $2L(1+r)^3 + 6L(1+r)$

where 'r' is the rate of interest. When r is high (above 100%), scenario A is preferred over B. Scenario A is likewise cheaper if the rate of interest is 0, that is when only labor costs count. At intermediate rates of interest, say, 60%, b is cheaper. Graphically:

Figure 35 Demand for capital per unit of labor and the rate of interest



Source: Samuelson, 1966, cited in Cohen and Harcourt, 2003: 203

At 100% profit, the value of the capital stock on labor suddenly falls. It increases suddenly at 50%: all the while, the rate of profit steadily and smoothly declines. Changes in the rate of interest can cause changes in the capital\labor package used in production, thereby contradicting the monotonic relationship assumed in standard APFs. The slope is not linear due to changes in capital intensities. There cannot be a single APF. Paraphrasing Robinson: the reswitching problem illustrates that a quantity of capital cannot be identified with value expressed in monetary terms, provided the stock of physical capital changes at different profit rates: ‘’[...] *a physical measurement of capital* [...] *is not possible in general, when the capital goods used with the different techniques are heterogeneous*.’’ (Pasinetti, 1978: 186)

Therefore, demand for capital and the rate of interest are not smoothly downward sloping. The rate of interest is endogenous to the model. The effects of changes in the rate of interest on distributions are ambiguous. Interestingly, Samuelson acknowledged the theoretical validity of the post-Keynesian critique on the reswitching problem (Felipe and McCombie, 2013: 42).

Assuming the ontological differences between labor and capital refutes the Hicksian premise of their substitutability, which Hicks used to argue the existence of perfect competition. As shown by Keynes, assuming substitutability implies industries react homogeneously with respect to changes in prices of inputs. However, if this assumption is rejected, different industries react differently to changes in input prices, therefore leading to imperfect competition (Garcìa Molina, 2005).

5.3.2 Algebraic identity

As the Cambridge Capital Controversy unfolded, neoclassical economists argued that despite the theoretical weaknesses of APFs, their empirical strength justified their use in empirical work. Economists could legitimately use a logically flawed model if its empirical dimensions could be tested (Cohen and Harcourt, 2003). As such, a much more ambitious (in our view) critique of APFs arose in the 1970s. In his seminal 1974 paper, Shaikh argues the empirical strengths of APFs is the result of an accounting identity. In other words, the empirical strength of production functions reflects a tautology, not an empirical measurement.

As shown by Shaikh (1974), the empirical correspondence between marginal productivity of inputs and their share of income in national income suggests, at first glance, that neoclassical production functions are empirically valid. He argues that this correspondence rests on an algebraic identity. Following Kant, one could argue that the correspondence between marginal productivity of inputs and their share of national income rests on an analytical judgment, an elucidation of the meaning of terms already known, not a synthetic judgment, whose truth rests upon empirical knowledge (Rey, 2022[2003]). National income is equal to wages paid to labor and interest, rent and profit paid to capital. By definition:

Equation 85

$$w = \frac{\partial Y}{\partial L}$$
$$r = \frac{\partial Y}{\partial K}$$

meaning wages and profits are equal to their marginal productivity. By construction, there is an identity between marginal productivity of labor and factor's share. Using a r*eductio ad absurdum*, Shaikh shows that a two-dimensions graph with capital per capita as the independent variable and output per capita as the dependent variable and fitting a Cobb-Douglas function can be used to draw a production function displaying the word ''HUMBUG'' on a graph, provided factor shares of national income and the growth rate of wages and profit remains constant (Fix, 2015: 9).

Bumas expresses the same idea in slightly different terms. As predicated upon the circulatory nature of income flows in an economy, the monetary value of output is necessarily equal to the share of labor plus the share of capital in income, that is value-added:
Equation 86

$$Q = (w * L) + (r*K)$$
$$= \alpha Q + \beta Q$$

As shown by Bumas: ''*In order for the product to be exhausted the sum of a and b must equal to one. But if the data trace out the value-added identity they have to equal one since value-added must manifest itself as a payment to labor and capital*.'' (Bumas, 2015: 146)

By the mid-1970s, most participants in the Cambridge capital controversy acknowledged the validity of difficulties raised by the post-Keynesians against neoclassical capital theory. In 1963, maybe to concede to post-Keynesian-minded economists on some of their criticisms, Solow developed a model of APF where capital and labor are not discreetly substitutable, but where the production of capital goods rest on fixed amounts of capital on labor (Solow, 1963). According to Robinson, such an attempt is akin to thinking of the function as a curve where different points represent isolated economies with no contact. Capital-labor ratios being constant, rates of profits are constant as well. Robinson argues this solution is unsatisfactory: two economies separated by geography would display technologies reflecting their geographies, whereby two economies separated by time do not share the same technological knowledge (Robinson, 1975: 38). Therefore, two different economies cannot be meaningfully compared by means of this production function.

5.4 Production functions in ecological economics

In this section, I review the literature in ecological economics on the relative merits (or lack thereof) of APFs and three proposals to model production functions using biophysical units of measurements, i.e. biophysical production functions (BPFs). I start with a review of the ecological critiques of APFs and continue with an introduction to BFPs, i.e. production functions where economic aggregates of interest (whether inputs, output or both, depending on the model) are measured in biophysical units.

5.4.1 Ecological and biophysical critiques of neoclassical APFs

Ecological economics stems from a reconceptualization of the economic process from a circular flow of income to a linear throughput model of flows of matter and energy, purported to be consistent with the discoveries of thermodynamics (Couix, 2019: 1358). From its inception with Georgescu-Roegen, ecological economists have criticized neoclassical models of economic growth, although the relevance of some of their features is a current area of debate.

Georgescu-Roegen proposed to model the economic process as an interaction between stock (finite quantities of organized matter and energy), flows and fund-services. Stocks are rival and excludable resources that can be stockpiled and that are transformed in production processes at rates that can be adapted, such as fossil fuels. On the other hand, funds are non-rival and non-excludable. They are not transformed during productive processes. The rate at which they are used is not malleable and cannot be stockpiled, such as most ecosystems' regulating services (Blanco and Costanza, in Cramer et. al. (dir.) 2019). As such, the multiplicative relationships between factors found in APFs are said to be inconsistent to the extent that the sum of shares of inputs does not correspond to biophysical reality, where output production is the result of transformation of two non-commensurate groups of inputs (Daly and Farley, 2010: 160). Georgescu-Roegen emphasized the ontological distinction in the production process between material transformation (flows) by some agents (fund) such as capital and labor (Couix, 2019: 1356). These two categories of factors are complements rather than substitutes (Blanco and Costanza, in Cramer et. al. (dir.) 2019), meaning extra output requires extra labor, capital and natural resources (Daly, 1997: 263).

As seen above, the argument made by most neoclassical economists reviewed on the role of energy in output growth is more sophisticated than a pure negation of its role. Rather, they argue factors such as energy and capital are substitutes (Berndt and Jorgenson, 1978, cited in Kümmel et. al., 1985: 286). Others argue that energy is not a factor per se as it is a product of labor and capital. Focusing on energy sources, the argument made by ecological economists on the limit to substitution is that infinite substitution tacitly assumes capital can be produced out of an infinitely small quantity of energy, whereby capital is an agent of resource transformation. However, substitution of one source of low-entropy stock of energy for another thanks to technological development does not add to the net quantity of low-entropy resources on Earth (Daly, 1997).

To argue energy is an intermediate input, the product of labor and capital, rests on a conceptual confusion on what is energy, which itself is not produced, but a product of nature, and energy carriers as man-made products, according to Kümmel et. al. (1985). ‘’Energy carriers’’ are natural resources containing energy whose caloric content can be used to perform work whereby ‘’energy’’ is the capacity to do work. As such, energy carriers are sources of energy but not energy itself. As a ‘’gift of nature’’, energy is a factor of production as it provides flows of useful energy to production: the joule-content of these flows are not in themselves by-products of labor and capital, although they actively participate in the production of value-added. Furthermore, by making total factor productivity the residual of the share of output growth that cannot be accounted for by the growth of capital and labor, Solow’s model is tautological: regardless of how large or small this coefficient is, the equation necessarily remains true. Whenever coefficient A(t) is given a value based on the discrepancy between output and input growth, the model produces an equality (Kümmel et. al., 1985: 290).

Finally, a comparison between technological progress A(t) and the purported role of energy as an intermediate factor reveals a contradiction. In Solow’s models, technological progress is exogenously given. On the contrary: technology results from large expenses in research and development and human labor. As such, it is an intermediate product, although it is incorporated into a production function as a coefficient. Ergo, if energy cannot account for a factor of production as it is an intermediate good, logically, nor should technological knowledge (Kümmel et. al., 1985)

5.4.2 Ecological and biophysical production functions

5.4.2.1 The first biophysical production function

Frederick Soddy was the first author to propose an energy-based model of output (‘’wealth’’ in Soddy’s words) production. For Soddy, production functions are conjunctions of three factors: diligence, available energy and discovery. Used in conjunction, they produce wealth which, physically speaking, is defined as a product of energy empowering life (Soddy, 1926: 116). Discovery is the successive findings by humans of new sources of energy nearer to their original sources: as hunting and gathering feeds human with the caloric intake metabolized by their prey, agriculture yields energy resulting from the transformation of solar flows by photosynthesis in plants (or ate by vertebrates in livestock farming) and fossil fuels, yielding energy from the decay of organic life. Once made, discoveries permanently alter the course of human history. Diligence is human labor, physical or not, that increases the quantity and quality of wealth. However, human labor transforms rather than creates wealth because it redirects flows of energy, but does not create them (Ibid, 112).

As such, energy sources are ‘’capital’’: the Sun, crude oil reservoirs, etc. They yield flows of energy, whose flows can appropriately be termed ‘’revenues’’. Waterpower is the only source of energy transforming the revenues of sun flows without the mediation of life itself (Ibid.: 39). However, capital stock (understood in Soddy’s terms) is not homogeneous. Some stocks yield energy flows only once, such as fossil fuels, after which the flows of free energy are dissipated into bounded energy. On the other hand, some natural elements yield renewable energy flows, such as plants, which are consumed by vertebrates: ‘’*With the doctrine of energy the real capitalist proves to be a plant*.’’ (Ibid., 30) What is commonly referred to as ‘’capital’’, that is factories and machines, are agents of production (Ibid., 49-50). But so does land, which generates revenues of wealth by making possible the production of goods carrying energy (plants and animals).

The control of the flows of energy by humans therefore means the ability of humans to perform deductions from energy flows used or stored in the wealth produced. As such, food and fuel are wealth. When producing tools, material and equipment, humans perform drafts upon the flows of available energy. Logically, energy availability predetermines production as the latter represents a deduction on available low-energy resources.

Two distinct forms of wealth must be defined in their relation to energy. The first are the internal stores of energy whose consumption releases their energy content to fulfill human needs. By nature, this form is perishable, and its value is derived from the energy flows derived during consumption, such as food, fuels, fertilizers, etc., all paying ‘’lump sums’’ of energy (Soddy’s terminology). In the second category, energy is used to overcome resistance or change the form of natural elements. They are essential in the production of wealth. The energy-content of the first form of wealth is an essential part of its nature in economic processes whereby its permanence (minus depreciation) rather than its dissolution in consumption defines the second form, such as clothes, material, equipment, which provide revenue in the form of hours of work saved. Formally, the first and second forms of wealth follow Equation 87:

Equation 87

Raw materials + available energy = 1st category of wealth = Life - energy flows + waste

Raw materials + available energy = 2nd category of wealth + waste

The second category of wealth is retroactively reinvested in the production of more wealth, but as an ‘’agent’’ of production, not a ‘’factor’’. The use of agents however requires human labor, a genuine factor. Agents of production embody the past diligence of human labor and the energy of nature (Ibid., 100). They are the products, not the elements, of wealth production. It is the use of inventions, not the inventions themselves, that generate wealth (inventions being inanimate in and of themselves). As Soddy emphasizes:

> So we may envisage the production of wealth as a transformation of the available energy of Nature into a flow available to the purpose of human life. [...] In intensive production [...] the energy so used is deducted from, not added to the product. [...] Its function is to change the quantity of the natural available energy into the form available for the needs of life, and the gain in quality is a consequence of a reduction in quantity. (Ibid.: 115)

5.4.2.2 Contemporary biophysical production functions

We conclude the theoretical section of the chapter with three BFPs, that is biophysical models of economic growth. These three models use the mathematical framework of production functions to represent the functional relations between inputs and output. However, unlike neoclassical models, they are using biophysical units of measure and are based on factors’ complementarity rather than substitutability. As such, these models can be regrouped into ‘’internal’’ critiques of APFs, as they share with them common mathematical forms and the use of monetary figures to aggregate capital (Pellegris, 2022). These models do not necessarily use the Cobb-Douglas model, as some authors argue more complex mathematical forms are required to represent complementarities between inputs.

The first model examined in this section estimates the role of energy in the economy in terms of exergy, i.e. useful work, in output growth: the Energy-Based Cobb-Douglas Production Functions (Keen et. al., 2019). The model stems from two major issues with energy-extended APFs as considered in Equation 81: theoretical and empirical. Theoretically, the model takes the form of a Cobb-Douglas functional form, where:

Equation 88

$$Y = f(L^{a}, K^{\beta}, E^{\chi})$$

As discussed above, this functional form is problematic as it allows the mathematically correct, yet theoretically insignificant proposition that energy inputs E can be 0 and output can still be produced, which is a physical impossibility. Furthermore, labor and capital cannot be used in any meaningful sense without being independently used *along with* energy flows. Adding a third factor E to a production function should lead to multicollinearity provided labor and capital are not independent of energy-use and vice-versa.

The empirical issue is more complex. Following Ayres and Warr (2005) (see Chapter 2), due to heat loss in energy-use processes, not every joule of potential work contained in energy carriers used as inputs are converted into useful work. In other words, the heat value of primary energy flows does not accurately reflect the fraction of heat really used in output production. As such, the flows of useful work, or the energy performing useful mechanical, chemical or thermal work after subtracting conversion losses, are the thermodynamically appropriate variables to account for the role of energy in output growth (Santos et. al., 2018). ‘’Useful work’’ is the sum of 1) muscle work; 2) mechanical work (fuel used to perform electric power generation or by mobile power sources) and 3) heat generation by industry (chemical work) and households (domestic use) (Ayres and Warr, 2005: 186-187). By using flows of useful work as a variable of production functions, Ayres and Warr have found the so-called Solow residual to be trivial for the United States for the period 1900-1988. What Solow defined as ‘’technological progress’’ is found to be the result of improvements in exergy conversion (Ibid., 197).

Keen et. al. (2019) examine the potential and shortcomings of incorporating energy use into a Cobb-Douglas production function following Solow's intuitions (see Equation 81) where ''E'' is energy-use and ''χ'' is estimated by the share of energy expenditures in American national accounts. Using data from the Energy Information Administration (EIA), Keen et. al. show that χ should be equal to 0.07. Intuitively, this value can hardly stand in a Cobb-Douglas production function where at equilibrium, marginal physical product is equal to the price of the marginal factor and therefore equal to its share of national income. Should a value of 0.07 for χ truly reflect its output elasticity, then an increase of energy input by 50% would raise output by 3% only (Keen et. al., 41). Furthermore, in this format, it is theoretically possible to reduce the share of any three inputs to 0 ($E^o = 1$) and still produce output: if more natural resources are thrown into production with capital and labor held constant, it would in theory be possible to produce more output with no extra physical unit of labor and capital (fund) added (Daly, 1997).[42]

Keen et. al. argue that a proper theory of growth must show how energy inputs are embedded and complement with capital and labour. Following Ayres and Warr (2005), they argue exergy is the real variable of interest to model the role of energy in output production as it represents physical work at the point where energy dissipates into heat to produce goods and services (Heun et. al., 2017). A BFP should therefore acknowledge that labor and capital use are both a function of exergy flows. Mathematically, this co-dependence means labor and capital should be redefined as sub-functions of exergy flows:

Equation 89

$$Q = F(L(Ex), K(Ex))$$

where ''L(E)'' means that labour is a sub-function of exergy ''Ex'':

Equation 90

$$L(E) = L * E_L * e_x^L$$

where ''E_L'' is defined as the aggregate energy consumption per worker (in joule of primary muscle work / hour) and ''e_x^L'' is the efficiency ratio whereby E_L is converted into exergy

[42] A review of neoclassical growth models assuming a Cobb-Douglas function form confirms the mismatch between the unitary elasticities of substitution of inputs and empirical data (Dissou et. al., 2015: 108-109).

(useful work), the latter being assumed constant. The product $E_L * e_x^L$ is equal to the flows of exergy empowering labor. Capital is equal to:

Equation 91

$$K(E) = K * E_K * e_x^k$$

where ‘’K’’ is an aggregate measure of the physical capital, ‘’E_K’’ is the aggregate energy consumption per unit of capital (in joules of mechanical work plus heat / unit of capital). The product $E_K * e_x^K$ is equal to the exergy flows empowering capital. Equations 90-91 state flows of labor, capital and exergy are complementary. Acknowledging the epistemological issues surrounding the definition of aggregate K raised by the post-Keynesians, Keen et. al. define it as the aggregate quantity of physical capital. Redefining the right-hand side of the production function in energy terms requires doing the same on the left-hand side. Therefore, the output measured by the production function becomes:

Equation 92

$$Q_E = E^{GDP} * (\frac{E_X^{GDP}}{E^{GDP}})$$

where ‘’E^{GDP}’’ is the total energy used to generate output and ‘E_X^{GDP}’ is an energy-exergy efficiency ratio. Substituting Equations 90 and 91 into 92 yields:

Equation 93

$$Q_E = (K * E_K * e_x^k)^a * (L * E_L * e_x^L)^{1-a}$$

The authors argue their model provides valuable insights for future empirical studies, namely the fact that their model respects the laws of thermodynamics and is empirically realistic as no energy-use yields no output. No labor or capital use yield an output of 0.

Following the intuition of Keen et. al. to examine economic growth in Portugal, Santos et. al. find ‘’[...] *very strong correlation between useful exergy consumption and economic output* [...]‘’ (Santos et. al., 2018: 112), whereby the correlation is indeterminate when primary energy is selected. Interestingly, measuring the relationship between capital formation and energy use, the authors find the causality to be bidirectional, which makes intuitive sense, as energy is required to operate capital and increasing capital leads to increasing flows of energy processed. Heun et. al. found the value of the Solow residual to be reduced by half when substituting useful exergy flows over flows of primary energy for Portugal and the United Kingdom from 1960 to 2009 (2017).

Kümmel and Lindenberger propose their own method to salvage production functions from the theoretical and logical problems emphasized by post-Keynesians, to whom they concede that neoclassical production functions fail to measure capital and output independently and that complete factor substitutability is impossible. According to Kümmel et. al. (1985) the claim that coefficients of output elasticities are equal, at equilibrium, with the share of factors in national income, is empirically meaningless once a rigorous definition of the output elasticities and monetary aggregates is provided. Prices measure purchasing power whilst coefficients of output elasticities measure productive power. No unit of currency is required to express output elasticity. Furthermore, complete factor substitutability is contradicted by the existing empirical complementarities between factors: factors combinations depend on technologies which may or may not exist. Furthermore, there might be a demand for goods which do not fit the minimum costs of factor combination, such as in the field of telecommunications where higher-quality goods require more capital and labor and less energy than their lower-cost substitutes (Kümmel et. al., 1985: 305).

However, Kümmel and Lindenberger argue that production functions are useful provided physical units of measurements are used to express inputs and output. From a biophysical perspective, capital can be aggregated in terms of the physical work (in joule or watts) it performs and the number of information (in bits) it processes. Due to the absence of high-quality data produced by national statistical agencies on the physical growth (in joule and bits) of the capital stock, the authors propose to use constant monetary measures of capital as a first step in the construction of physical aggregates. They argue that monetary valuations (in constant currency units) of capital reflect its capacity to perform work and process information (Kümmel and Lindenberger, 2020: 3; Kümmel et. al., 1985: 294). The average product of useful work and information per unit of capital processed should be proportionate to its price in constant monetary value. The authors propose to use kilowatt-hour (kWh) to measure work and kilobit (kB) to measure information processing by the capital stock. The sum of the average of kilowatt-hour and kilobit consumed in the production of output is expressed into an Energy and Information (ENIN) index, akin to a ‘’physical’’ index of value added:

Equation 94

$$ENIN = \frac{1}{M}\sum_{i=1}^{M} W_i * kWh * V_i * kB$$

where ‘’V_i’’ is the number of kilobits (kB) processed and ‘’W_i.’’ is the number of kilowatt-hour (kWh) consumed in the production of output. The physical output of an economy can be measured by multiplying the ENIN index by the monetary output M of the economy. An equivalence coefficient between the monetary and physical measurements of output can be derived as:

Equation 95

$$\frac{Y}{Q} = \frac{\mu}{\xi} * \frac{Mark}{kWh * kB}$$

$$\xi = \frac{1}{M}\sum_{i=1}^{M} W_i * V_i$$

where ‘μ’ denotes the quantity of currency in the system under analysis, ‘‘Mark’’ is the unit of currency of the system under analysis and the conversion factor ξ is a genuine biophysical measure of national output measured in physical units (Kümmel and Lindenberger, 2020: 5). Thus, output can be expressed in physical unit as a function of kWh and kB processed by the capital stock, although monetary aggregate μ is required to estimate the units of capital that can generate watts and process bits.

To address the post-Keynesian critique, Kümmel and Lindenbder argue capital can be aggregated physically by formalizing the quantity of kWh the capital stock can perform and the information it can process by converting monetary measures of capital into units of watts bits. The capital stock can then be estimated physically as:

Equation 96

$$K_{phys} = \sum_{i=1}^{N} S_i * kW * T_i * \frac{kB}{sec}$$

where 'sec' means 'seconds' S_i is the number of kW and T_i is the number of kilobits/second the capital stock (measured in units of currency) can perform. Solving for S_i and T_i is therefore dependent on a monetary-based measure of the capital stock:

Equation 97

$$K_{phys} = K = N(t)\nu Mark$$

where ''νMark'' is the monetary value of the capital stock found in national accounts. An equivalence factor κ is proposed to convert the physical potential of the capital stock to process energy and information in terms of its monetary value

Equation 98

$$\frac{K_{mon}}{K_{phys}} = \frac{\nu}{\kappa} * \frac{Mark}{kW * kB/s}$$

As the authors put it:

> The S_i can be obtained from the specifications of the machines, and the T_i are given by the number of switching processes that per unit time block or let pass the energy flows in the machines at maximum utilization of $K_{i,mon}$. [...] The physical magnitude of the capital stock, K_{phys} [...] is νMark. (Kümmel and Lindenberg, 2020: 5)

In fine, the value of K_{phys} upon an aggregate of capital denominated in units of currency. Labor is measured in man-hours and energy using the enthalpy (heat value) of the energy carriers entering the system under study. Monetary measures of capital are essential as a proxy to build physical measures of capital stock. A Linear-exponential (LINEX) BFP can then be defined in physical units (see Kümmel and Lindenberger, 2020, Equation 22, 4) where output depends linearly on factor E and exponentially on the ratios of factors:

Equation 99

$$Y_1 = Y_0(t) * \frac{E}{E_0} * \exp\left((\alpha(t)(2 - \frac{\frac{L}{L_0} + \frac{E}{E_0}}{\frac{K}{K_0}}) + \alpha(t)c(t)(\frac{\frac{L}{L_0}}{\frac{E}{E_0}})\right.$$

$$a(t) = \frac{K}{Y} * \frac{\delta Y}{\delta K}$$

where ''c(t)'' is a factor for human ingenuity and creativity, defined as:

[…] *when human ideas, inventions and value decisions, in short ‘’creativity’’ influence technological efficiencies, structural changes and the monetary valuation of work performance and information processing.* (Kümmel and Linderberger, 2020: 5).

A BFP like Equation 99 empirically invalidates the cost-share theorem. Factors’ output elasticities are estimated econometrically. Doing so disproves the cost-share theorem as the cost-share of energy is seldom equal with its output elasticity. Furthermore, constraints on capital-use induce gaps between the marginal productivity of capital and its share in national income.

We present one last BFP, the Resource-Exergy Service model by Ayres and Warr (2005). The authors argue that rigorous thermodynamic thinking requires the use of exergy services as a variable in an economic growth model which can be estimated following a linear-expoential relationship between economic output, useful exergy flows and energy inputs:

Equation 100

$$Y = \left(\frac{U}{E} * B\right) * \left(\frac{Y}{U} * B\right) = \left(\frac{Y}{U} * E\right) * U_E = AUexp(\frac{aL}{U} - \beta\frac{U+L}{K})$$

where ‘’B’’ means all natural resources embodying energy (fossil fuels, agricultural products, etc.) and ‘’K’’ is measured as ‘’[…] *a construct of accumulated investment less depreciation* […]‘’ (Ayres and Warr, 2005: 190), whose value is estimated using data from the Bureau of Economic Analysis and ‘’U’’ denotes the flows of useful exergy. Finding the values of their coefficients by partial integration rather than by logarithmic differentiation, their production function follows the LINEX form shown in Equation 100.

Plotting their function over the American GDP from 1900 to 1988 yields a mean-squared error of 0.9, therefore suggesting no technological multiplier is required to explain growth over the 1900-1988, which can be explained by historical progress in thermodynamic efficiency. A growing residue is observed after 1985 up until 2000, to be attributed to the rising importance of information technologies in the capital stock (Ayres and Warr, 2005).

5.5 Discussion

This section has reviewed how contemporary microeconomics model production functions at the microeconomic level. We have reviewed how early marginalists economists have modeled the first versions of APFs where labor and land were the two major inputs whose relations with output were explored. When the first generation of marginalist economists attempted to incorporate capital as a factor of production, they stumbled across significant conceptual difficulties. Circumventing these difficulties and observing the relationships between changes in labor, capital and output econometrically, Cobb and Douglas believed they had validated the marginalist theory of distribution. However, the Cobb-Douglas function, in its original version published in 1928, did not account for technological progress, a feature of modern capitalism economists of all stripes would acknowledge. Over 20 years later, Robert Solow incorporated technological progress in APFs, believing the difference observed between changes in output on the one hand and changes in inputs on the other hand to be the result of technological progress. As Solow published his results, a major controversy erupted between neoclassical and post-Keynesian economists, the latter believing the very notion of a capital aggregate using monetary figures was empirically meaningless. The purported empirical strength of Solow's functions was argued to be the result of an unacknowledged accounting identity. In the field of ecological economics, several critics were raised against APFs, namely: their lack of empirical realism, i.e. the complementarity in input substitution over their substitution, the conceptual confusion over the intermediate nature of energy as an input, etc. We reviewed three models of biophysical production functions put forward by ecological economists, where economic aggregates were measured in biophysical units. The next chapter turns to an empirical testing of the series of models examined in this chapter.

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PREFACE TO CHAPTER 6

In chapter 5, the history and the post-Keynesian critique of APFs were reviewed. Post-Keynesians have argued APFs fail to measure meaningful empirical relationships between inputs and output, provided they rest on accounting identities and since the volume of capital cannot be measured by a price index. The critique of APFs by ecological economists was reviewed, whereby the role of energy as a factor enabling the use of man-made factors was emphasized and contrasted with Solow's approach of adding energy as a third input to a Cobb-Douglas APF. Finally, the ecological critique of the assumed infinite substitutability between capital and natural resources in neoclassical economics was emphasized.

With the theoretical background reviewed, I now test my hypothesis on the existence of a significant and positive correlation between both quality and non-quality corrected measures of energy use and economic output as well as causal pathways between the two sets of indicators. To do so, two groups of models are used: one using non-corrected measures of energy (primary and secondary energy-use) and using Solow APFs mathematical structure (first-differences in output regressed over first-differences in three inputs, labor, capital and energy). The objective of testing these models is to examine the potential of ''energy-extended'' Cobb-Douglas APFs to measure correlations between changes in inputs and output, despite the criticisms raised against them as reviewed in chapter 5. Finally, a BFP is tested, whereby the ecological critique of APFs surrounding the complementarity and non-substitutability of energy with man-made inputs is tested. After the two groups of models are tested, the results are compared and discussed in a theoretical context, briefly revisiting the history of APFs and BFPs outlined in chapter 5 and the meaning of these debates for my results.

Chapter 6 Estimating the share of energy flows in output growth in Canada, 1961-2022

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Chapter 5 has reviewed the history of APFs, their critique by post-Keynesian economists and three proposals made by ecological economists to measure the technical relationships between inputs and output using biophysical units of measurement. Chapter 6 turns to empirical testing of several models of APFs and BPFs considering the discussions from Chapter 5 and using the recent history of economic growth in Canada from 1961 to 2022 to test the models. Data availability and the tests of specific hypotheses on the relationships between energy and output production require the use of several models. We start by testing the relationship between output growth and primary and secondary energy use, labor and capital, following with models testing the share of energy via net-energy ratios of energy consumed and produced in Canada. We conclude with models testing the relationships between output and labor and capital modeled as sub-functions of flows of exergy (muscle and mechanical work and heat). Most models use multivariate regression measuring the correlation between inputs and output. Different models are used as a function of data availability, as will be shown below.

To address the research questions outlined in Chapter 1, APFs and one BFP are tested using three different measures accounting for energy-quality: 1) primary and secondary energy flows (not corrected for quality: 2) net-energy ratio of primary energy consumed/Standard Energy Return on Energy Invested ($EROI_{st}$) of primary energy produced in Canada and 3) exergy flows, where 2) and 3) are corrected for quality. The objective of this chapter is to determine whether the use of quality-corrected measures of energy influence the correlation observed in different models of output production and detect causality, if any, between these measures and changes in output measured in monetary units. Models used to test the correlation between output and labor, capital and measures 1) and 2) of energy flows are defined as ‘’energy-*extended*’’ APF following Solow’s model (Equation 81) since they model energy and net-energy ratios as a third and fourth factor of an APF where labor is measured in units of time and capital in flows of capital investment. The model used to test the correlation between output and measure 3) is defined as an ‘’energy-*dependent* BFP’’ as inputs are partially measured in biophysical units of measurements.

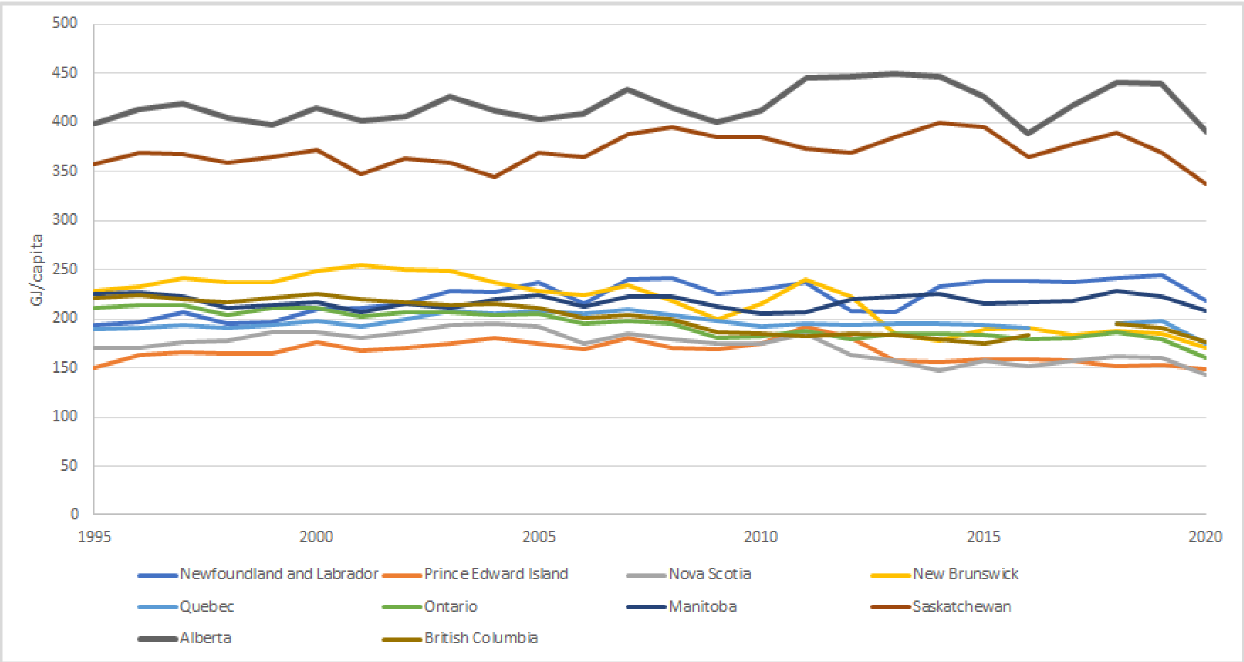
The rationale for the construction of the time series used to test the models was to obtain as many observations as possible. The first group of models (1-8) tests the correlation between output production over labor, capital and flows of primary and secondary energy using provincially disaggregated data from 1997 to 2020, which we refer to as a ‘’three-inputs models.’’ The time frame is chosen because provincially disaggregated data for each factor are available during the period. We use a counterfactual in this section to further enhance our understanding of output production as a function of flows of primary and secondary energy. Three-inputs models are compared with standard, two-inputs models to test the different models’ predictive powers of output growth for Canada between 1997 to 2020. We follow with a production function testing the impact of net-energy ratios as a fourth factor along with primary and secondary energy flows, capital and labor on output production from 1978 to 2022, hoping to assess the connection (if any) between output production and changes in the quantity of primary energy flows required to produce economically useful energy products (gasoline, diesel, etc.) The time frame stems from the fact that provincially disaggregated data are no longer available with the data required to estimate net-energy ratios (Statistics Canada *Energy Supply and Demand Tables*, which start in 1978 (2024a; 2024b), a disadvantage that is somewhat compensated by the fact the time series can be started earlier in time. Data available to estimate exergy flows in Canada (Marshall et. al., 2024) allow us to start our time series in 1961.

The chapter is divided as follows. Each group of models (using measures 1), 2) and 3) of energy flows) is discussed in a distinct section. Each section follows the same structure. The first section introduces the sources of the data used to test the models. The second section discusses their mathematical construction and, when necessary, the assumptions made to build them. The third section presents the results of the regressions, followed by a short discussion on the results where we discuss the realism of the model based on the results found. Following Ayres and Warr (2005), we reject models yielding coefficient with negative values given the empirical implausibility that increases in input-use would cause a decrease in output growth. Each section concludes with a test of causality between inputs and output for the models succeeding this first test of plausibility. Co-integration of the time series is tested to detect common stochastic trend and non-stationary time series and transform them into first differences if necessary (Hanck et. al., 2024).

6.1 Models 1-8: Models testing for flows of primary – secondary energy use

The first models (1-8) consider the geography and diversified energy-use profiles of the 10 Canadian provinces over a relatively short period of time. Figure 36 shows a significant difference in energy-use per capita across Canadian provinces. A proper estimation of the share of energy-use in output production must account for the diversified energy-use profiles across provinces. As such, the first six models use interprovincial variabilities of energy-use per capita across time. Per capita data are used to control for demographic effects of provinces, such as Ontario with a population of over 14 million and a population of over 150,000 in Prince Edward Island as of 2021 (Statistics Canada, 2023a). Figure 36 shows the sum of primary and secondary energy-use per capita of the province of Alberta and Saskatchewan to be higher than the 8 other provinces.

Figure 36 Primary and secondary energy-use per capita per Canadian province, 1995-2020



Source: Statistics Canada: Supply and demand for primary and secondary energy, Table 21-10-0029-01

The first series of models therefore use disaggregated data on energy-use per capita per province for the period 1997-2020.

6.1.1 Sources of data

We use data on GDP, net capital investment (both in constant Canadian dollars), primary and secondary energy-use (in joule) and labor (in hours worked) at the provincial level. For all four variables, we were able to use publicly available data from Statistics Canada's, the country's national statistical agency. For energy-use, we use data on the final demand of primary and secondary energy per province. Disaggregated data on the final demand of primary energy only for each province are not available. Thus, the sum of primary and secondary energy is used. Statistics Canada defines ‘‘final demand’’ as the summation of primary and secondary (Statistics Canada, 2021) energy used in mining, oil and gas extraction, manufacturing, forestry (goods and support services), construction, transportation, agriculture, residential, public administration and institutional, in terajoule (Statistics Canada, 2023b). Final demand of primary and secondary energy is therefore a relevant variable for a production function as all these sectors are output-generating.

To measure output production, we used the income-based Gross Domestic Product (GDP) tables (Statistics Canada, 2024c) adjusted in constant 2018 Canadian dollars. To measure labor services, we used total hours worked for all jobs (Statistics Canada, 2024d). Statistics Canada disaggregates hours-worked per paid worker and self-employed from 1997 onwards. We find no reason to exclude the latter from our dataset.

Finding data for the value of capital services was trickier. We have seen in section 5.3 the logical difficulties associated with aggregating and measuring the capital stock using monetary units. Because capital is, stricto sensu, a stock whereby a production function measures flows of services, we used data on Business Gross Fixed Capital formation from Statistics Canada's expenditure-based Gross Domestic Product table (2024e), defined as the acquisition of new and existing non-financial assets by businesses less the value of disposals in non-financial assets in residential structures plus non-residential structures (machinery and equipment (Statistics Canada, 2018)). In other words, ‘‘Business gross fixed capital formation’’ by businesses capture the annual flows to non-financial capital stock, thereby moderating (hopefully) the first difficulty of aggregating capital as stock, since we can measure capital as flows.

We now build models of APFs for the Canadian economy, disaggregating the respective share of primary and secondary energy-use, labor and capital investment into output growth, all per capita. We use a panel data set where observations are disaggregated per Canadian provinces from 1997-2020. Such a data set leads to possible effects arising from omitted variables that are constant over time but different across provinces or vice-versa. As such, we use a two-way fixed effects regressions to control for time-constant and province-constant heterogeneity via a time and a province fixed-effects regression, respectively (Stock and Watson, 2020), moderating the effects of omitted variables arising from the nature of the data.

To control the effects of inflation over time, monetary values in current dollars are converted into constant 2018 Canadian dollars using Statistics Canada's national Implicit Price Index, Gross Domestic Product where 2017=100. As mentioned in the introduction, we started this research when the base index was 2012=100. When necessary, data collected in constant Canadian dollars with 2017 as its base index were converted into 2012 = 100 (Statistics Canada, 2024f). In the spirit of production functions, we seek to obtain the value of each factor's coefficient in terms of elasticity with respect to economic output, where a percentage change in one of the independent variables induces a 1% change in output per capita. Thus, except for the first two models, all our data (in real value per capita) are converted into their natural logarithm, and we use the logarithmic form of our observations henceforth.

The simplest version of the model (Models 1-2) is shown in Equations 101 and 101. Model 1 (Equation 101) is a standard, two-inputs APF as reviewed in section 5.2. Model 2 (Equation 102) adds primary and secondary energy flows as an input to the function, akin to Solow's three-inputs function:

Equation 101

$$\ln(\frac{Y}{C})_{it} = b_o + b_1 * ln(\frac{L}{C})_{it} + b_2 * ln(\frac{K}{C})_{it} + \alpha_i + \delta_t + \varepsilon_{it}$$

Equation 102

$$ln(\frac{Y}{C})_{it} = b_o + b_1 * ln(\frac{E}{C})_{it} + b_2 * ln(\frac{L}{C})_{it} + b_3 * ln(\frac{K}{C})_{it} + \alpha_i + \delta_t + \varepsilon_{it}$$

where the subscripts ''t'' and ''i'' respectively refer to the i^{th} province and the t^{th} year, ''Y''' is the value of output in constant 2018 Canadian dollars, ''C'' is ''capita'', ''e'' is the flows of primary and secondary energy use in gigajoule, , ''α_i'' is ''province fixed effects'' and ''δ_t'' is ''time fixed effects''.

To address potential non-stationarity in the data used in Models 1-2, Model 3 uses first/annual differences as its observations. Model 3 (Equation 103) is narrowed down to the impacts of annual changes in the three inputs on annual changes in output production. Model 4 (see Table 8) follows the same mathematical form but is limited to a two-inputs model without energy-use:

Equation 103

$$\Delta ln(\frac{Y}{C})_{it} = b_o + b_1 * \Delta\, ln(\frac{E}{C})_{it} + b_2 * \Delta ln(\frac{L}{C})_{it} + b_3 * \Delta ln(\frac{K}{C})_{it} + \alpha_i + \delta_t + \varepsilon_{it}$$

where 'Δ' is the first-difference operator ($\Delta Y_{it} = Y_{it} - Y_{it-1}$). The last step is to include lagged variables. Taking possible lags into account is required to provide an elementary estimate of the dynamic effects of input changes across time. For example, investment in capital can take several years before its effects on productivity and output can be observed (Ayres and Warr, 2005: 185). Energy-use in the construction and setting up of capital goods can generate an effect on output production only after a delay that annual observations can fail to capture.

Using first differences and lagged variables considerably reduces the number of observations we can use. Our original time-series starts in 1997. Using first differences means our first observation results from the subtraction of the value of the observation for 1998-1997. Furthermore, introducing a lagged variable meant the first year of observation we could use was 1999, accounting for the lagged first difference 1998-1997. The data set for Model 5 (Equation 104) spans from 1999 to 2020:

Equation 104

$$\Delta ln(\frac{Y}{C})_{it} = b_o + (b_1 * \Delta\, ln(\frac{E}{C})_{it} + (b_2 * (\Delta\, ln(\frac{E}{C})_{it-1}) + (b_3 * \Delta ln(\frac{L}{C})_{it}) + (b_4 * (\Delta\, ln(\frac{L}{C})_{it-1}) + b_5 * (\Delta ln(\frac{K}{C})_{it}) + b_6 * (\Delta ln((\frac{K}{C})_{it-1}) + \alpha_i + \delta_t + \varepsilon_{it}$$

6.1.2 Results

Using a 5% level of statistical significance, we test the null hypothesis of a non-significant to negative relationship between the variables, the alternative hypothesis stating the relationship is positive. We use a 5% critical threshold and a two-tailed test ($t_c = 1.984$) to test the null hypothesis. Table 8 below shows the results of the regressions which are interpreted below.

Table 8 Regression results for models 1-6

	Model 1 (Equation 101)	Model 2 (Equation 102)	Model 3 (Equation 103)	Model 4	Model 5 (Equation 104)	Model 6
Energy use per capita		0.410 (0.066)***				
Energy use per capita, first difference			0.180 (0.076)*		0.178 (0.077)*	0.167 (0.072)*
Energy use per capita, first difference, lagged					-0.109 (0.078)	-0.132 (0.073)
Hours of work per capita	1.413 (0.192)***	1.586 (0.180)***				
Hours of work per capita, first difference			0.723 (0.209)**	0.70 (0.21)**	0.717 (0.21)***	0.532 (0.188)**
Hours of work, first difference, lagged					0.229 (0.227)	0.247 (0.203)
Net capital investment per capita	0.146 (0.033)***	0.067 (0.032)*				
Net capital investment per capita, first difference			0.091 (0.35)**	0.104 (0.036)**	0.097 (0.037)**	0.025 (0.034)

Net capital investment per capita, first difference, lagged					-0.051 (0.036)	-0.073 (0.033)*
Number of observations	240	240	230	230	220	188
Adjusted R^2	0.932	0.944	0.343	0.329	0.343	0.290
Standard errors are in parentheses * statistical significance at 5% ** statistical significance at 1% *** statistical significance at 0.1%						

Comparing Models 1 and 2, we observe adding flows of primary and secondary energy adds 0.012 point of Adjusted R^2 to the model. Despite the small change, we conclude adding flows of primary and secondary energy does increase the model's accuracy, albeit modestly, yielding a model with higher predictive power over a two-factors model. With Model 2, we reject the null hypothesis for our three coefficients at a 5% level of statistical significance. Model 2 suggests a 1% change in energy use per capita induces a 0.41% change in output per capita across the period. The impact is higher than net capital investment but lower than hours worked, a result which must be interpreted with care provided the effects of capital investments on output growth are much likely felt over a long period of time. Energy use and labor are statistically significant at 0.1%.

However, the validity of Model 2 is limited by potential stationarity in the data and the dynamic effects of input changes on output changes, two problems Models 3, 4 and 5 were built to mitigate. With Models 3 and 5, we reject the null hypothesis for our three coefficients in first differences. In Model 5, we observe lagged coefficients are either negative or failing to reach the threshold of statistical significance set at 5%. Models 3 and 5 display constant return to scale, the three coefficients summing to 1, a sign of their empirical plausibility. Model 4 uses the two standard inputs of neoclassical growth theory in first differences. As with Models 1 and 2, when comparing Models 3 and 4, we find adding energy to the production function increases the Adjusted R^2 of the model by 0.67. As such, we conclude adding first differences of primary and secondary energy-flows to the model modestly increases its predictive power. Model 5 uses lagged variables to consider dynamic effects. Focusing on energy-use, Model 5 suggests a 1% change in the non-lagged annual difference of energy-use per capita induces a 0.18% change in the annual difference in output per capita, a result lower than annual changes in labor but superior to capital investment, a result analogous to Model 3. The output elasticity of labor being higher than capital is consistent with neoclassical models.

Model 5 is the most complete model testing for the correlation of flows of primary and secondary energy on output growth, using both first difference and lagged variables. We therefore use it to test for causality, provided: a) it yields no negative coefficient of the non-lagged variables; b) non-lagged variables display constant returns to scale, suggesting it is an empirically plausible model. We first test for the non-stationary of the time series in first differences to determine whether the series are co-integrated, as shown in Table 9:

Table 9 Augmented Dickey-Fuller (ADF) with drift and linear trend for first differences of output and primary and secondary energy flows per capita (Equation 104)

	Augmented Dickey-Fuller Number of lags = 1	Number of observations
Output per capita – First differences $\Delta\ln(\frac{Y}{C})$	-12.65 (> 0.01)	220
Flows of primary and secondary energy per capita – First difference $\Delta\ln(\frac{E}{C})$	-16.12 (> 0.01)	220

In both cases, the null hypothesis of non-stationary of the time series in first difference can be safely rejected. The time series are integrated of order 1. We now test for Granger causality between the two time series in both directions, following the econometric literature. The VAR package we use on R-studio to transform the time series into vector auto-regression models suggest the optimal number of lags to be used in the Granger-causality for the time series involved in Model 5 test is two.

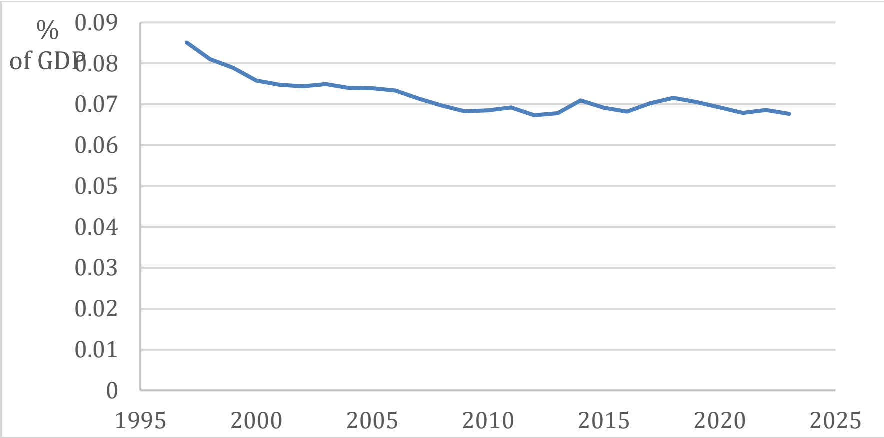
Table 10 Granger causality test for flows of primary and secondary energy use causing changes in output using time series of Model 5

	F-statistic	Number of observations
Cause: Flows of primary and secondary energy use causing output growth (in– First difference (Model 5) Number of lags = 2 $\Delta\ln\frac{Y}{C} \sim \Delta\ln\frac{E}{C}$	3.09 (0.047)	220
Cause: Flows of output causing growth in flows of primary and secondary energy use work – First difference (Model 5) Number of lags = 2 $\Delta\ln\frac{E}{C} \sim \Delta\ln\frac{Y}{C}$	6.95 (> 0.01)	220

Granger-causality test shows bi-directional causality between output growth and flows of primary and secondary energy use. Our data suggest growth in output cause an increase in energy-use, which via a feedback loop, cause output to grow.

We now test the cost-share theorem against the value of the coefficients of energy-use found in Models 3 and 5, where we found the output elasticity of primary and secondary energy use to be in the range of 0.178 – 0.18. As per the cost share theorem, we should expect the share of energy producing sectors in national accounts to be roughly equal to 18% of national income. We use Statistics Canada Gross Domestic Product by industry to determine the share of the energy producing sector in output. Statistics Canada defines the ‘’Energy sector’’ as the sum of the following sub-sectors: oil and gas extraction, coal mining, other metal ore mining, oil and gas drilling, services to oil and gas industry, electric power generation, distribution and transmission, natural gas distribution, petroleum refineries and pipeline transportation. Dividing the income of this sector over total output (in current dollars) over 1997-2023 yields:

Figure 37 Share of the energy producing sector in national income, Canada, 1997-2023



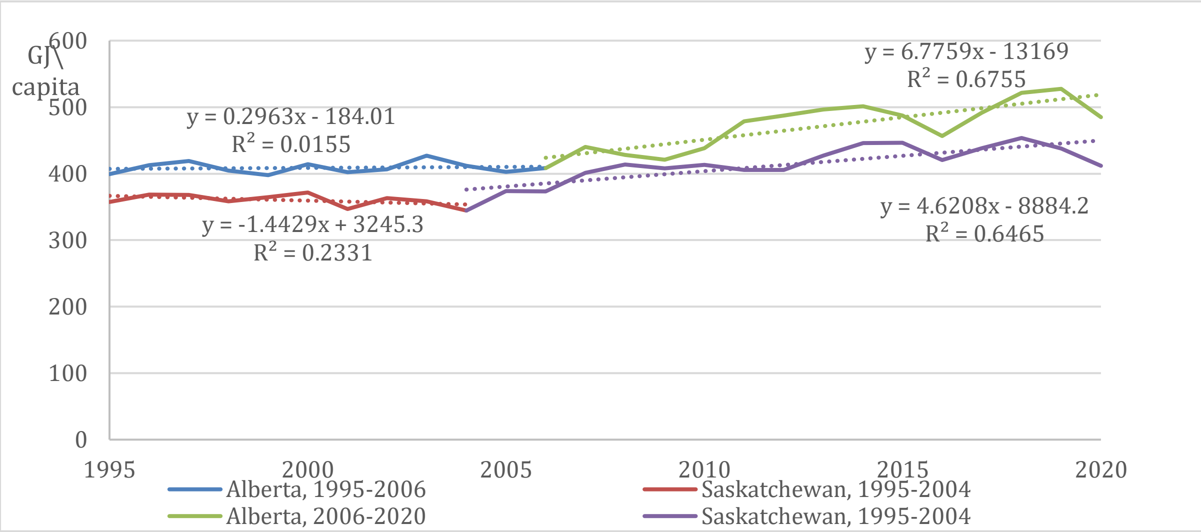
Source: Statistics Canada, Gross domestic product at basic prices, by industry, annual averages, Table 36-100434-03

Figure 37 suggests the share of total income by the energy sector declined from 8.5% in 1997 to a little below 7% in 2023, about half of the value of output elasticity coefficients found. Our data suggests the cost-share theorem must be rejected.

6.1.3 Counterfactual

A second method to estimate the impact of primary and secondary energy-use on output production involves the use of a counterfactual. The use of a counterfactual is motivated by the following observation: Model 6 excludes observations for the two energy producing provinces in Canada, Alberta and Saskatchewan, after sudden changes were observed in their energy-use profiles per capita, as shown in Figure 38. Excluding these observations yield a lower Adjusted R^2, suggesting higher energy-use is indeed related to output. Figure 36 has shown Alberta and Saskatchewan stand alone in terms of energy-use per capita. Figure 38 shows the linear trend in energy-use per capita for the two provinces. Interestingly, we notice changes in the trends starting in 2006 in Alberta and 2004 for Saskatchewan as suggested by changes in the values of the slopes of the two regressions:

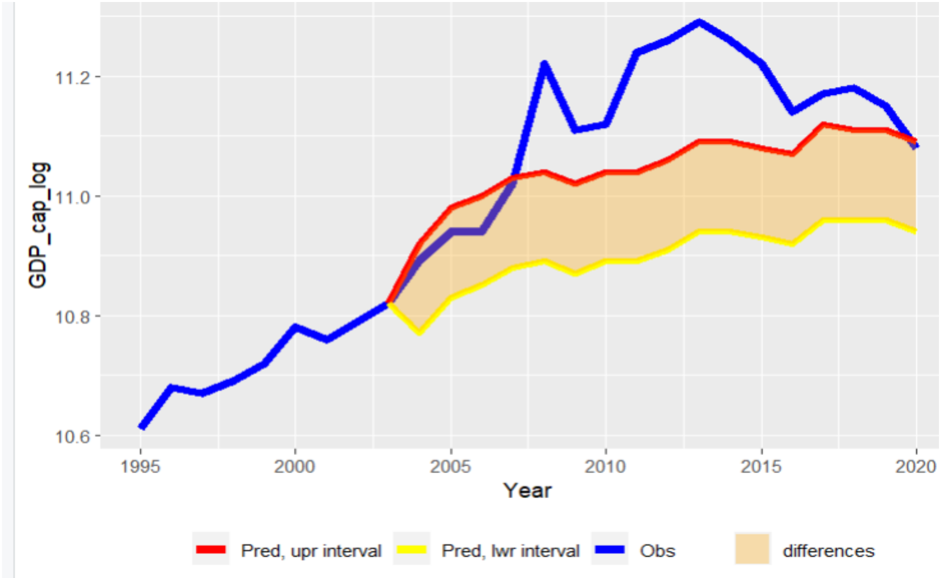
Figure 38 Primary and secondary energy-use per capita and respective linear trends, Alberta (1995-2006; 2006-2020) and Saskatchewan (1995-2004; 2004-2020)



Source: Statistics Canada, Supply and demand of primary and secondary energy in terajoules, annual, Table 25-10-0029-01

We hypothesize that should energy-use/capita be positively and significantly related to the production of output, then one should 1) estimate the value of the coefficients of Model 5 excluding the value for Alberta (2006-2020) and Saskatchewan (2004-2020) after the changes in trends; 2) use the model devised in 1), that is Model 5 minus post-change observations, to predict what would the first difference in output per capita would have been for these two provinces excluding the post-change observations. The hypothesis is that the predictions performed in 2) should yield a significant difference between predicted and observed values, thus allowing to reject the null-hypothesis of an absence of correlation between the variables. Model 6 excludes the changes in energy-use per capita in Saskatchewan for 2004-2020 and Alberta for 2006-2020 from the dataset. Model 6 yields the mean predicted value of the coefficients. Given variability around the mean predicted value, we compute the lower and upper prediction on a 95% prediction interval. Figures 39 and 40 show observed output per capita and the predictions using the lower and upper bounds of the prediction intervals.

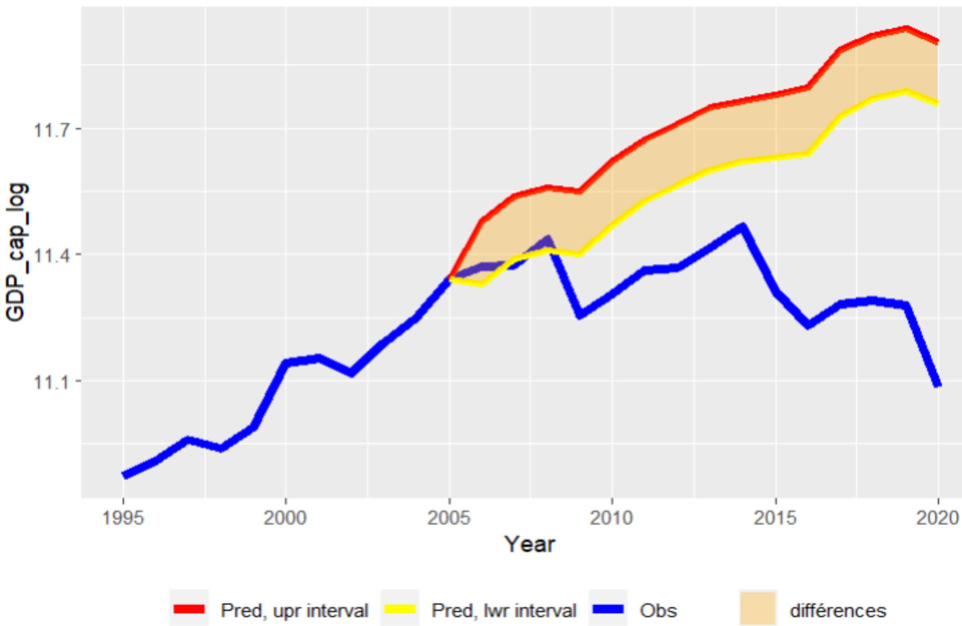
Figure 39 Output per capita for Saskatchewan, observed (blue) and predicted (upper and lower intervals), in log



Source: Statistics Canada, Gross domestic product, income-based, provincial and territorial, annual (x 1,000,000), Table 36-10-0221-01

Figure 39 confirms our intuition for the province of Saskatchewan. The observed values of output per capita are higher than those predicted by a model subtracting the post-change values of energy-use in the province, thus suggesting a positive relationship between the two.

Figure 40 Output per capita, Alberta, observed (blue) and predicted (lower and upper intervals), in log

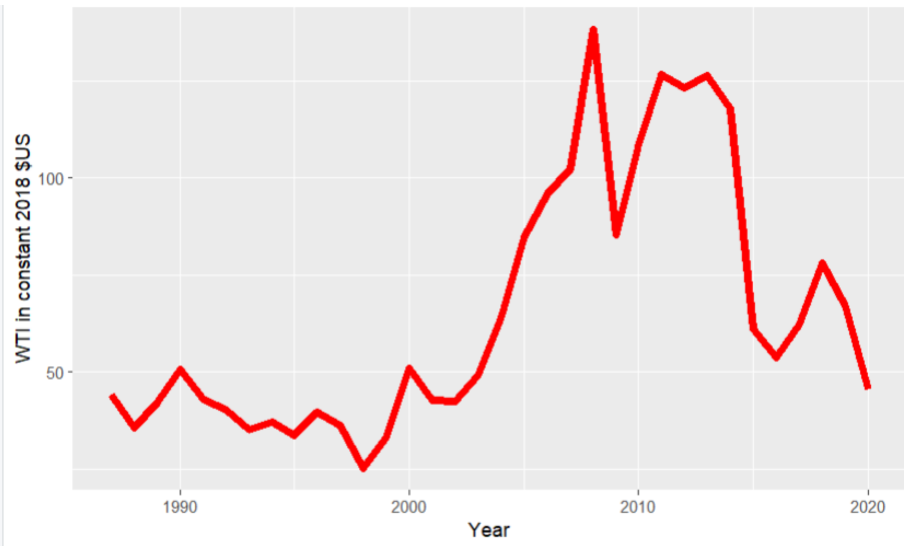


Source: Statistics Canada, Gross domestic product, income-based, provincial and territorial, annual (x 1,000,000), Table 36-10-0221-01

Figure 40 is surprising. The observations of output per capita in Alberta are lower than those predicted by Model 6. A possible explanation has to do with Alberta being the most important crude-oil producing province in Canada. As such, changes in the price of crude are much more likely to impact its output on the income side via income changes of its energy-producing sector. Provided abrupt changes in crude oil prices occurred during the period with the collapse in global crude oil benchmarks in 2008 and 2014, the hypothesis that Albertan output is significantly related to crude oil prices must be investigated further. Changes in crude oil benchmarks should cause changes in the income of the Alberta energy-producing sector and on its output. A higher price per barrel means higher revenues for the energy sector and vice-versa.

To estimate the validity of this hypothesis, we re-estimate Model 5 with observations from Alberta only and add another variable: the price of crude oil. We use the North American reference benchmark, the West Texas Intermediate (WTI) expressed in constant 2018 U.S. dollars, since the price of Canadian benchmarks closely follows changes in the WTI (Canada Energy Regulator, 2023). As shown in Figure 41, after rising steadily over the 1999-2008 period, the WTI fell in 2008 and 2014 and stabilized afterwards.

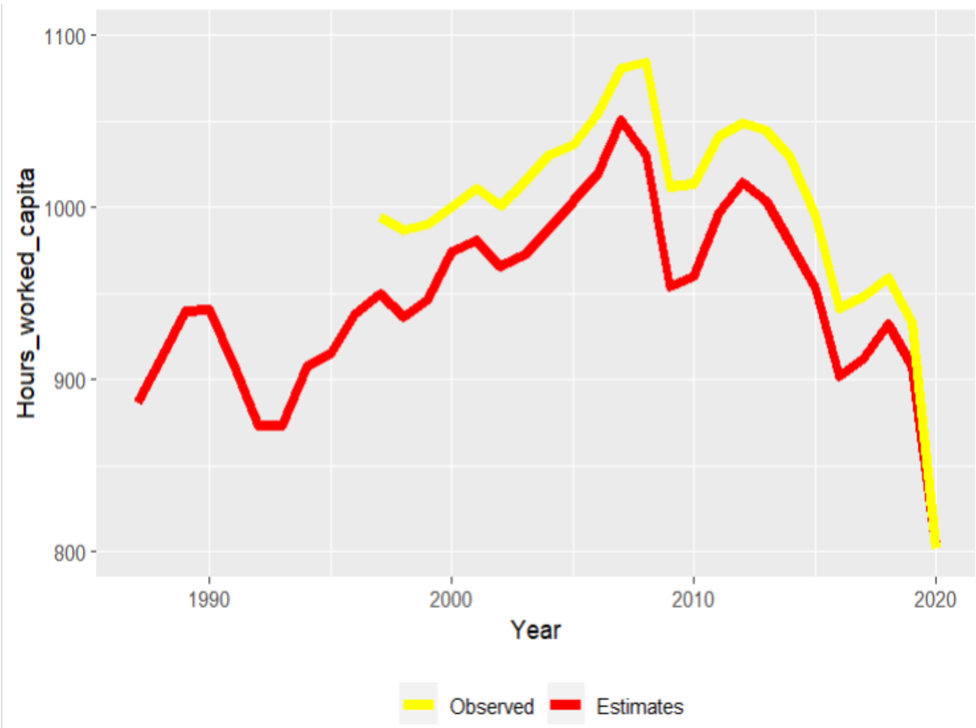
Figure 41 West Texas Intermediate at Cushing, spot price in constant 2018 $US



Source: Energy Information Administration (2024), Cushing, OK, WTI Spot price; Federal Reserve Bank of Saint-Louis (2024); Gross National Product: Implicit Price Deflator

Using the sources of data used for Models 5 to model a production function for Alberta would yield 22 observations only, making the test of our hypothesis difficult. Using another time series from Statistics Canada to estimate (rather than observe, as in Table 36-10-0489-01) hours of work in Alberta only (Statistics Canada, 2024g), we estimated the total hours worked in the province of Alberta from 1987 to 2020, thus adding 10 observations to the section of our original dataset for Alberta. Table 14-10-0037-01 provides data on total workers employed (all hours) and the average hours per workweek. We multiplied the total number of workers in the workforce by the average hours per work week times 52 to obtain an estimate of total hours worked. Figure 42 compares our estimates on total hours worked in Alberta for the years 1987-2020 from the observations from 1997 to 2020 used to estimate the coefficients of Models 1-6.

Figure 42 Hours worked per capita, Alberta, observed (yellow) and estimated (red), 1987-2020



Source: Statistics Canada (2024). Actual hours worked by industry, Table 14-10-0037-01; Labour statistics consistent with the System of National Accounts, Table 36-10-0489-01

Figure 42 shows our estimates to be close to the observed values of hours worked per capita for the period 1997-2020, with an average annual difference of 38.19 hours, or 4% of the average observed annual hours worked per capita, between the two series. We feel confident to use the expanded dataset to estimate the coefficients of the model of Alberta only. Table 11 shows the results of the regressions, with (Model 8) and without (Model 7) inclusion of the price of the WTI in the regressions and excluding the province fixed-effects from Models 1-6. To stay consistent with Models 1-6, we used first differences of the WTI.

Table 11 Regressions results for models 7 and 8

	Model 7: Alberta only without crude oil prices	Model 8: Alberta only with crude oil prices
Energy use per capita, first difference	0.02 (0.24)	-0.005 (0.18)
Energy use per capita, first difference, lagged	-0.25 (0.22)	-0.08 (0.17)
Hours of work per capita, first difference	0.97 (0.37)*	0.30 (0.32)
Hours of work, first difference, lagged	0.57 (0.44)	-0.11 (0.41)
Net capital investment per capita, first difference	0.28 (0.07)***	0.23 (0.05)***
Net capital investment per capita, first difference, lagged	-0.16 (0.07)*	0.00 (0.07)
Crude oil price (WTI), first difference		0.16 (0.03)***
Crude oil price (WTI) first difference, lagged		0.02 (0.04)
Adjusted R^2	0.73	0.84
Number of observations	32	32

Model 7 shows the first differences of the two standard inputs to be statistically significant. However, it shows non-lagged capital investment to be more statistically significant than hours worked, which goes against basic economic intuition. Furthermore, it shows energy-use to be non-significant. Model 8 shows net capital investment and crude oil prices to be statistically significant, whilst labor and energy-use are non-significant. The negative values of the coefficients (lagged and non-lagged) go against basic intuition. Nonetheless, the model displays a higher Adjusted R^2, suggesting that incorporating crude oil prices yield a higher explanatory power to the model. Model 8 thus shows the price of crude oil to be a variable of greater importance to output production in a crude-oil producing province like Alberta than energy-use.

Based on the number of negative coefficients yielded by Models 7 and 8, both fail Ayres and Warr's conditions of plausibility. We therefore do not test for causality between inputs and output of the models.

6.2 Models 9-10: models using net-energy ratios

Models 1-8 use final demand of primary and secondary energy flows to account for the share of energy in output growth. However, one of the main contributions of Biophysical Economics involves net-energy analysis, the estimates of the quantity of energy (in joule) required to produce energy flows used in the economy. A biophysically grounded model of output growth in Canada should try to estimate the impact of net energy ratios on output growth.

We build two time series of net-energy ratios in Canada according to two definitions of ‘‘energy output’’: a) produced and a) consumed in Canada. All energy produced in Canada is part of Canada's economic output. Yet, a significant portion of that output is exported, i.e. not used in the production of non-energy goods and services. Moreover, some energy products consumed in Canada are imported from abroad. Therefore, we need two different measures of net-energy according to whether energy-flows are consumed in the production of non-energy economic output only or not. In the first case (Model 9), we shall speak of ‘’net-energy ratio’’. In the second case (Model 10), one can speak of a genuine $EROI_{st}$ ratio which accounts for total energy output as its numerator. In both cases, the time series found are added to Model 5 (Equation 104) as a fourth factor to the production function, accounting for energy quality.

Models 9, 10, 11 and 12 all drop δ_t (time fixed effects). As the number of observations from Models 1-6 to 9-12 decline from [188-240] to [29-61], adding a time fixed effects would produce too many coefficients over the number of entries, therefore making regressions impossible.

6.2.1 Source of data

6.2.1.1 Model 9

To estimate the net-energy ratios of primary energy *consumed* in Canada, we cannot use standard net-accounting methodology used to estimate $EROI_{st}$ ratios using Canada as our accounting perimeter. Indeed, a portion of energy consumed in Canada is imported and a portion of energy produced in Canada is exported, thus falling outside of the area for which we have data. Another methodology is required. *Energy Supply and Demand Table*s report several categories of supply and demand on primary and secondary energy which can be used to estimate net-energy ratios of energy consumption in Canada. Although these tables include disaggregated provincial data, several key observations required to estimate net energy ratios for provinces are missing, making the use of disaggregated data for all provinces impossible. Thus, we use national data to produce a time series for net-energy ratios for Canada.

Net-energy ratios are estimated using the following method. The *Energy Supply and Demand Tables* provide data on primary energy availability, which is the sum of primary energy produced and imported into Canada minus exports. ‘‘Primary energy’’ includes coal, crude oil, natural gas, gas plant natural gas liquids, primary electricity (hydroelectric and nuclear) and steam (Statistics Canada, 2024a; 2024b). We argue that by dividing data on energy availability by the energy value of the transformation processes involved in the conversion of primary energy available into economically useful products, we obtain a rough estimate of net-energy ratios. For example: the tables provide data on fossil fuels transformed into electricity by utilities for household consumption and firm consumption, crude oil transformed into refined petroleum products in refining, coke transformed into manufactured gases, etc. Furthermore, the tables also provide data on ‘‘Producer consumption’’, i.e. the quantity of their own output consumed by energy producers (Statistics Canada, 2019a).

We argue that by subtracting from primary energy available all the flows involved in the transformation of primary energy into economically useful products, we obtain a proxy of energy inputs involved in the production of consumable energy flows to the economy. We estimate net-energy ratios following Equation 105:

Equation 105

$$NER = \frac{Av}{(A - TE_u - TE_i - T_{co} - T_{rp} - T_s) + P_c}$$

where ''NER'' is ''net energy ratio'', ''Av'' is 'energy availability (produced + imported - exported), ''TE_u'' is ''fossil fuels transformed into electricity by utilities'', ''TE_i'' is ''fossil fuels transformed into electricity by industry'', ''T_{co}'' is ''coal transformed into coke and oven gas'', ''T_{rp}'' is ''crude oil transformed into refined petroleum products'', "T_s" is 'fossil fuels transformed into steam' and ''P_C'' is for ''producer consumption''. Equation 105 is not equal to an EROI ratio for energy consumed in Canada since: 1) energy available includes energy imported in Canada from abroad; 2) the denominator of the ratio does not include embodied energy into indirect inputs, a key feature of net-energy analysis (Murphy et. al., 2011). Our time series for net-energy ratios extend from 1978 to 2022, the years for which data using the method described in this section is available.

Model 9 uses the same mathematical form as Models 3-6, using natural logarithms of the first differences of the variables but adds a fourth factor for net-energy-ratio into Equation 104 along with a lagged variable of net-energy ratios.

6.2.1.2 Model 10

Following Murphy et. al. (2011), we estimate the standard EROI ($EROI_{st}$) ratios of primary energy sources produced in Canada. $EROI_{st}$ is defined as the energy value of output leaving extraction and production facilities (mine-mouth) over the direct and indirect energy consumption of these facilities. We follow Freise (2011) and Poisson and Hall (2013) who used a similar method as the outlined below to estimate the EROI of conventional oil and gas and oil sands, respectively, in Canada.

We use the value primary energy of fossil fuels and electricity produced in Canada to account for energy output, using Statistics Canada's *Energy Supply and Demand Tables*. To estimate the energy value of direct and indirect inputs, we use Statistics Canada's Physical-Flow accounts. These tables follow the same classification structure as Statistics Canada's Input-Output tables, dividing the economy into sub-sectors following the classification of the North American Industry Classification System (Statistics Canada, 2019b). It estimates energy intensity of economic sectors by summing direct energy consumption and indirect energy intensity of the sectors (Statistics Canada, 2024h). ''Indirect intensity'' is defined as ''[…] *changes due to inter-industry purchases as they respond to the new demands of the directly affected industries. This includes the chain reaction of output up the production stream* [...]''

(Statistics Canada, 2024i). The value of these intensities is obtained using input-output multipliers. Data are available from 1990 to 2020 for Canada only: thus, our observations are at the national level only for a 30-year period.

Energy intensities are reported in joule/dollar of output, representing the quantity of energy consumed in the production of economic output. We use the ratios of energy intensity for the 7 sectors responsible for energy production, either as direct energy producers or in a supporting capacity to direct energy producers, as reported in the Physical-Flow Accounts: a) oil and gas extraction; b) coal mining; c) support activities for mining and oil and gas extraction and; d) electric power generation, transmission and distribution; e) oil and gas engineering construction; f) electric power engineering construction and g) pipeline transportation. We multiply each sector's energy intensity by the current dollar value of their respective output as reported in Statistics Canada Gross Domestic Product disaggregated by economic sectors, i.e. the North American Industry Classification System (2024j; 2024k). The product is thus an estimate of the energy intensity of direct and indirect inputs. We then use the energy value of output over the energy intensity of inputs to estimate the $EROI_{st}$ ratios of primary energy produced in Canada following Equation 106:

Equation 106

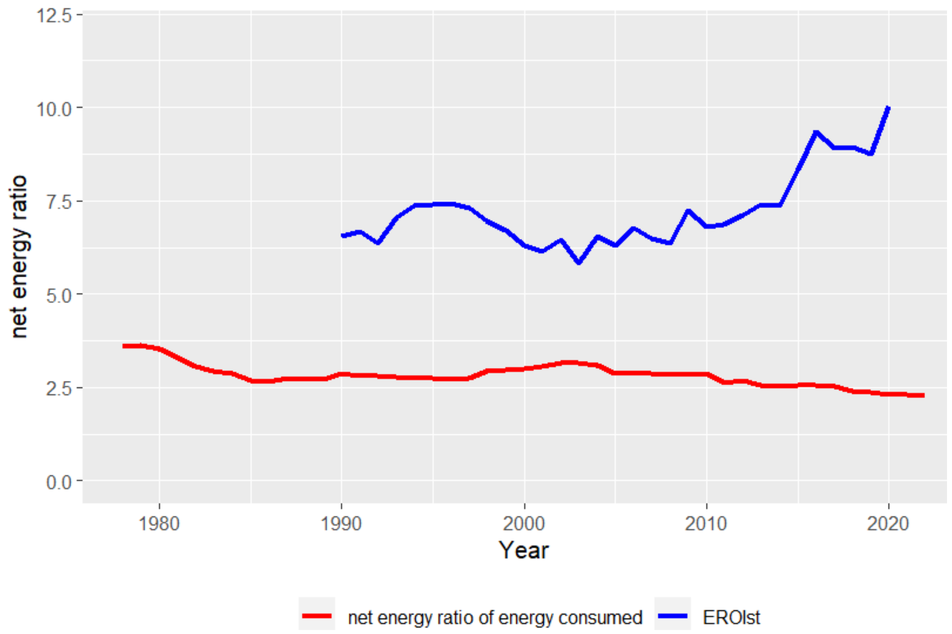
$$EROI_{st} = \frac{\sum_{i=1}^{N}(ELEC_j + co_j + ng_j + o_j)_{prod}}{(Y_{ext} * \frac{E}{Y_{ext}}) + (Y_{co} * \frac{E}{Y_{co}}) + (Y_{sup.ext} * \frac{E}{Y_{sup.ext}}) + (Y_{ELEC} * \frac{E}{Y_{ELEC}}) \ldots + (Y_n * \frac{E}{Y_n})}$$

where the subscript ''ext'' refers to ''oil and gas extraction'', ''sup.ext'' refers to ''support activities for oil and gas extraction'', ''ELEC'' means ''production of primary electricity'' and the subscript ''prod'' means the energy sources summed in the numerator were all produced in Canada. The $EROI_{st}$ ratios are added into Equation 104 as a fourth variable accounting for energy quality along with a lagged $EROI_{st}$ variable.

6.2.2 Results

We compute the value of NER from 1978 to 2022 in Figure 43, which also report $EROI_{st}$ ratios for energy produced in Canada from 1990 to 2020.

Figure 43 Net-energy ratio and $EROI_{st}$, Canada, 1978-2022



Source : Archived – Supply and demand of primary and secondary energy in terajoules, quarterly, with data for 1978-2001, Table 25-10-000401; Supply and demand of primary and secondary energy in terajoules, annual, Table 25-10-0029-01; Archived – Direct plus indirect energy intensity, by industry, Table 38-10-0108-01; Direct plus indirect energy and greenhouse gas emissions intensity, by industry, Table 38-10-0098-01; Gross Domestic Product (GDP) at basic price in current dollars, System of National Accounts (SNA) benchmark values, by North American Industry Classification System (NAICS), Table 36-10-0394-01

Figure 43 shows net-energy-ratios to decline slowly yet steadily across the period, whereas the $EROI_{st}$ ratios rise significantly after 2008, resulting from the rapid growth in oil sands production and export to the United States (see Chapters 3 and 4). We now run two regressions to estimate the impact of net-energy ratios on output growth. Our model follows the same framework as Equation 104, using first differences measures of primary and secondary energy-use, hours worked and capital investment per capita in natural logarithms, but uses national instead of provincial data, thus removing 'α_i' (province fixed effects). Model 9 uses net-energy ratios as its variable of net-energy and Model 10 uses $EROI_{st}$. Table 12 presents the results of the regressions performed using Model 9-10.

Table 12 Result of the regressions, models 9-10

	Model 9	Model 10
Energy use, final demand,	0.23	0.3

first difference	(0.162)	(0.20)
Energy use, final demand, first difference, lagged	-0.29 (0.15)	-0.70 (0.19)**
Hours worked, first difference	-0.02 (0.18)	0.07 (0.22)
Hours worked, first difference, lagged	0.09 (0.19)	0.72 (0.36)
Net capital investment, first difference	0.18 (0.07)*	0.12 (0.07)
Net capital investment, first difference, lagged	-0.03 (0.07)	-0.05 (0.09)
Net energy ratio, first difference	0.07 (0.11)	
Net energy ratio, first difference, lagged	0.05 (0.12)	
EROIst, first difference		0.08 (0.06)
EROIst, first difference, lagged		-0.02 (0.06)
Adjusted R^2	0.31	0.43
Number of observations	43	29

Model 9 suggests no statistically significant correlation between output production and the variables save for capital investment. It shows the output elasticity of lagged energy-use to be negative along with labor-use. Following Ayres and Warr (2005), it is unlikely for the output elasticity of energy-use to be negative as it would mean an increase in flows of energy-use is correlated with a decline in output. The statistical significance found for capital investment is surprising, given the typically lagged effects of capital investment on output growth. The model shows a weaker Adjusted R^2 than the model testing for $EROI_{st}$. A more thorough testing of the relationships between net-energy ratios and output production would require access to provincial data or data going further back in time, which are not available (to our knowledge). International comparisons using the same accounting categories would be a plausible avenue to enhance the validity of the inference proposed in this section.

Model 10 suggests lagged energy use to be statistically significant, although the coefficient is negative as in Model 9, where the same remark on the coefficient's plausibility applies. $EROI_{st}$ do not appear to be correlated with output. It does however display a higher Adjusted R^2 than Model 9, which suggests incorporating $EROI_{st}$ ratios produces models with higher predictive power. The absence of statistical significance for the coefficient accounting for the relationship between $EROI_{st}$ and output might be the consequence of $EROI_{st}$ in levels being measured mostly in energy units while output in levels is measured in monetary units exclusively. With the dramatic rise in oil sands export from Canada to the United States in the early 2000s, it is unsurprising $EROI_{st}$ rises rapidly, whereas monetary output generated via fossil production varies following the international price of the resources, with Figure 41 showing important variations. As such, a rise in the $EROI_{st}$ ratio of energy produced in Canada might not be reflected in monetary output. As for the realism of the models, neither Model 9 nor 10 displays constant returns to scale.

Based on the number of negative coefficients yielded by Models 9 and 10, both models fail Ayres and Warr's conditions of plausibility. We therefore do not test for causality between inputs and output of the models.

6.2.3 Model testing for exergy flows

We conclude the empirical section of the chapter with two models estimating the share of exergy services, i.e. flows of useful work, in output growth. Model 11 directly address our research questions and estimates the correlation between inputs modeled as sub-functions of exergy flows and output measured in units of constant Canadian dollars. Model 12 estimates the correlation between the same inputs but measures output in units of exergy flows.

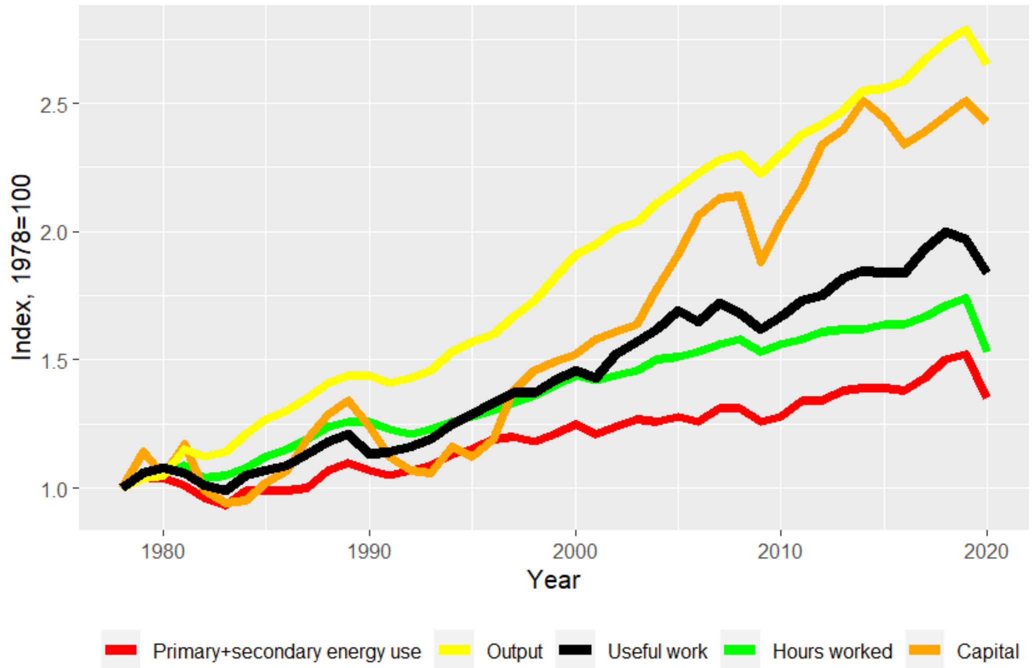
There are two major issues with production functions as considered in Models 1-10: theoretical and empirical. Theoretically, these models are all using a Cobb-Douglas functional form (see Equation 47.) As discussed in section 5.4.2.2, this functional form is problematic as it allows the mathematically correct, yet theoretically insignificant proposition that energy inputs E can be 0 and output can still be produced, which is a physical impossibility. Furthermore, this form does not show how in reality, labor and capital cannot be used in any meaningful sense without being enabled by flows of energy. Physically, energy is not a third factor of production, but a factor enabling flows of labor and capital services.

The empirical issue is more complex. Following Ayres and Warr (2005), due to heat loss in energy-use processes, not every joule of potential work contained in primary energy carriers used as inputs are converted into useful work. In other words, the heat value of primary and secondary energy flows used in Models 1-10 does not accurately reflect the fraction of useful energy really used in output production. As such, the flows of useful work, or the energy performing useful mechanical, chemical or thermal work after subtracting the loss incurred in energy-use processes by a ratio of thermodynamic efficiency are the thermodynamically appropriate variables to account for the role of energy in output growth. Thermodynamically speaking, exergy flows reflect the quantity of energy services to the economy once subtracted conversion losses (Santos et. al., 2018). ‘’Useful work’’ is the sum of 1) muscle work performed by human and non-human animals; 2) mechanical work (fuel used to perform electric power generation or by mobile power sources) and 3) heat generation by industry (chemical work) and households (domestic use) (Ayres and Warr, 2005: 186-187). By using flows of useful work as a variable of production functions, Ayres and Warr have found the so-called Solow residual to be trivial for the United States for the period 1900-1988. What Solow defined as ‘’technological progress’’ is found to be the result of improvements in exergy conversion (Ibid., 197).

Until recently, data on flows of useful work were not available for Canada (to our knowledge). This situation was changed by Marshall et. al.’s (2024) groundbreaking dataset containing data from 1961 to 2020 on primary, final (energy received by the end-use consumers (Ritchie, 2022)) and useful energy/exergy consumption per country as well as primary-to-useful exergy efficiency ratios used to convert primary energy flows into final and useful exergy flows. The dataset was built using data from the International Energy Agency to estimate mechanical work and heat generation and from the Food and Agriculture Organization to estimate flows of exergy from muscle work (Marshall et. al., 2024).

Ayres and Warr used exergy flows in production functions and tested the existence of the Solow residual for the United States over a 100-years period. We need to estimate if such a residual is observed in Canada. Marshall et. al. time series span from 1961 to 2020. We build our times series for Model 11 using Statistics Canada’s data on output, capital and labor growth from 1961 to 2020, therefore adding 15 observations over the time series used for Models 9 and 10. National data only can be used for the time period. Examining our time series non-corrected for population for Model 11, one can observe the following trends:

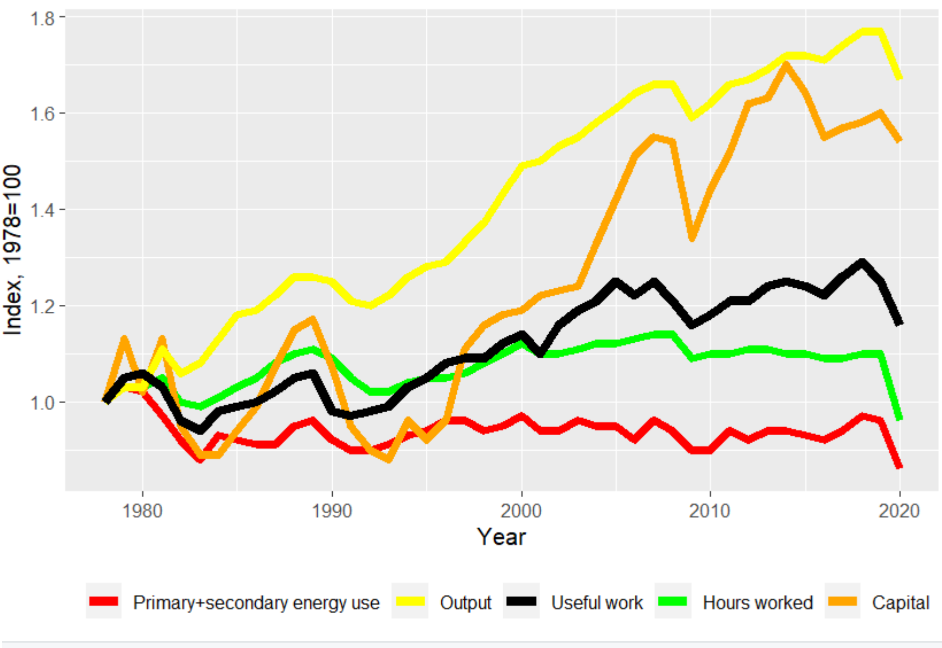
Figure 44 Index of growth of inputs and output, Canada, 1978-2020 (1978 = 1) non-corrected for population



Source: Statistics Canada: Archived – Supply and demand of primary and secondary energy in terajoules, quarterly, with data for 1978-2001, Table 25-10-0004-10; Supply and demand for primary and secondary energy, Table 21-10-0029-01; Archived – Labour productivity and related variables, by industry according to the Canadian System of National Accounts; Labour statistics consistent with the System of National Accounts (SNA), by job category and industry, Table 36-10-0489-01; Gross domestic product, expenditure-based, provincial and territorial, Table 36-10-0222-01

Figure 44 shows that from 1978 to 2020, flows of primary and secondary energy have increased by 35%, labor by 53%, useful work by 84%, capital by 143% and GDP by 165%. Following Solow's reasoning, one could argue there actually was a decline in technological progress in Canada between 1988 and 2014, observed via a declining productivity per unit of capital investment. Thus, the value of the multiplier would be decreasing from 1988 to 2014, where capital investment rises faster than output.

Figure 45 Index of growth of inputs and output per capita Canada, 1978-2020 (1978 = 1)



Source: Statistics Canada: Archived – Supply and demand of primary and secondary energy in terajoules, quarterly, with data for 1978-2001, Table 25-10-0004-10; Supply and demand for primary and secondary energy, Table 21-10-0029-01; Archived – Labour productivity and related variables, by industry according to the Canadian System of National Accounts; Labour statistics consistent with the System of National Accounts (SNA), by job category and industry, Table 36-10-0489-01; Gross domestic product, expenditure-based, provincial and territorial, Table 36-10-0222-01; Population estimates, quarterly, Table 17-10-0009-01

Index growth in inputs and output per capita displayed on Figure 45 show that flows of primary and secondary energy and hours worked per capita has declined by 14% and 4% respectively across the period studied. Capital investment, output and useful work have increased by 54%, 67% and 16%.

We now model BFPs and test whether using exergy-based inputs yields higher predictive capacity over Models 1-10. Model 11 replaces flows of primary and secondary energy use by exergy services using Marshall et. al.'s data set on the estimated heat generation, mechanical work and muscle work for Canada from 1961 to 2020. Marshall et. al. disaggregates final and useful exergy flows into ''net'' and ''gross'', where ''net'' excludes the energy used by the energy-producing sector. We use ''gross'' estimates: as an energy-superpower, we argue it is imperative to incorporate exergy services consumed by the energy sector to account for Canadian growth.

To model the relationships between exergy flows and output production, we use Keen et. al. (2019) proposal of an ‘’Energy-Dependent Cobb-Douglas production function’’ where labor and capital are *a function of exergy services* rather than independent inputs. Because Marshall et. al. already provides estimates of useful exergy flows for muscle work (labor) and mechanical work plus heat (capital), the use of thermodynamic ratios in Equations 91 and 92 are not necessary:

Equation 107

$$\frac{Y}{C} = (\frac{K}{C} * E_{\chi}^{K})^{a} * (\frac{L}{C} * E_{\chi}^{L})^{\beta}$$

$$E_{\chi}^{K} = \frac{MECW_{U} + HE_{u}}{K}$$

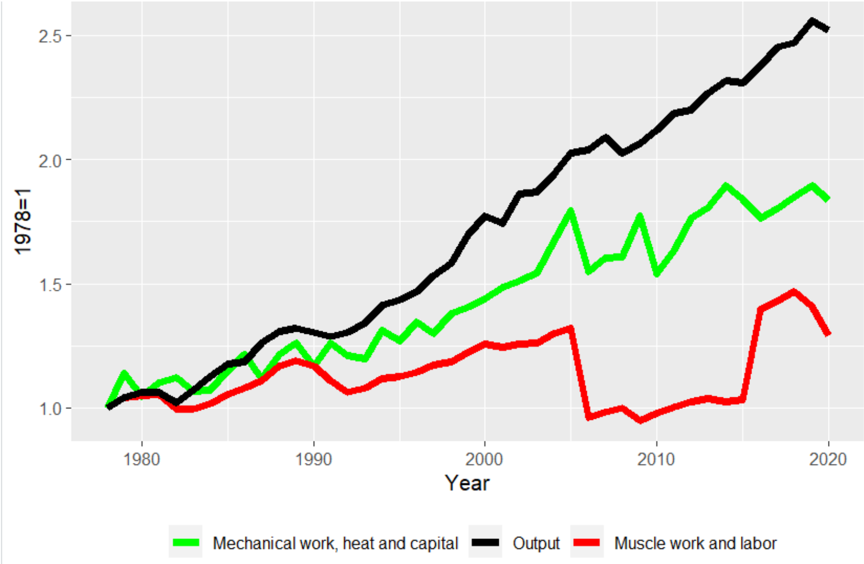
$$E_{\chi}^{L} = \frac{MUSW_{U}}{L}$$

where ‘’$MUSW_U$’’ refers to flows of useful muscle work, ‘’$MECW_U$’’ refers to flows of useful mechanical work and ‘’HE_U’’ refers to flows of useful heat. The problems associated with defining K were discussed in section 5.3. Ignoring these problems for the time being, we define K as the flows of net capital investment measured in constant 2018 constant Canadian dollars as in models 1-10. Keen et. al. argue that owing to the right side of the equality being measured in joule, the left-side (output) should be measured in the same unit of measurement.[43] We acknowledge the theoretical validity of the authors’ position. However, we stick to a monetary measure of output in constant dollars per capita for the time being to address our research question on the relationships between energy flows on monetary output. We use the same units of measurements used in the previous modes to estimate the size of labor (in man-hours) and capital flows (in annual flows of business gross fixed capital formation) and output.

When first using Marshall et. al.’s data set on flows of muscle work, mechanical work and heat, we found out a series of errors on the value of muscle work estimated between 2005 and 2015 in Canada, as shown in Figure 46:

[43] Although it is unclear how the physical size of ‘’capital’’ can be measured without using monetary units.

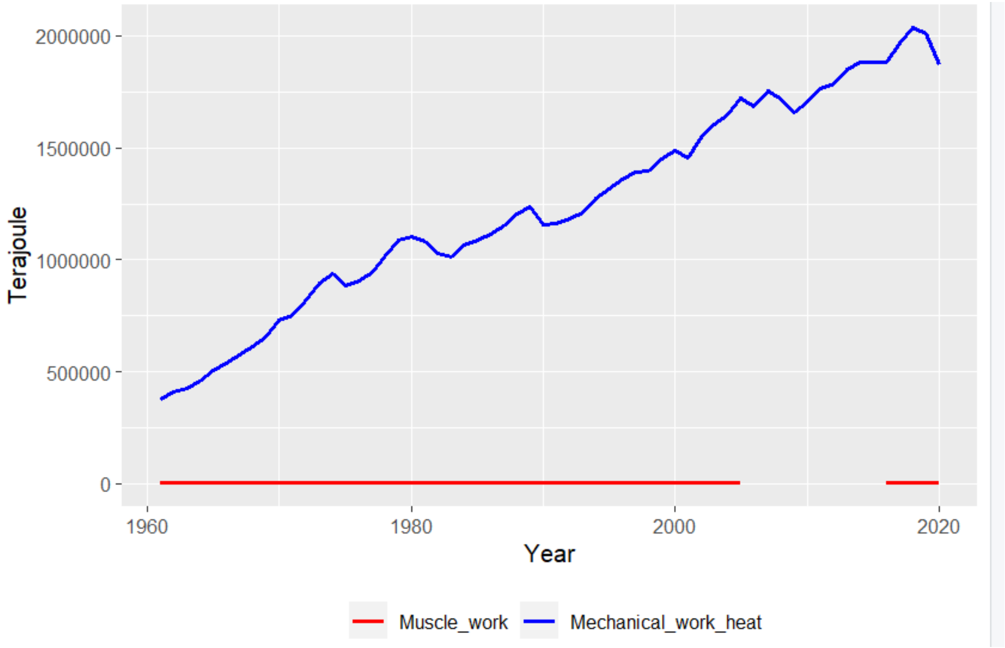
Figure 46 Index growth of output (in dollars), mechanical work, heat and muscle work



Source: Marshall, Z. et. al. (2024). A Country-Level Primary-Final-Useful (CL-PFU) energy and exergy database v1.2, 1960-2020; Statistics Canada (2024), Gross-domestic product, expenditure-based, provincial and territorial, annual (x 1,000,000), Table 36-10-0222-01

The editors of the dataset were immediately notified and acknowledged the errors. As of writing, the errors detected have not been corrected. However, these errors do not mean estimating the correlation between monetary output and useful work is impossible. Indeed, upon closer examination of the data, we found the value of muscle work (in joule) in the total flows of useful exergy in the Canadian economy to be insignificant. For example, in 2020, muscle work represented 0.16% of total flows of joules of useful energy in the Canadian economy. Figure 47 illustrates total flows of useful exergy disaggregated by type from 1961 to 2020 in terajoules excluding the errors in the values of muscle work for 2005-2015 identified in Figure 46:

Figure 47 Flows of muscle work, mechanical work and heat in Canada, 1961-2020, in terajoules



Source: Marshall, Z. et. al. (2024). A Country-Level Primary-Final-Useful (CL-PFU) energy and exergy database v1.2, 1960-2020

Figure 47 suggests the flows of muscle work have been relatively constant and trivial across the period studied. This is consistent with Keen et. al. (2019) for whom the flows of energy enabled by human labor per se must have been relatively constant across history. The value of the flows of muscle work being very low, we can estimate the correlation between output production and capital as a sub-function of mechanical work and heat without the risk of ignoring significant variables. This is what we do in Model 11A, where flows of mechanical work and heat empowering capital flows is the sole regressor. We introduce a lag in the model to remain consistent with the mathematical framework used throughout this chapter. Model 11B tests the complete Keen et. al.'s model but subtracts the 10 observations for the year where the value of flows of muscle work are the result of an error (see Figure 46). Model 11B therefore uses values for 1961-2005 and 2015-2020 as its observations for the two inputs.

We test for the non-stationarity and co-integration of the time series used to test Equation 107 (Model 11) before running the model. Visual inspection of the values for capital as a sub-function of flows of mechanical work and heat and output per capita suggests both time-series are non-stationary, as shown in Figure 48, where the variables are expressed in their natural logarithms:

Figure 48 Output per capita and capital as a sub-function of flows of mechanical work and heat, in natural logarithm, 1961-2020

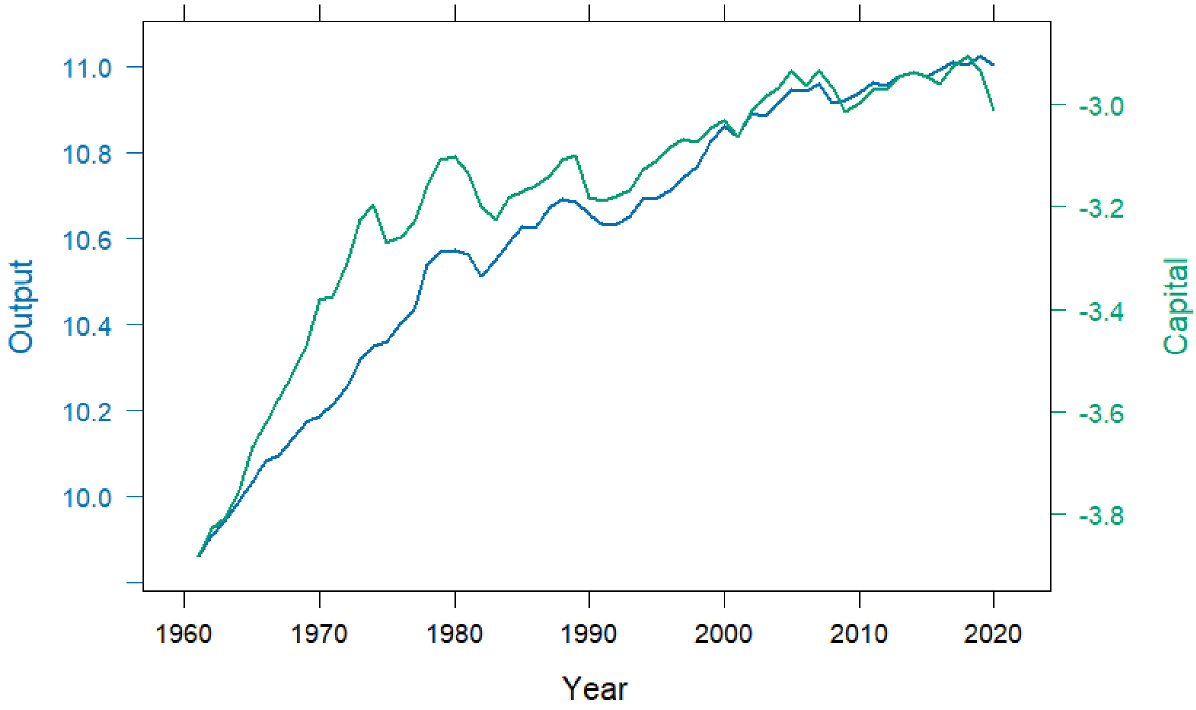
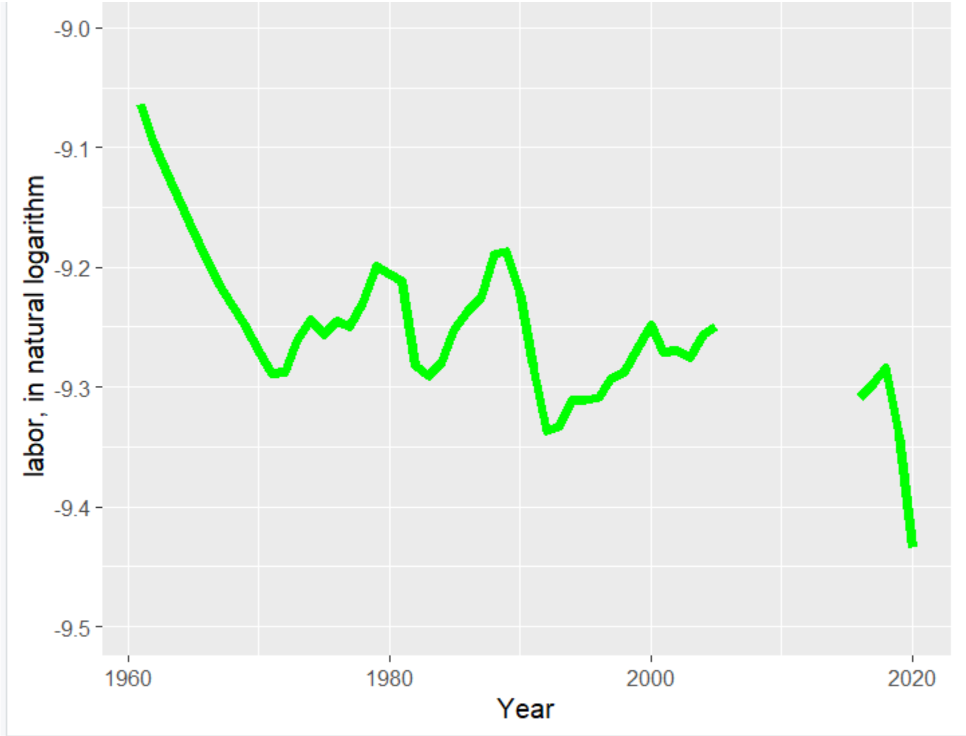


Figure 49 displays labor as a sub-function of muscle flow:

Figure 49 Labor as a sub-function of muscle work, in natural logarithm, 1961-2005, 2016-2020



Visual inspection of Figures 48 and 49 advise for further testing on the non-stationarity and co-integration of the time-series. We run two Engle-Granger Augmented Dickey-Fuller tests for Unit Root (Hanck et. al., 2024), one for each input regressed over output, both in levels, from Equation 107, to test for co-integration:

Table 13 Augmented Dickey-Fuller test for unit for the two time-series of input regressed over output in levels

	Augmented Dickey-Fuller test for unit root / Co-integration test Test-statistic	Number of observations
Output regressed over capital/mechanical work + heat, in levels $ln\frac{Y}{C} \sim \ln(\frac{K}{C} * E_{\chi}^{K})$	-1.51	60
Output regressed over labor/muscle work, in levels $ln\frac{Y}{C} \sim \ln(\frac{L}{C} * E_{\chi}^{L})$	-2.42	50

In both cases, the null hypothesis of no co-integration cannot be rejected. The time-series in levels are therefore non-stationary. We then reiterate the test by taking the first difference of the time series and find we can safely reject the null hypothesis of no co-integration for the first difference. The time series in levels are integrated of order 1 and their first difference are stationary and co-integrated, as shown in Table 14:

Table 14 Augmented Dickey-Fuller test for unit for the two time-series of input regressed over output in first difference

	Augmented Dickey-Fuller test for unit root / Co-integration test Test-statistic	Number of observations
Output regressed over capital/mechanical work + heat, in first differences $\Delta ln\frac{Y}{C} \sim \Delta \ln(\frac{K}{C} * E_{\chi}^{K})$	-4.69	59
Output regressed over labor/muscle work, in first differences $\Delta ln\frac{Y}{C} \sim \Delta \ln(\frac{L}{C} * E_{\chi}^{L})$	-3.93	49

Table 14 confirms the time-series in first difference of output regressed over inputs are stationary and co-integrated. These tests are by no mean trivial: if the data are cointegrated, then there must by Granger causality between them (Santos et. al., 2018). Co-integration is a sign of the causality we are looking for. Because of the importance of the result, we complete our testing of the co-integration of the time series by testing for the stationarity (or lack thereof) of the three time series involved in Equation 107 using a Type 3 Augmented Dickey-Fuller (ADF) test with a drift and linear trend for each series in levels as well as in first difference, using a 5% threshold of statistical significance. We transform each time series into vector auto-regression models to determine the optimal level of lags to be used to run the Augmented Dickey-Fuller tests with the VAR statistical package on R-studio. Each vector auto-regression model show one level of lag is optimal for the two group of time-series, in levels as well as in first differences. The results are shown in Table 15.

Table 15 Augmented Dickey-Fuller (ADF) with drift and linear trend for the three variables of Equation 107 and their first difference

	Augmented Dickey-Fuller Lag = 1	Number of observations
Output per capita - Levels $ln\frac{Y}{C}$	-1.86 (0.626)	60
Flows of useful mechanical work and heat times capital flows - Levels $ln(\frac{K}{C} * E_{\chi}^{K})^{a}$	-1.83 (0.639)	60
Flows of muscle work times hours worked per capita - Levels $ln(\frac{L}{C} * E_{\chi}^{L})^{\beta}$	-2.68 (0.295)	50
Output per capita – First difference $\Delta ln\frac{Y}{C}$	-4.92 (0.01)	59
Flows of useful mechanical work and heat times capital flows – First difference $\Delta ln(\frac{K}{C} * E_{\chi}^{K})^{a}$	-5.28 (0.01)	59
Flows of muscle work times hours worked per capita – First difference $\Delta ln(\frac{L}{C} * E_{\chi}^{L})^{\beta}$	-3.76 (0.03)	49

For all three time series in levels, we cannot reject the null hypothesis of non-stationarity. The time series in level turn out to be integrated of order 1. Therefore, we can safely use the first differences of the variables to perform our testing of Model 11 (Stock and Watson, 2020: 659) Tables 14 and 15 suggest there must be Granger causality between inputs and output provided we detected co-integration.

Table 16 reports the results of the regression using Equation 107.

Table 16 Results of the regression, Model 11

	Model 11A	Model 11B
Flows of useful mechanical work and heat times capital flows, first difference	0.503 (0.075)***	0.466 (0.083)***
Flows of useful mechanical work and heat times capital flows, first difference - Lagged	-0.051 (0.078)	-0.053 (0.088)
Flows of muscle work times hours worked per capita – first difference		0.109 (0.063)
Flows of muscle work times hours worked per capita – first difference - Lagged		-0.067 (0.064)
Adjusted R^2	0.447	0.444
Number of observations	60	50

Model 11A finds that for a 1% change in the flows of mechanical work and heat in the economy, monetary output increases by almost 0.5%. Provided Model 11A is coherent, we argue one can safely infer the flows of mechanical work and heat per unit of capital are closely correlated to the production of monetary output. The lagged coefficient is negative yet fail to meet the critical threshold of statistical significance. We therefore reject it. As suggested by the Adjusted R^2, Model 11A yields the strongest correlation found so far. Model 11B shows virtually the same statistical significance and value of elasticity of output for capital. Output elasticity of labor fails to reach any critical threshold of statistical significance. Lagged coefficients are negative, they are therefore rejected. Based on the results in Table 16, we cannot infer much in terms of the theoretical significance of modelling labor as a sub-function of energy flows.

Model 11 is not entirely consistent. Following Keen et. al. (2019), denominating the inputs of a BFP in joule would require measuring output in joule as well. Provided BFPs are relatively recent, we do not know of any attempt at modelling and testing such a function in purely biophysical terms. A theoretical proposition on how to empirically measure the correlation between inputs and output using joules to measure output was made by Pellegris (2022)[44] who proposes to measure economic output in terms of flows of useful exergy, defined as the true ‘’wealth‘’ of the community, i.e. its ability to perform work. Inputs are measured not in terms of useful exergy, but final energy, i.e. energy received by the end-use consumers, in this case laborers and capitalists, converting these flows into flows of labor and capital. Production functions then measure the ability of an economy (i.e. of capital and labor) to transform the flows of final energy inputs it receives into useful work. Equation 108 models the technical relationships between flows labor and capital modeled as sub-functions of final energy of muscle work, mechanical work and heat and output measured in units of useful exergy per capita (Model 12):

Equation 108

$$\frac{U}{C} = (\frac{MUSC_{Fi}}{L} * \frac{L}{C})^{a} + (\frac{HE_{Fi} + MW_{Fi}}{K} * \frac{K}{C})^{\beta}$$

Table 17 reports the results of the regression performed using Equation 108, for the same period covered by Model 11B, that is 1961-2005 and 2016-2020, excluding the years when the value for muscle work in Marshall et. al’s data set are erroneous:

Table 17 Results of regression, Model 12

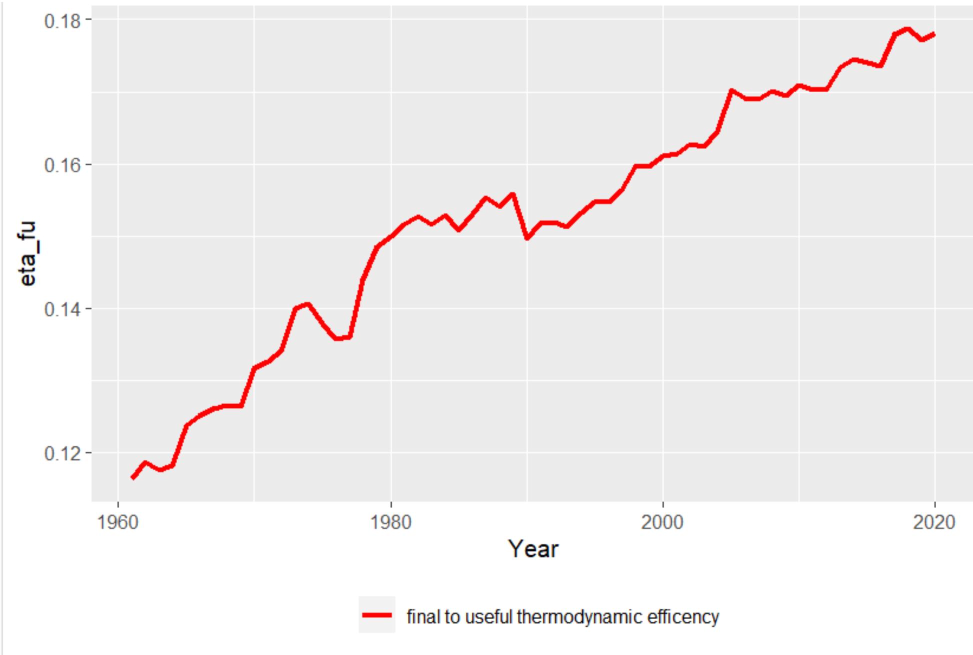
	Model 12
Flows of final mechanical work and heat per unit of capital, first difference	1.090 (0.084)***
Flows of final mechanical work and heat per unit of capital, first difference - Lagged	0.116 (0.091)
Flows of final muscle work per unit of labor, first difference	-0.033 (0.054)
Flows of final muscle work per unit of labor, first difference - Lagged	0.073 (0.054)
Adjusted R^2	0.82

[44] Pellegris does not test the model himself, but rather propose what a valid exergy-dependent model should look like.

Number of observations	50

As expected, Model 12 reports a powerful correlation between flows of capital modeled as a sub-function of flows of final mechanical work and heat and useful exergy per capita. No other coefficient, lagged or not, meet the critical threshold of statistical significance. The reason why the coefficient for capital as a sub-function of final mechanical work and heat flows reported in Table 17 is above 1 is due to improvements in thermodynamic efficiency across the period studied, meaning the thermodynamic conversion ratio of useful over final energy has increased over the period, as shown in Figure 50:

Figure 50 Final to useful thermodynamic efficiency, Canada, 1961-2020



Source: Marshall, Z. et. al. (2024). A Country-Level Primary-Final-Useful (CL-PFU) energy and exergy database v1.2, 1960-2020

Should we follow Pellegris and define useful work as wealth and final flows of energy as the biophysical inputs empowering labor and capital, then a technical relationship between the two most certainly exists. However, the measure of the aggregate K still requires the use of monetary figures. As such, Model 12 does not completely address the post-Keynesian critiques of APFs.

Model 11 has shown the highest Adjusted R^2 of all models measuring output in monetary units, which seems to suggest it is the model with the highest predictive power. Yet, correlation does not imply causality. At the heart of our own research questions are the causal relationships (if any) between energy use and output growth. These questions are at the core of biophysical economics. We therefore conclude the chapter with Granger-causality tests of Model 11, trying to detect the presence and direction of causal chains between output measured in monetary units and inputs measured in terms of flows of useful exergy.

First, we transform our time series into vector auto-regression models to determine the optimal level of lags to be incorporated into the Granger causality tests. For capital, we find one lag is optimal whereby 6 lags are found to be optimal for labor. We use a Granger-causality test for both inputs and test whether they Granger cause output growth measured in monetary units.

Table 18 Granger causality test for inputs causing changes in output using time series of Model 11A and 11B

	F-statistic	Number of observations
Cause: Flows of useful mechanical work and heat times capital flows – First difference (Model 11A) Number of lags = 1 $\Delta ln(\frac{K}{C} * E_{\chi}^{K})^{a}$	0.04 (0.844)	59
Cause: Flows of muscle work times hours worked per capita – First difference (Model 11B) Number of lags = 6 $\Delta ln(\frac{L}{C} * E_{\chi}^{L})^{\beta}$	1.60 (0.164)	49

Table 18 shows we cannot reject the null hypothesis neither input Granger-causes output growth. The Granger causality test performed on the time series used to test Model 11B (1961-2005 and 2016-2020) fails to detect causation from labor as a sub-function of muscle work to output. Therefore, the F-statistic found for this input is not surprising. However, Model 11A and 11B both suggested a statistically significant correlation between output and capital as a sub-function of mechanical work and heat. However, when we run a Granger-causality test on the time-series, we are unable to reject the null hypothesis capital does not Granger-cause output. The results of Table 18 are therefore puzzling.

Our first intuition to explain these results is that our dataset displays heteroskedasticity and therefore, non-linear Granger causality tests should be used. Indeed, the linear modelling package used in R-studio to conduct the regressions thus far was designed to fit linear models (R Documentation). However, in the presence of heteroskedasticity, linear modelling may be inappropriate (Frost, 2024).

Therefore, we test for heteroskedasticity of the time series. A telltale sign of heteroskedasticity is that as the predicted values of the model increases, the residuals, i.e. the difference between the predicted and observed values, increase as well. Figure 51 shows the residuals plotted against fitted values of Model 11A regressing output per capita over capital as a sub-function of mechanical work and heat:

Figure 51 Projected values and residuals of output regressed over capital as a sub-function of mechanical work and heat using Model 11A

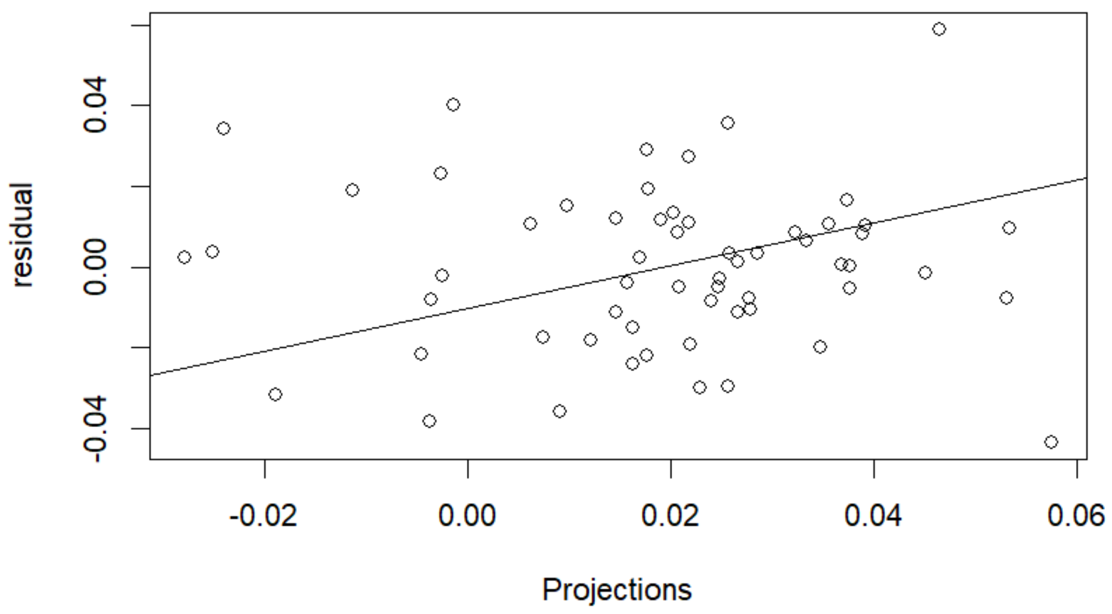


Figure 51 suggests homoskedasticity in the dataset: as the fitted value of output increases, the residual does not increase. No discernable cone shape can be observed around the line of best fit, a typical sign of heteroskedasticity. We further test for heteroskedasticity by running a Breusch-Pagan test on the data used in Model 11a and find a score of 0.009 and a p-value of 0.92. Therefore, we cannot reject the null hypothesis of homoskedasticity.

After two tests confirming the data are homoscedastic, we reiterate Granger-causality testing but in the opposite direction, testing whether output Granger-cause changes in inputs.

Table 19 Granger causality test for output as cause of changes in inputs using time series of Models 11A and 11B

	F-statistic	Number of observations
Cause: Flows of output per capita (in dollars) regressed over capital as a sub-function of mechanical work and heat – First difference (Model 11A) Number of lags = 1 $\Delta\ln\left(\frac{K}{C} * E_{\chi}^{K}\right) \sim \Delta\ln\frac{Y}{C}$	7.09 (> 0.01)	59
Cause: Flows of output per capita (in dollars) regressed over labor as a sub-function of muscle work – First difference (Model 11B) Number of lags = 6 $\Delta ln(\frac{L}{C} * E_{\chi}^{L})^{\beta} \sim \Delta\ln\frac{Y}{C}$	5.683 (> 0.01)	49

Table 19 shows changes in output to Granger-cause changes in inputs. In both cases, the p-value of the F-statistic found is below 0.01, which confirm the conservation hypothesis (see Chapter 2, section 2.2). These results are surprising. They do confirm causality, but suggest it is unidirectional, whereby our hypothesis was that causality was bidirectional.

6.3 Discussion

In this section, we revisit each model tested in section 6.2, discuss whether these models accurately reflect really existing technical relationships between inputs and output and consider whether they can help answer the research questions outlined in Chapter 1.

We start with considering the merits of incorporating flows of primary and secondary energy-use as a variable for energy-use in Cobb-Douglas functions with Models 1-8. Models 1 and 4 are two standard, two-inputs Cobb-Douglas production functions, the latter using first differences as its observations. When compared with their equivalent adding a third factor for primary and secondary energy use (Model 2 and 3, respectively), we observe a modest increase in the Adjusted R^2 of 0.012 and 0.016, respectively. We therefore conclude that adding a third factor accounting for flows of primary and secondary energy use slightly increase the models' predictive power.

On the relative impact of factors on productivity, all models adding a third factor for energy-use (2, 3, 5 and 6) found output elasticity of non-lagged flows primary and secondary energy-use to be superior to the output elasticity of non-lagged capital flows but inferior to non-lagged flows labor. Provided the effects of capital investments on productivity can take several years to manifest, comparing the output elasticity of capital and energy must be done with care. We find the output elasticity of non-lagged primary and secondary energy to be one-fourth of the output elasticity of labor with Models 3 and 5, suggesting the output elasticity of the former is non-trivial. Models 3 and 5 both display constant returns to scale, where the sum of coefficients of output elasticities is equal to 1. As such, we argue Models 3 and 5 meet Ayres and Warr's condition of plausibility whereby under the assumption of constant returns to scale, the sum of factors' output elasticities should be equal to one.

All models in first differences incorporating energy (3, 5 and 6) display an output elasticity for energy much higher than the sector's share in national income as shown in Figure 37. We therefore safely reject the cost-share theorem. When comparing the effects of flows of primary and secondary energy-use over the price of energy in Alberta (Models 7 and 8), we found the output elasticity of primary and secondary energy to fade in comparison with the price of crude oil (West Texas Intermediate). Therefore, we conclude that in energy-producing jurisdictions, the price of fossil fuel resources is a better predictor of output growth than energy-use.

Using Granger-causality test on Model 5, we find causality between flows of primary and secondary energy use and output to be bidirectional, as we expected as per our hypothesis.

In terms of the models' plausibility, we follow Ayres and Warr (2005) in rejecting models yielding negative coefficients of output elasticities. We argue it is unreasonable to expect a rise in input use to cause a decrease in output production. Model 8 shows a 1% change in non-lagged energy use per capita to cause a -0.005% change in output per capita. Furthermore, it shows a 1% change in labor cause a -0.11% change in output. These results are unlikely to reflect reality. As such, we argue it is unlikely Model 8 reflects genuine technical relationships involved in production meaningfully. However, none of these negative coefficients meet the 5% threshold of statistical significance.

Likewise, Model 9, measuring the relationship between output and inputs using a ratio of net-energy return of energy consumed in Canada, displays an output elasticity of the non-lagged first difference in hours worked of -0.02. Furthermore, only one coefficient (lagged capital flows) meets the 5% threshold of statistical significance. Model 9 does not yield any result that can be used to conclude anything on the relationship between inputs and output. Three of the 8 coefficients found are negative (lagged energy use, hours worked and lagged capital investment). The Adjusted R^2 found is lower than Models 3 and 5, which do not incorporate any variable for energy quality. For all these reasons, we reject the plausibility of Model 9. A larger dataset with data going prior to 1978 or observations for other economies comparable to Canada are required to make a definitive statement on the model's validity.

In our view, the most interesting results found in Chapter 6 pertain to models 10-12. With Model 10, when adding $EROI_{st}$ ratios to a three-inputs Cobb-Douglas function as a fourth factor, we found an Adjusted R^2 much higher than the previous models using non-corrected measures of energy quality. However, three of the lagged variables display negative coefficients of output elasticity, including lagged energy-use, which also displays statistical significance. Therefore, it is hard to fully accept the model's empirical plausibility. Moreover, the coefficient for $EROI_{st}$ ratios fails to meet the threshold of statistical significance. However, Model 10 shows that including a corrected measure of energy quality produces a model with a higher Adjusted R^2 over models using non-corrected measures of energy-quality (1-8). Since we are able to generate a dataset of 30 observations only for Model 10, international comparisons and access to data going prior to 1990 to compute more $EROI_{st}$ ratios and expand our dataset are required to strengthen the model. Because of all the issues with the model's plausibility raised in this paragraph, we reject the model's empirical plausibility.

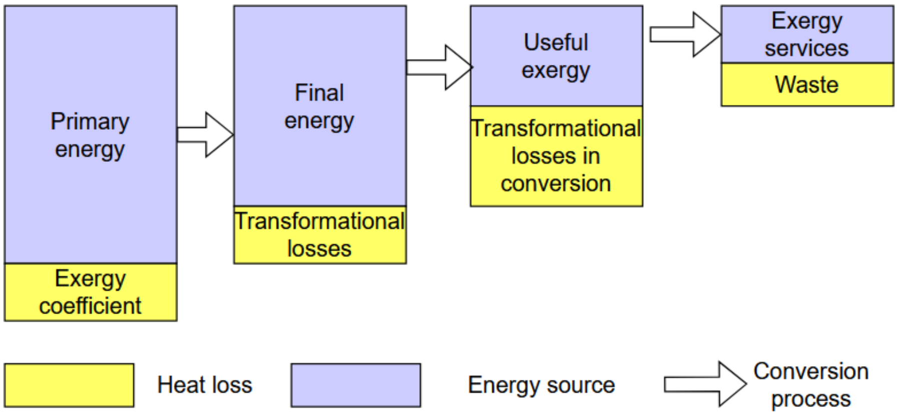
The most empirically meaningful result found in Chapter 6 comes from Model 11, where monetary output is regressed over man-made capital as sub-functions of useful exergy. When testing for capital flows only, we find the coefficient for capital modeled as a sub-function of mechanical work and heat to display an output elasticity of 0.49 over monetary output per capita and the model to display an Adjusted R^2 of 0.45, the highest result found for our models using monetary figures to measure output. Such results suggest a quality-corrected measure of energy empowering man-made inputs is a very strong predictor of monetary output growth. Subtracting the observations for 2005-2015 to test for the share of labor in output, we found our results confirmed, although the value of output elasticity of labor is non-significant statistically. This result suggests our hypothesis on the correlation between corrected measures of energy and output measured in dollars was right. When measuring output in terms of useful exergy, the correlation found was even much stronger.

Our results from Model 11A and 11B suggest a strong correlation between output measured in monetary units and capital measured in monetary units as a subfunction of biophysical units empowering them. The times series used to run the regression are co-integrated, implying Granger causality. When running a Granger causality test running from inputs to output, we failed to reject the null hypothesis of no causality, which was puzzling. Following the econometric literature, we test for causality in the opposite direction, following our hypothesis of bidirectional causality and find output Granger cause changes in inputs but not the other way around.

The issue of causality is by no means trivial. Shaikh (1974) has shown how the coefficient of correlation found by neoclassical APFs was the result of an underlying accounting identity. In order to test whether BFP genuinely detect a causal relationship instead of an identity, biophysical modelers (Santos et. al. 2018) argue Granger-causality test must be performed on time series used to test models. If time series are co-integrated, then there is Granger causality between them, therefore suggesting the BFP is not merely capturing an accounting identity. Our own tests show Granger causality stemming from output to inputs to be very strong. We are therefore confident Model 11A and 11B measure an empirical causal relationship at the macroeconomic level.

The model showing the best Adjusted R^2 is Model 12, where output is measured in flows of useful exergy per capita, and inputs are modeled as final flows of muscle, mechanical work and heat over the man-made inputs they empower. However, the strength of the correlation detected in Model 12 is somewhat trivial. Useful energy is the quantity of energy used in energy-consuming processes whereby final energy is the quantity of energy received by the end-use consumer, prior to use. In other words, the production of flows of useful exergy is the necessary physical outcome of final energy use, as shown in Figure 52:

Figure 52 Primary to final to useful conversion stages of energy flow



Source: Sakai et. al., 2018: 2.

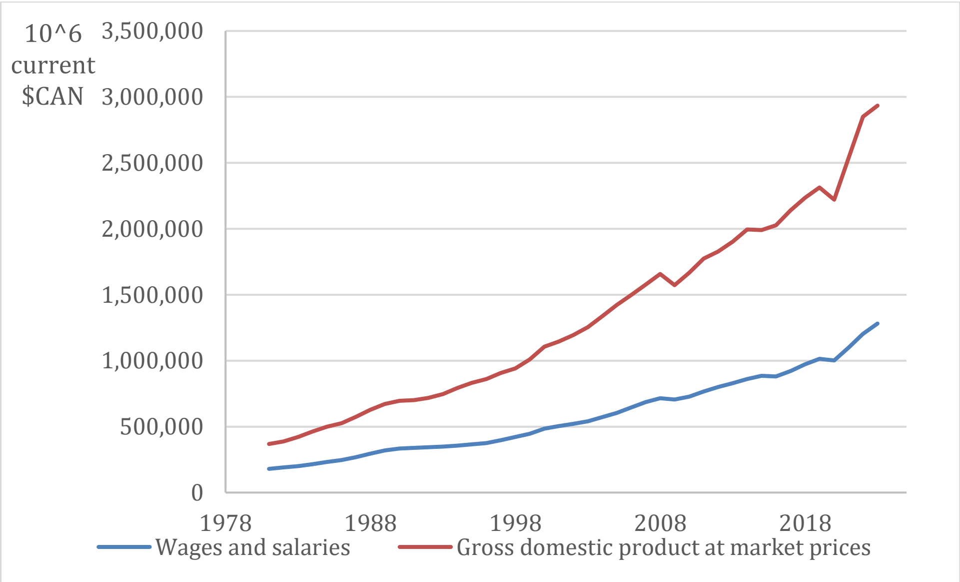
As shown in Figure 52, useful exergy is the necessary physical by-product of final energy use minus thermodynamic loss. We argue the proposal to model flows of useful exergy per capita as a community's wealth and flows of inputs as sub-functions of flows of final energy produces a trivially strong correlation that is not economically meaningful. As pointed out in the introduction to this thesis, our research questions on the relationships between biophysical quality and monetary value stems from the observations that in a capitalist economy, agents' decision-making is based on monetary value. In other words: monetary figures make sense for agents (Pellegris, 2022). By modelling output in terms of flows of useful exergy, it is unclear how Model 12 can be used to explain agents' behavior.

On the other hand, the correlation between inputs measured as exergy-flows along the man-made inputs they empower over monetary output per capita is not a trivial, as the debates reviewed in Section 2.3 and Chapter 4 have shown. Unlike the relationships modeled in Model

12, there is no a priori reason to assume a mathematical form of the correlation between monetary output with flows of useful exergy. Furthermore, the dependent variable (output per capita) is economically *and* phenomenologically meaningful for agents. Therefore, we argue the original results found in Model 11 produce more original knowledge of the interactions between the economy and its biophysical milieu than any other models tested in this chapter. Indeed, although Model 5 shows signs of bidirectional causality, it models man-made inputs independently from energy flows, which is theoretically problematic.

Our contention on the merits of Model 11 over Model 12 does not mean Model 11 is free of ambiguities. Figure 53 has shown that from 1961 to 2004 and from 2016 to 2020, the share of muscle work in total flows of useful exergy in the economy was less than 1%. Yet, the share of labor in Canadian national income is incomparably higher:

Figure 53 Wages and salaries and gross domestic product at market prices, in 1,000,000 current Canadian dollars, 1981-2020



Source: Statistics Canada (2024). Gross domestic product, income-based, provincial and territorial, annual (x 1,000,000), Table 36-10-0221-01

Clearly, the share of labor's income in total income is not reflected by the share of flows of useful exergy empowered by labor. Model 11 does not provide a satisfactory theory on factor's income and its relationships with output elasticity and productivity. A factor, enabled by flows of useful energy or not, whose share is less than 1% of total flows of factors used in the economy whilst receiving 45% of total income on average between 1981 and 2021 cannot exist in a world in which there an equality between the output elasticity of factors and the prices paid for the use of the marginal unit of labor and capital. Model 11 further reinforces our rejection of the cost-share theorem but does not offer a satisfactory theory of distribution.

All models used in Chapter 6 face the same limitation as they all depend on monetary units to estimate the value of annual flows of capital investments. Section 5.3 has shown the logical problems stemming from using monetary figures to estimate the size of capital stock and flows. We argue Model 11 is a step towards a realistic measure of the *physical magnitudes* of capital flows as it uses both exergy and monetary flows to estimate the size of capital flows. BFPs are a step toward realistic production functions. However, because Model 11 uses monetary data from the Canadian national accounts on the monetary value of capital flows, we cannot disprove that our results are influenced by an underlying accounting identity between capital and output (Shaikh, 1974), although the results of the Granger causality tests suggest we are not merely capturing an identity. The purported empirical strength of Model 11 must therefore be interpreted with care.

Indeed, our results must be interpreted in relation with debates on economic theory during the Cambridge Capital Controversy. By the late 1960s, major figures in neoclassical economics conceded the validity of several criticisms raised by post-Keynesian economists over APFs, with Hahn stating APFs ‘’[…] *cannot be shown to follow from proper [general equilibrium] theory and in general [are] therefore open to several logical objections.*‘’ (Hahn, 1972, cited in Cohen and Harcourt, 2003: 206). Regardless, several neoclassical economists continued to use APFs as heuristic models in empirical work, ‘’as if ‘’ observations were the effects of an underlying APF (Ibid.). Solow argues the empirical results are the ultimate criteria to determine a model’s usefulness (Solow, 1966, cited in Felipe and McCombie, 2013: 45). Solow’s position echoes Friedman’s instrumentalist epistemology, whereby the correspondence between an assumption and the real world is of secondary importance compared to the ability of the model to make accurate empirical predictions (Ibid., 48).

We disagree with Solow and Friedman’s epistemology on logical grounds. In his defense of APFs, Solow argued empirical data on factor’s output elasticity or shares of national income should be regarded *as if* they resulted from an underlying APF. In doing so, he tacitly performs an inference between the ontological reality of the model and its potential to explain the causality underlying observations. However, for an inference to be sound, its premises must be true (Mitchell, 2019[1967]: 12). Modern logic defines an inference as valid if it would be impossible for its premises to be true and its conclusion false. However, a valid inference is not necessarily sound. An inference is sound when its premises and the conclusion are true. Unless the premises are true, one cannot logically infer the conclusion to be true (Gensler, 2017). By performing inferences from the model to the data whilst simultaneously holding the model to be based on non-true, ‘’as if’’ premisses, we argue the use of APFs rests on unsound inferences. Although logical validity is not premised on the existence of entities used in inferences, soundness is. Any conclusion based on inferences on non-existing entities cannot be held to be true.

The same critics apply to the BFP modeled in Model 11 as it uses monetary figures to aggregate capital. Section 5.3 has shown how unlikely it is for homogeneous units of dollars to genuinely reflect heterogeneous capital goods. As such, Model 11 is not theoretically consistent provided we accept the post-Keynesian critiques of APFs. We argue inferences made based on Model 11 are valid. We cannot ascertain they are true.

Furthermore, all models used in Chapter 5 use a homogeneous measure of labor in hours and capital in annual flows of dollars, therefore tacitly assuming each unit of both to be equally productive across the period studied. Recent neoclassical models have acknowledged the consequences of this limitation and have developed quality-adjusted measures of inputs corrected for education and skills for labor and for flows of services per class of capital goods (Santos et. al., 2018). Furthermore, none of our models test a APF with energy as third factor using the mathematical form of constant elasticity of substitution (CES) with nested-structures (Lagomarsino, 2020). Therefore, our models do not pretend to invalidate any empirical findings made with these models.

A final limitation of our models is that they do not consider the non-monetary reproductive labor and care within households which makes production possible. Without the gendered division of reproductive labor, the various production functions discussed in this chapter would be meaningless (Exploring Economics, 2016).

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Chapter 7 Comprehensive Scholarly Discussion

I conclude my thesis by a comprehensive discussion on the results of the research. I will discuss my research findings in relationships with the hypotheses outlined in Chapter 1 and the theories discussed in Chapter 2. The methodological limitations and their consequences over the interpretations of the results. Finally, I shall briefly discuss the implications of the results for policy.

My thesis investigates the existence of a statistically significant relationship between indicators of biophysical quality of energy sources (primary and secondary energy flows, net-energy ratios of energy consumed and produced and flows of useful exergy) and their associated monetary indicators (price, costs of production, profitability and monetary output) as well as causal chains between energy inputs and output production. I tested the hypothesis at two different scales: at the level of one source of primary energy, i.e. oil-sands derived crude extracted via open-pit mining and at the level of the Canadian economy. Chapter 3 has found the $EROI_{st}$ of diluted bitumen to be higher than syncrude's. The $EROI_{st}$ ratios of the two energy sources are above 3:1, therefore suggesting they both represent genuine energy sources at the point of use. My hypotheses were shown to be correct. Diluted bitumen was shown to display an increasing $EROI_{st}$ over the period studied. A rise in the $EROI_{st}$ of fossil fuels is seldom found in net-energy analysis. My preliminary explanatory hypothesis suggested relatively constant monetary investment in production over an increasing output is a plausible explanation for this rise. Furthermore, it is possible (but not certain) the oil sands of higher quality are extracted first.

Any implication from these findings must be deduced with care. Due to data availability, I was not able to compare the $EROI_{st}$ ratios of oil-sands derived crude produced via open-pit mining with crude produced via in-situ mining. To perform such a comparison is an essential area for future research to achieve a more fact-based grasp of the net-energy potential of oil sands. Furthermore, I was able to use primary sources to estimate $EROI_{st}$ ratios of oil sands-derived crude from 1997 to 2016 only. More research is required to find the primary sources to be used to estimate net-energy ratios prior to 1997 so that a more thorough understanding of the net-energy potential of this source of primary energy in the long run can be discussed.

Chapter 4 investigated the correlation between indicators of quality, i.e. $EROI_{st}$, of diluted bitumen and synthetic crude and associated monetary indicators of price, cost of production and profitability for each crude stream from 1997 to 2016. No statistically significant relation was found between any indicator for either crude stream. My hypotheses were incorrect. The very small size of the data set available to test my econometric model might explains the failure to detect a significant relationship at the level of the resource: 15 observations for diluted bitumen and 19 for synthetic crude. The conclusions that can be legitimately drawn from such a limited set of observations are limited. A larger dataset on $EROI_{st}$ ratios for oil sands-derived crude going prior to 1997 or a comparison with other energy resources would be required to further test the hypotheses. Furthermore, a systematic test of my research hypotheses would require testing them with data from a variety of fossil fuels.

In theoretical terms, if one admits $EROI_{st}$ is a valid measure of the economic usefulness/utility of a resource, my results rebut the claims made by neoclassical economics that there should be a correlation between willingness to pay/utility and prices when comparing two energy sources at the mine-mouth. I hypothesized higher net-energy flows reflected by higher $EROI_{st}$ ratios would mean higher willingness to pay by energy consumers. Econometric testing invalidated the hypothesis. Furthermore, my results challenge the Embodied Energy School (see section 2.3.4.2). Scholars of these traditions argue there is a direct, tangible relationship between embodied energy (energy used in production processes) and monetary indicators, namely price. The hypotheses I outlined in Chapter 1 were informed by this school of thought.[45] However, empirical testing failed to detect such a relationship in the data available. However, my results are insufficient to reject the claims of Embodied energy scholars, who have shown a strong correlation exists between embodied energy and prices at the macroeconomic level using data from input-output tables (Costanza and Herendeen, 1984). All I can conclude from my work is that such relationships are not observed at the level of one source of primary energy produced via one mode of mining.

Chapter 6 investigated the correlation between monetary output and biophysical indicators of quality of energy resources used at the macroeconomic level, using the theoretical framework of aggregate production functions (APFs), whose history was reviewed in Chapter 5. Chapter 6 used biophysical units to partially measure inputs to test the potential of biophysical

[45] Appendix II provides a logical justification of the hypothesis.

production functions (BPFs) to model technical relationships between inputs and output. I used a series of log-log multivariate regression models testing for different measures of energy quality: flows of primary and secondary energy use, net-energy ratios of energy consumed and produced in Canada and flows of useful exergy. A provincially disaggregated model of output production regressed over labor, capital and primary and secondary energy use suggests energy to be a statistically significant input in monetary output production. It found causation to be bidirectional between output and primary and secondary energy, lending credence to the feedback hypothesis (see Chapter 2) as well as my own hypothesis.

However, I found the output elasticity of primary and secondary energy use to be between one-fourth of the output elasticity of labor, unlike what I expected to find. I found the introduction of flows of primary and secondary energy-use as a third factor to modestly strengthens the model's accuracy over a standard, two-inputs model. Despite these results, I argue the mathematical framework used in these models, which is inspired by Solow's three-inputs model, is problematic. Not only does it fail to show how physically speaking, labor and capital use are empowered by energy flows, but it allows the theoretically insignificant result of having no energy flows and positive output production simultaneously. Comparing the value of the coefficient of output elasticity for primary and secondary energy use in Model 3 and 5 with the share of the energy sector in Canadian national accounts, I rejected the cost-share theorem. Based on these results, I reject the plausibility of neoclassical three-inputs APF as developed by Solow.

My original hypothesis on energy-use being a statistically significant factor of production was correct, although the output elasticity of final demand of primary and secondary energy was found to be less significant than labor, unlike what I expected. Furthermore, adding the price of energy in the model and testing it for Alberta found the price of crude oil to be much more significant than energy-use, itself found to be non-significant in this model, a conclusion I did not anticipate.

I tested whether output production in Canada was correlated with changes in net-energy ratios as a fourth factor. My original hypothesis, informed by the literature in biophysical economics, surmised the larger the ratio of net-energy, the larger the energy flows to be used in capital accumulation and discretionary spending, and thus the higher the monetary output further reinvested in expanding energy production. Owing to Canada being a major energy producer and exporter, I hypothesized two distinct measures of net-energy ratios should be used to test the hypothesis as not every joule of energy produced in Canada is consumed there. I used a measure of net-energy ratios for energy consumed in Canada and $EROI_{st}$ ratios of energy produced in Canada. Testing the correlation between these two measures of net-energy flows along with labor, capital and primary and secondary energy use over output production for Canada, I found neither net-energy ratio to be statistically significant as such. However, the model using $EROI_{st}$ as a variable of net-energy production was found to display a higher predictive power. My original hypothesis on $EROI_{st}$ being positively and strongly correlated with output was not proven correct, thus invalidating a strict interpretation of the claims made by neophysiocrats whereby net-energy ratios are directly and causally related to output growth.

Finally, I tested a BFP modeling output growth as a function of man-made inputs, themselves sub-functions of exergy flows. The model displayed the highest Adjusted R^2 of all models tested in the chapter. My results show capital flows modeled as sub-functions of exergy flows to be statistically significant when regressed over output measured in dollars, proving my hypothesis correct for inputs of capital flows. Model 11B has shown a coefficient of output elasticity of labor which failed to meet any threshold of statistical significance. I am therefore unable to conclude anything meaningful regarding the relationship between output and labor as a sub-function of muscular flows. Testing for causality, I found no causation from exergy flows to output but found causation from output to exergy-use, which leads credence to the conservation hypothesis (see chapter 2).

From the results of Chapter 6, I find my original hypothesis on the correlation between output growth and energy-corrected measured of energy to be accurate *if* capital flows are modeled as sub-functions of the flows of exergy they enable. ‘’Exergy’’ being a measure of energy corrected for thermodynamic efficiency, I conclude that quality-corrected measures of energy quality *are* correlated to monetary output. These results lead me to conclude the following about my general research question: *output production measured in dollar units and biophysical indicators of energy quality are indeed correlated provided the joule value of energy flows is estimated using unit of energy at its useful stage and if monetary units used to estimate the size of capital is modeled as a sub-function of exergy flows. Energy quality and output production measured in dollars are not independent. Economic wealth, measured in constant dollars, is related to the quality of energy sources used at the level of the economy.* Of the various theories of value reviewed in Chapter 2, the claim by the neophysiocratic school that quality-corrected measures of energy are correlated with monetary value is confirmed by my empirical results.

Furthermore, *there is* a causal relationship between output and inputs modeled as sub-functions of exergy flows: changes in output measured in dollars cause changes in inputs measured in monetary and biophysical units. The causal relationships detected suggest BFP do not merely capture an accounting identity, but measure an empirical causal relationship, showing the existence of an empirical causal connection between output measured in money and inputs measured in money and energy flows.

However, the theoretical validity of the correlations detected in Model 11 must be circumscribed as it rests on the assumption that homogenous units of dollars can meaningfully measure the size of heterogeneous capital flows. Several arguments have been raised by post-Keynesian economists on why this assumption is not realistic. They have shown APFs are irremediably flawed as they aggregate heterogeneous capital goods over a single monetary index. My own measure of annual flows of capital goods uses monetary figures (annual net flows of investment). As such, my model multiplies annual flows of mechanical work and heat per unit of capital flows by the annual flows of capital per capita, finding a much stronger correlation than any other model tested. As such, I believe the model to be more realistic as it does not exclusively rely on monetary figures. However, the use of monetary figures to aggregate capital is required. Thus, the model suffers from the same theoretical flaws as all models tested in Chapter 5. If the post-Keynesian critique is accurate, then the very notion of APFs might be irremediably flawed, including BFPs using monetary figures to estimate the size of annual flows of capital investment. I have argued any inference based on non-true premises is unsound. Post-Keynesian economists have shown there is no such thing as a homogenous capital entity. Any inference based on heterogeneous capital flows measured with homogeneous monetary data may be valid, yet its conclusions cannot be held true prima facie. Should this conclusion be valid, then strictly biophysical models would be required to model the flows of matters and energy within an economy, such as the stock-flow fund-service models (Couix, 2020), environmentally extended input-output analysis (Blair and Miller, 2009) or input-output analysis using physical units (Leontieff, 1986). Future research on biophysical modelling is required to determine the potential of these approaches to address the post-Keynesian critiques and provide meaningful modelling techniques for ecological economists.

My interpretations of the results from Chapter 6 partially leads credence to the neophysiocratic school (see section 2.3.2.3). Figure 1 represents the economy as a linear throughput with a positive feedback loop between the economy and energy inputs. Flows of energy provides man-made economic sectors with the input it needs to activate labor and capital, which in returns provide the energy sector with the inputs it needs to increase the size of energy flows. Measuring energy flows inputs to the Canadian economy in terms of primary and secondary energy has shown this bidirectional causal chains to exist. However, measuring energy inputs in terms of useful energy has shown unidirectional causation from output to input growth, which invalidates the claim of a positive feedback loop. More importantly, neophysiocrats argue the quality of energy determine, in fine, the size of economic flows between economic sectors (see Figure 2). Although my results lead to a different interpretation of the causal chains from those found in Figure 2, I argue my results confirm neophysiocratic claims of the existence of a relationship between energy quality and monetary indicators in the economy.

Several limitations apply to the analysis shown in Chapter 6. First, not every type of APFs used in contemporary neoclassical economics are tested. Contemporary neoclassical modelers use nested-structures of inputs to model interactions between inputs in constant elasticity of substitution (CES) functions. The critiques raised in Chapters 5 and 6 are relevant to models of APFs as used by the neoclassical authors reviewed in Chapter 5. The same limitation applies to biophysical models. As seen in Equations 99 and 100, contemporary biophysical scholars use linear-exponential models to test their biophysical models, an approach Chapter 6 did not model nor tested.

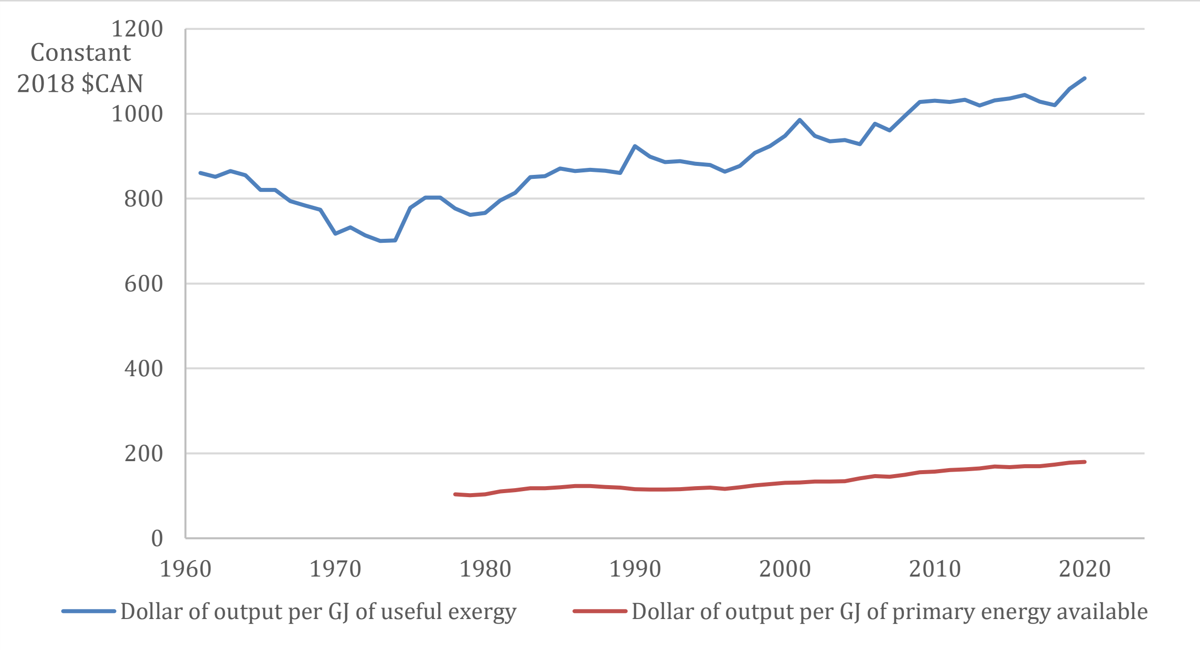
Furthermore, the net-energy ratios of primary energy resources estimated do not use quality-corrected measures of the joule-value of electricity. Doing so would require data on the price of a joule of energy from fossil fuels as well as an alternative joule of electricity across all Canada (see Chapter 3, section 3.5.2). To produce quality correction ratios for electricity across all the geography and time periods covered in Chapter 6 would mean finding the average price of electricity and coal, natural gas or crude oil a) across all 10 provincial Canadian jurisdictions and b) the different American states from which primary electricity is imported. To succeed with b), not only knowledge of the sub-regions of the United States from where electricity is imported would be required, but data on the average price per said region would be necessary as well. This methodology would follow what has been developed in Net-Energy Accounting to estimate a ‘’quality-corrected‘’ adjustment factor for a joule of electricity over a joule of primary energy from fossil fuels. Such methodologies can be conducted relatively easily when the area under analysis is relatively small and data on the price of electricity is available, as in Chapter 23 But for the boundary of analysis considered in Chapter 5, no data on the exact sub-region of the United States from which electricity is imported into Canada exists.

The data available to estimate the correlation between output and net-energy ratio at the national level are limited. To estimate $EROI_{st}$ ratios, I use annual data from Statistics Canada Physical-flow accounts on energy intensities per sector of the Canadian economy. To the best of my knowledge, the first year for which data on energy intensity is available in Canada is 1990, meaning the dataset is limited to 30 observations. To estimate net-energy ratios of energy consumed in Canada, I use Statistics Canada Energy Supply and Demand tables on annual energy availability, import, export, transformation by utilities and industries and producer consumption. To the best of my knowledge, the first data available for each of these categories is 1978, meaning the dataset is limited to 45 observations. More solid statistical inference over the values of the coefficients found would require a larger dataset. The same frame is used to test the correlation between output and $EROI_{st}$ ratio since the same data set are used. To test the correlation between output and exergy flows, I was able to start my time series in 1961, yielding 61 observations.

Finally, each model requires the use of monetary units to measure the flows of capital services. Post-Keynesian economists have shown the numerous difficulties with using homogeneous units of currency to measure heterogeneous capital goods. Chapter 4 will show how according to some post-Keynesians, APFs display powerful coefficient of correlation not because they measure an empirical relationship, but because of an underlying and unacknowledged accounting identity. Thus, the models tested in Chapter 5 must be judged on whether they really measure empirical relationships, not accounting/algebraic identities between inputs and output.

In my view, the most serious limitation of my work stems from the post-Keynesian critique which does not merely point out to errors in measurements, but to the very possibility to measure capital in monetary units. To my knowledge, no satisfactory rebuttal of the post-Keynesian claims exists. As such, other methods have been recently developed in ecological economics to investigate the biophysical foundations of economic systems while avoiding the use of APFs. Giraud and Kahraman (2014) circumvent the use of a capital aggregate in the estimation of the correlation between energy flows and monetary output by estimating the ratio of dependency of an economy on energy flows, where GDP is divided over annual flows of primary energy. I use their method for Canada based on available data (see Chapter 6, section 6.1 and 6.2), using Canadian output in 2018 constant Canadian dollar over flows of primary energy available and flows of useful exergy in GJ:

Figure 54 Constant 2018 Canadian dollars over annual flows of primary energy available and useful exergy, 1961-2020



Source: Marshall et. al. (2024); Source: Statistics Canada, Archived - Gross domestic product at basic prices, System of National Accounts, annual (x 1,000,000), Table 36-10-0395-01; Gross domestic product at basic prices by industry, annual averages (x 1,000,000); Table 36-10-0434-03; Statistics Canada: Archived – Supply and demand of primary and secondary energy in terajoules, quarterly, with data for 1978-2001, Table 25-10-0004-10; Supply and demand for primary and secondary energy, Table 21-10-0029-01.

Giraud and Kahraman's methodology show how dependent on energy flows output production has been in Canada over the last 60 years, as the flat curves show how little variations has taken place in the inputs of energy flows required to produce monetary output. This methodology has the advantage of avoiding the use of a capital aggregate, instead relying on the sum of compensation of employees and the gross operating surplus of corporations.

Ecological and biophysical economics are still relatively young disciplines. More work is required to develop empirically meaningful and realistic methodologies to estimate the dependence of the economy on biophysical sources and advise governments, firms and civil society on how to avoid the dire prospects forecasted year after year by the Intergovernmental Panel on Climate Change.

On the policy front, my interpretation of my own results is that they lead credence to the theory of material limits to growth (Meadows et. al., 1972)[46]. My results show not only that there is a correlation between flows of energy (primary and useful) and monetary output, but a causal chain between the two. In 1995, 35% of marketed energy in the global economy was derived from crude oil, closely followed by coal (27%) and natural gas (23%), the sum of the three representing 85% of the total global supply of primary energy (Daly and Farley, 2010). Despite several international conferences to coordinate a global energy transition toward renewable sources since the Kyoto Protocol, 80.9% of the world's supply of primary energy was derived from fossil fuels in 2020 (International Energy Agency, 2021). In Canada, in 2022, 49.2% of the supply of primary energy was derived from crude oil, followed by natural gas with 32.8% (Statistics Canada, 2023).

By definition, fossil fuels are non-renewable. As such, unless all the energy from stemming from non-renewable can be replaced by renewable sources, it is doubtful the share of output growth stemming from energy can be continued forever. The debate over the potential of renewable sources of energy to replace non-renewable while maintaining the growth of monetary output is beyond the reach of this dissertation. What the result of my thesis highlights is the existence of a statistically significant relationship between the two. Rational discussions on energy policy and future must acknowledge that fact.

[46] I do not discuss the concept of social limits to growth (Hirsch, 1876), which is an area of research based on a literature and methodologies I know almost nothing about

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Conclusion and summary of the key findings

I conclude the thesis with a summary of the research findings. Chapter 3 has found the $EROI_{st}$ of diluted bitumen to be higher than syncrude's over the period 1997-2016. Both energy sources display net-energy ratios above 3:1 and I found the $EROI_{st}$ of diluted bitumen to increase over the period studied. Chapter 4 found no statistically significant relation between costs of production, price and profitability and $EROI_{st}$ for either crude stream over the same period. Chapter 6 identified statistically significant correlations and bidirectional causation between monetary output and energy inputs measured in units of primary and secondary energy flows as a third factor of production. I found the correlation coefficients between flows of primary and secondary energy flows to be higher than flows of capital but lower than flows of labor. However, theoretical and logical arguments led me to reject the results based on energy inputs measured in terms of flows of primary and secondary energy. I found statistically significant correlation between monetary output regressed over capital measured as sub-functions of mechanical work and heat. Furthermore, I found unidirectional causation between output growth and input growth. Because the model used to test relationships between monetary output growth and input growth measured as sub-functions of flows of useful energy cannot yield output without positive energy flows, the model is theoretically and logically sound. I therefore consider these results to be a reliable basis for future discussions in Ecological Macroeconomic modelling. Testing the correlation between monetary output and ratios of net-energy returns, I found the models to produce unreliable results, leading me to reject the models. Finally, following the literature, I tested whether measuring inputs of labor and capital along with the flows of final energy empowering them and output measured as flows of useful exergy, I found much stronger correlation than models measuring output in monetary units. However, useful energy being the result of dissipated final energy, I believe these results to be somewhat trivial in regard with my results measuring output in monetary units and inputs using (partially) biophysical units. Based on these results, I conclude that the hypothesized correlation and causation between monetary indicators and biophysical quality cannot be said to exist at the resource level based on my results. However, my results show correlation and causation to exist between useful energy and monetary output at the macroeconomic level. However, these conclusions depend on the validity of using monetary figures to estimate the size of capital flows. Post-Keynesians economists have shown why a strictly monetary measure leads to contradictions. Keen's et. al. model does not rely exclusively on monetary measures. Therefore, the model is more consistent theoretically.

On the policy implications of my research, chapter 2 has shown the commitment by the Government of Canada to meet both the target of GHG emission reductions set by the Paris Agreement and economic growth, something the theory of decoupling suggests is possible. Model 11 has shown a 0.46 coefficient of output elasticity between capital investment and energy-use, over 80% of which originates from fossil-fuels. Furthermore, following Giraud and Kahraman, Figure 54 has shown how energy intensity of output in Canada has been remarkably constant. In this context, this research cast doubts over the theoretical possibility of decoupling.

Appendix I Methodological issues surrounding the conversion of nominal into real monetary units

The research questions of the thesis (outlined in Chapter 1) come with epistemological difficulties. I endeavor to study the connections between biophysical flows of energy measured in joules and monetary flows measured in units of currency. Appendix I discusses one of these difficulties. Whereby the energy value of biophysical flows can be objectively assessed in an unambiguous unit of measurement (the joule), the same cannot be said of monetary measures. Nominal prices can change following arbitrary changes in the money supply and changes in the ratio of the money supply over the bundle of goods and services money can buy, i.e. inflation. This is why economists propose to use two measures of monetary value: nominal and real, where ‘’nominal’’ prices measure price in terms of money and ‘’real’’ prices purport to measure prices in terms of goods and services. This dualism assumes that nominal prices measure ‘’value’’ whereby ‘’real’’ prices measure an underlying physical quantity (Fix, 2015: 11).

But ‘’real’’ monetary values are not straightforward as they seem. Economists use the Price Index to correct prices for inflation. Price indexes are calculated by estimating price changes of a fixed set of goods and services across a period (Organization for Economic Co-operation and Development, 2024). Changes in patterns of purchases of goods and services lead statistical agencies to periodically change the base year (where the base year = 100) used to correct for inflation. Changes in base year can lead to unambiguous estimates of real Gross Domestic Product (GDP) if and only if price changes across different categories of commodities are homogenous. If changes in base year occur whilst price changes across different commodities are heterogeneous, then a different price index would be found over the ‘’homogeneous changes’’ and thus, to different estimates of real GDP for an equivalent value of nominal GDP. Real GDP, which depends on price indexes, is therefore not an unambiguous measure of ‘’real’’ growth. Fix (2015) illustrates the problem like so:

Table 20 Output estimates and prices indices

Year	Quantity A	Quantity B	Price A $	Price B$	Price Index	Output (in $)
1	100	500	20	10	1.0	7000
2	200	500	40	20	2.0	9000
3	200	500	80	40	4.0	9000
4	200	500	160	20	3.7	11,308

Year	Nominal value (in $)	Price index (Year 1)	Price index (Year 4)	Output (Year 1) ($)	Output (Year 4) ($)
1	7000	1.0	1.0	7000	7000
2	18000	2.0	1.6	9000	11,340
3	36,000	4.0	3.2	9000	11,340
4	42,000	4.7	3.7	9000	11,340

Source: Fix, 2015: 24

A price index is the ratio of a representative basket of goods and services sold at current year prices over the value of the *same* basket sold at prices of a year of reference, or a base year:
Equation 109

$$PI = \frac{(Q_A^R * P_A^{current}) + (Q_B^R * P_B^{current})}{\left(Q_A^R * P_A^{base}\right) + (Q_{*B}^{\ R} * P_B^{base})}$$

where ‘‘PI’’ is a price index, ‘‘Q^R’’ is the constant quantity of a good set to be represented in the representative basket of goods and services and ‘‘P’’ is the commodity’s price. Referring to Fix’s example in table 20 and assuming we are taking the quantity of goods and services sold at Year 4 as our representative basket, then the price index between Year 4 and 1 is equal to the value of the representative basket sold at prices of Year 4 over the same basket sold at prices of Year 1:
Equation 110

$$\frac{(200 * 160) + (500 * 20)}{(200 * 20) + (500 * 10)} = 4.7$$

Then, diving the nominal GDP of Year 4 per the Price Index found in Equation 110 yields a real GDP of 8,936,17. If, however, we had chosen the quantity sold at Year 1 as our representative basket, then the price index would have been:

Equation 111

$$\frac{(100 * 160) + (500 * 20)}{(100 * 20) + (500 * 10)} = 3.7$$

Then, the real GDP for Year 4 would be estimated at 11,351$. Between Equations 110 and 111, only the quantity of good A in the representative basket has changed. Yet, the indexes found show a 29% difference, exactly what ‘’real’’ measures of GDP are meant to correct for. Without access to raw data, an analyst might assume this is the result of a homogeneous 29% change in goods A and B in the representative basket, but this is not the case. From Year 1 to Year 4, there is a 100% change in the quantity of good A sold and a 0% change in the quantity of B. Depending on the representative basket chosen, the estimate of real output has changed, meaning real output can be an ambiguous estimate of inflation-corrected output.

To avoid the type of confusions shown by Fix, my thesis sticks to one base year only per chapter each time it uses monetary data from Statistics Canada. Changes from one base year to another might lead to different estimates of real GDP for a single year. During my research, Statistics Canada changed its base year from 2012 to 2017. To avoid confusion in monetary measurements induced by that change, price values retrieved from datasets using 2017 as its base year are used to complete Chapter 5 and 6, whereby price values retrieved from datasets using 2012 as its base year are used to complete Chapters 3 and 4. In other words: constant Canadian dollars should not be compared between the pairs of chapters 3-4 and 5-6.

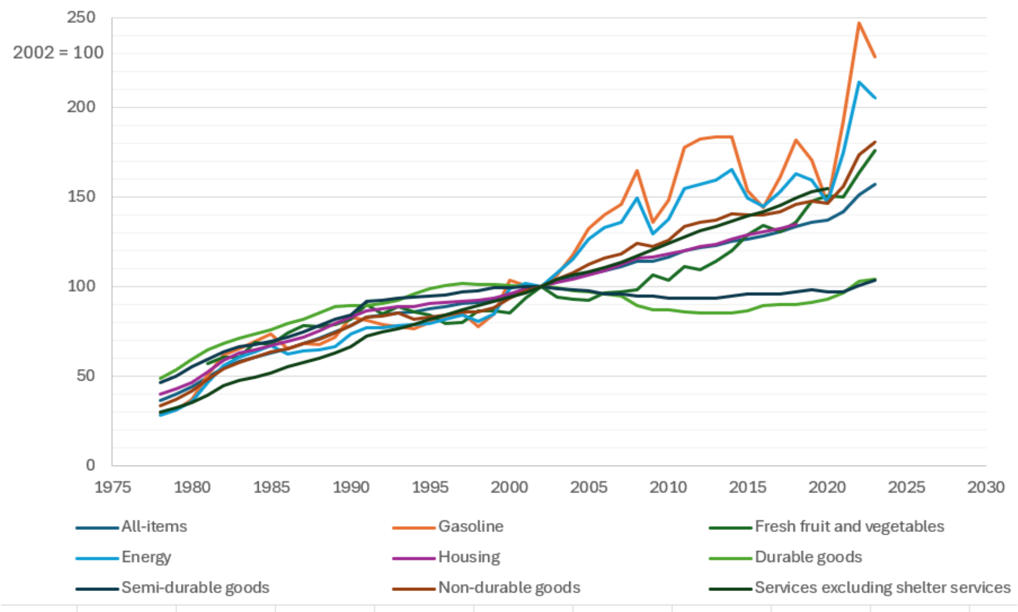
In Chapter 6, I use monetary data from 1961 to 1986. To convert these into constant Canadian dollars, I use Statistics Canada Price Index series for 1926 to 1986 where the price index is 1981 = 100 (Statistics Canada, 2024a). I need to harmonize the price index time series as the two base years are 31 years apart. I did so following Equation 112, where I wish to convert current Canadian dollars in 1980 into 2018 constant Canadian. I must use the price index series with base year 1981 = 100 and harmonize it with the price index series where 2017 = 100:

Equation 112

$$\$CAN_{1980}^{2018\ constant} = \$CAN_{1980}^{current} * \frac{100}{(PI)_{1981}^{2017=100}} * \frac{(PI)_{2018}^{2017=100}}{(PI)_{1980}^{1981=100}}$$

Confusions and problems associated with changes in base year arise particularly over long periods of time, where changes in patterns of consumption of goods and services are particularly patent, as shown by Fix. My period of study sticks to 1961-2022, during which changes in the price index of different goods and services in Canada were relatively homogeneous. Relatively homogeneous changes in the price of different goods should not lead to mischaracterizations of GDP based on heterogeneous, erratic price changes across different categories of goods and services as shown in Figure 55 for the period 1978-2022:

Figure 55 Consumer Price Index of 9 categories of goods and services in Canada, 1978-2022



Source: Statistics Canada (2024b), Consumer Price Index, Annual averages, Table 18-10-0005-16

Figure 55 shows that except for energy and gasoline, the price index of 7 common categories of goods and services have been relatively homogeneous in Canada from 1978 to 2022. Therefore, I believe I can convert measures from current Canadian dollars into constant dollars without significant risks of underestimating or overestimating the value of observations measured in constant Canadian dollars.

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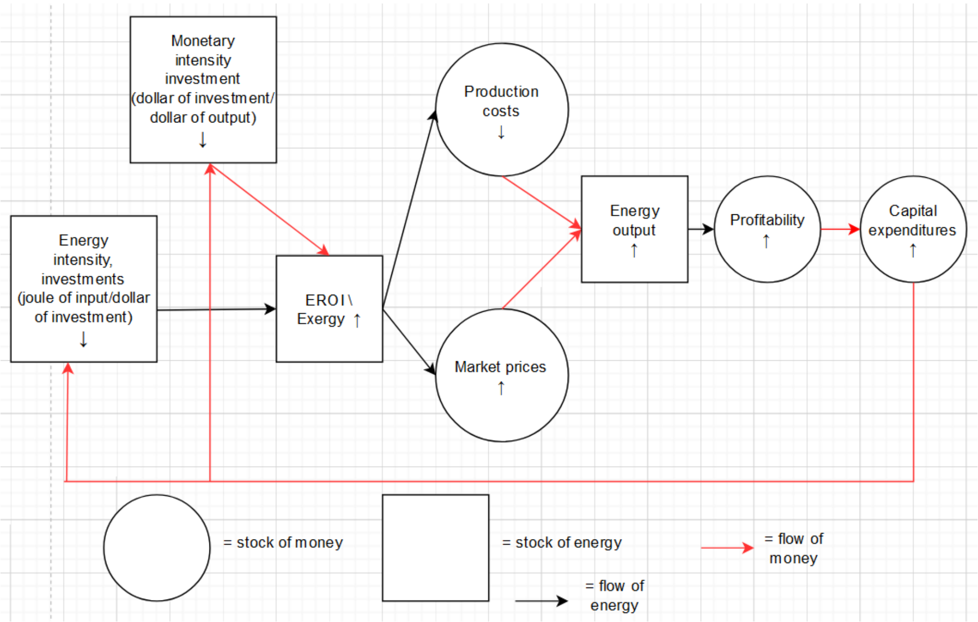
Appendix II Assumptions and hypotheses

My research was originally informed by the following assumptions:

1) Biophysical and (constant) monetary values are positively connected. In plain language: constant prices reflect biophysical quality of energy flows. An energy source embodying higher primary, exergy flows/EROI value should generate a) higher market prices; b) higher profitability and c) lower production costs per joule produced. Indeed, higher biophysical quality should reflect lower flows of direct energy inputs and lower energy/monetary intensity (dollar produced over dollar and joule invested) of investments in the production of output (on a per joule basis), meaning more discretionary monetary and energy spending to be used to further expand output production. Graphically:

Figure 56 Monetary and energy flow diagram



In other words: high-EROI/exergy of energy sources should display lower energy and monetary costs of production and higher prices that market actors are willing to pay for, thus generating higher profit for producers, more investments and increasing output. Buyers of energy products are willing to pay for energy flows of a higher quality, as it reflects higher utility of the energy product (net-energy flows and useful work being the physical basis of the potential to fulfill human utility).

2) Capital and labor cannot produce anything without energy flows. Should it be possible to measure output as a function of the flows of muscle enabling labor plus the flows of mechanical work plus heat enabling capital, the correlation between both should be perfect.
3) Capitalism is a monetary production economy where money is the pre-requirement of production (Fontana and Sawyer, 2016): without money, there would be no unit of account making commodities commensurable. In a monetized economy, production is restricted by access to money (Fix, 2015). Furthermore, any economy is predicated on energy-flows. Ergo, monetary and energy flows must be related.
4) Innovation in extractive industries leads to less monetary and indirect energy investments required to produce energy, thus lower monetary and energy intensity of investments, leading to higher profits, all in a per-joule basis. Innovation leads to higher-quality resources fetching higher relative prices on the market over low-quality resources, thus impacting both the market price of the resource and the price of the inputs required to produce it, as illustrated in Figure 58. However, because the rise in prices causes a higher relative rise in the output/numerator over the energy/monetary intensity of investments/denominator, higher prices of energy sources should result in higher profits (for a more sophisticated version of this intuition, see King and Hall, 2011).
5) Monism: energy is intrinsically valuable for its ability to perform useful work (on value monism, see O'Neill, in Spash (dir.), 2017). Money is an indirect measure of energy-value due to its contingencies (exchange rates, inflation, arbitrary changes in the money supply, etc.) Value derives from biophysical reality. Therefore, materialism is an appropriate epistemological framework for a theory of value.
6) Phenomenology: capitalism is an economy where monetary units provide the ‘’grammar’’ and psychological incentives for decision-making for most agents (Svartzman et. al., in Costanza et. al (dir.) (2018)). Market value is a reality (Kallis, 2018). Thus, if monetary and biophysical indicators align, then we can expect biophysical reality to be reflected in a monetary-based framework of decision-making.

Based on these assumptions, I argue the following hypotheses can be tested. Below, the coherence and interest for research of these assumptions can are premised in logical grounds:

1) On the $EROI_{st}$ of oil sands: owing to the different monetary and energy intensities involved in their production, the $EROI_{st}$ ratios of synthetic crude should be lower than diluted bitumen:

1.1) As synthetic crude involves the upgrading of bitumen feedstock, synthetic crude production is more energy and capital intensive than diluted bitumen production. The $EROI_{st}$ ratios of the former should be lower than the latter;

1.2) The higher $EROI_{st}$ ratio of diluted bitumen should be a function of the lower embodied energy in monetary expenditures on indirect inputs to produce it (transportation material and services, financial services, material and equipment, etc.);

1.3) The $EROI_{st}$ of the two crude streams should be above 3:1, the ratio required for an energy source to display an $EROI_{pou}$ ratio above 1:1. The two crude streams should therefore be genuine sources of energy (Hall et. al., 2009).

2) On the correlation between biophysical indicators of quality and monetary indicators at the level of the resource: I expect a moderate correlation between $EROI_{st}$ and monetary indicators of oil sands-derived crude streams:

2.1) I expect a negative relationship between $EROI_{st}$ and the costs of production of energy sources. Energy and monetary intensity of investments are positively correlated as higher monetary investments mean higher embodied energy into investments and thus a lower $EROI_{st}$. Because diluted bitumen requires less monetary and energy investment on a per-joule basis than synthetic crude, its costs of production should be lower and its $EROI_{st}$ should be higher and the relationship, negative.

2.2) I expect to find a moderately positive relationship between prices and $EROI_{st}$. Higher net-energy flows reflected by higher $EROI_{st}$ ratios should mean higher willingness to pay by energy consumers. However, the $EROI_{st}$ ratios I will estimate use the oil sands mine-mouths as their boundaries (see section 2.4). Consistency requires the prices of oil sands-derived crude used to estimate the correlation to be at the mine-mouths as well, i.e. when exported to refiners. The prices for fossil fuels are set internationally. Rising international benchmark prices, independent from the biophysical quality of the resources, should incentivize oil sands producers to explore and extract lower-quality deposits yielding crude of lower $EROI_{st}$ ratios. This could lead to a negative price-$EROI_{st}$ relationship at the margin. As such, the correlation will be moderate: the combined effect of a positive relationship between an energy source's quality and willingness to pay along with the impacts of international prices on reserves extracted at the margin will moderate the expected positive relationship. Finally, this hypothesis is valid for fossil fuels produced at the mine-mouth only. Should I extend the boundaries of analysis to EROI at the point of use ($EROI_{pou}$), I would incorporate refined energy products (gasoline, bunker oil, etc.) whose production require more energy flows than the extraction of primary energy sources. These products would display much lower $EROI_{pou}$ and yet a much higher economic usefulness on a per-joule basis. Using extended boundaries of analysis would find a negative relationship between biophysical quality and monetary value.

2.3) I expect to find a moderate connection between $EROI_{st}$ and profitability. Profitability is a function of prices and costs. Whereby prices of fossil fuels are set internationally, costs depend on the resources and deposits qualities, technologies, etc. of various crude streams. Because I expect the costs of production of diluted bitumen to be lower and its $EROI_{st}$ higher than synthetic crude, the correlation between $EROI_{st}$ and profit should be positive. Because I expect (2.1) a negative relationship between costs and $EROI_{st}$ and (2.2) a moderate positive relationship between prices and $EROI_{st}$, the relationship between biophysical quality and profitability should be moderately positive.

3) On the correlation between biophysical indicators of quality and monetary indicators at the macroeconomic level: using APFs to test the correlation between inputs (labor, capital and energy) and output production at the national level:
3.1) I expect to find a strong correlation between primary and secondary energy use and output production at the national level. Furthermore, I expect bidirectional causation between the two. Not only is energy-use the physical condition for work in its broadest sense, but output production generates capital goods and investments which unlocks further energy sources to be extracted and used. To put it differently: a certain level of output is required for human societies to harness electric power, for example. As such, the correlation between primary energy-use and output production should be strong and the causation bi-directional. Despite the issues involved in measuring output in real prices (see section 1.2), the use of one price index only (where 2012=100) to convert data from current to constant Canadian dollars should mitigate potential ambiguities on measures of output in real prices.

3.2) Canada is a major energy-producer, posing important challenges in term of how to measure the correlation between monetary output and net energy flows; a) if the objective is to estimate the correlation between net-energy ratios and the production of non-energy goods and services in Canada, then the test should focus on the net-energy ratio of energy consumed in Canada. However; b) a significant portion of energy produced in Canada is exported. This share of energy production generates monetary output, with a portion presumably reinvested in Canada to expand production, another portion paid to Canadian-based shareholders, etc. Yet, exported energy is not consumed in Canada. Standard net-energy accounting measures energy output at the mine-mouth, regardless of where it is consumed (Murphy et. al., 2011). As such, net-energy accounting can be used to build $EROI_{st}$ ratios of energy produced in Canada, but not of energy consumed. However, using Statistics Canada *Energy Supply and Demand* tables, it should be possible to estimate the net-energy ratios of fossil fuels consumed in Canada. Using two series of net-energy ratios, I can test the correlation between net-energy ratios of energy consumed and produced in Canada and output production.

3.2a) On the correlation between net-energy ratios of energy consumed in Canada and output production: the analysis should reveal a strong correlation and bidirectional causation between the two for the same reasons as in 3.1).

3.2b) On $EROI_{st}$ and output production: the analysis should reveal bidirectional causation from $EROI_{st}$ and output and vice-versa. However, the correlation should be weaker from the one found in 3.2a), provided not all energy produced in Canada is used there. However, I expect to observe the growth in $EROI_{st}$ (provided the recent and rapid growth in oil sands production in Canada over relatively constant investment) to be correlated to a growth in monetary output with a portion reinvested in expanding energy production. the correlation between the $EROI_{st}$ of energy produced in Canada and output should be positive and the causation bidirectional.

3.3) I expect a strong correlation and bidirectional causality between monetary output and man-made factors of labor and capital modeled as sub-functions of the flows of useful exergy empowering them. Until recently, no disaggregate dataset on exergy flows per country existed. Thanks to the work of Marshall et. al. (2024), disaggregate national estimates of muscle, mechanical work and heat flows per country from 1971 to 2020 are now available. Using data for Canada, testing the correlation between these flows and output production should reveal a stronger correlation when compared with 3.1) and 3.2). Indeed, in 3.1), data on primary and secondary energy flows do not account for the quantity of entropy generated in energy-consumption. Marshall et. al.'s data on exergy flows correct for this deficiency. Net-energy ratios do not account for entropy generation either. Furthermore, $EROI_{st}$ account for fuel produced but not consumed in Canada. To sum up: the correlation between flows of useful energy and output should the strongest of the three correlations tested in this section of the thesis.

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Appendix III Example of the methodology used to estimate the embodied energy in indirect inputs used in oil sands open-pit mining

Energy output and direct energy input

Table 21 shows how to estimate the energy value of energy outputs by converting data on the deliveries of energy carriers from mines from volume into energy units. It uses data from Suncor, the largest oil sands mine by output in 2008 and 2016 and the conversion factors found in Table 2:

Table 21 Energy value of output, Suncor, 2008, 2016

Mine's name	Type of output and use	Quantity (in physical units)	Energy density (in TJ)	Type of output and use	Quantity (in physical units)	Energy density (in TJ)
	2008			2016		
Suncor	Synthetic crude delivered	13,155,517 m^3	518,327	Synthetic crude delivered	16,136,913 m^3	635,794
	Bitumen delivered	140,789 m^3	6,026	Bitumen delivered	6,710,528 m^3	287,211
	Diluent naphtha delivered	1,148,689 m^3	41,008	Diluent naphtha delivered	2,707,175 m^3	95,211
	Process gas delivered	303,140 10^3 m^3	11,307	Process gas delivered	818,534 10^3 m^3	30,531
	Electricity exported	1,322,417 MWh	4,761	Electricity exported	2,757,5861 MWh	9,927
	Natural gas delivered	591,900 10^3 m^3	22,427	Natural gas delivered	13,077 10^3 m^3	495
	Coke delivered	344,653 MWh	9,995	Coke delivered	307,784 tons	8,926
Total output (in TJ)	613,851			1,068,095		

Source: Alberta Energy Regulator (2021), Statistical Reports 39, 2016

Estimating the energy value of direct inputs is done following the same process.

Table 22 Energy value of input, Suncor, 2008, 2016

Mine's name	Type of input and use	Quantity (in physical units)	Energy value (in TJ)	Type of input and use	Quantity (in physical units)	Energy value (in TJ)
	2008			2016		
Suncor	Bitumen – further processed	16,837,218 m^3	720,633	Bitumen – further processed	19,268,578 m^3	824,695
	Process gas used as fuel	504,086 10^3 m^3	18,802	Process gas used as fuel	702,809 10^3 m^3	26,215
	Coke used as fuel	845,945 tons	24,532	Coke used as fuel	452,146 tons	13,112
	Synthetic crude used as fuel + plant use	283,761 m^3	11,180	Synthetic crude used as fuel	311,674 m^3	12,280
	-			Synthetic crude – Plant use	40,281 m^3	1,587
	Natural gas – further processing	368,542 10^3 m^3	13,964	Natural gas – further processing	391,779 10^3 m^3	14,845
	Natural gas used as fuel			Natural gas used as fuel	1,008,258 10^3 m^3	38,203
	Natural gas – plant use	1,140,976 10^3 m^3	43,232	Natural gas – plant use	8,760 10^3 m^3	332
	Electricity purchased	5,124 MWh	18	Electricity purchased	2,296,351 MWh	8,267
Total input (in TJ)	111,855			114,840		

Indirect energy input

Estimating the embodied energy of indirect inputs is a three-step process: 1) indirect inputs used in oil sands extraction are identified; 2) their monetary values are converted in 2016 constant Canadian dollars; 3) these are then multiplied by the energy intensity of the sector for the year under study. Table 23 exemplifies the method with 8 inputs from the four different categories of indirect inputs:

Table 23 Energy density of indirect inputs used in the oil sands extractions sector in 2016

Category of input	Name of the input	Monetary value of the input, in current 1,000 Canadian dollars	Name of the closest sector in the Physical flow accounts	Energy density of the sector (GJ/1000$ of production at basic prices)	Embodied energy of the input, in TJ
Material and equipment	Diesel and biofuels products	215,855	BS32400 Petroleum and coal products manufacturing	16.74	3,054
	Iron and steel pipes and tubing	487,492	BS33200 Fabricated metal products manufacturing	8.06	2,737
	Logging, mining and construction machinery and equipment	1,014,130	Support activities for mining and oil and gas extraction	5.80	3,236
Transportation and services	Freight transportation arrangement and custom brokering services	347,352	Transit, ground passenger and scenic and sightseeing transportation, taxi and limousine services and support activities for transportation	5.63	1,4231
Services	Support services for oil and gas extraction (except exploration)	2,315,417	Support activities for mining, and oil and gas extraction	7.44	14,942
	Architectural, engineering and related services	1,727,034	Legal, accounting and architectural and engineering and related services	2.22	2,234

	Office administrative services	629,144	Administrative and support services	2.50	826
Financial services	Holding company services and other financial investment and related activities	1,509,821	Other finance, insurance, real estate services and management of companies and enterprises	3.39	6,794
	Deposit intermediation services indirectly measured	218,112	Depository credit intermediation and monetary authorities	3.39	661

Source: Statistics Canada (2021a), Supply and Use table, 2016 and Physical-flow accounts (2021b), Direct plus indirect energy and greenhouse gas emissions intensity, by industry (Table 38-10-0098-01)

As shown in Section 2.5.3, estimating the energy value of the inputs from 1997 to 2008 using Statistics Canada's supply and use tables require: 1) identifying the monetary value of expenditures in the oil and gas extraction sector in the year under analysis and converting it to constant 2016 Canadian dollars and 2) performing Equations 24 to 28:

Table 24 Approximate monetary value of the indirect inputs in the unconventional oil sands sector in Canada in 2018 (in 2016 constant Canadian dollars)

Category of input	Name of the input	Monetary value of the input, Oil and gas extraction (in constant 1,000,000 $CAN)	Average value (in %) of inputs in non-conventional / total oil and gas sector, 2009-2016 (in %)	Name of the closest category: physical-flow accounts	Energy density of the sector (GJ/1000$ of production at basic prices)	Embodied energy of the input, in TJ

Material and equipment	Diesel fuel	424	43	Petroleum and coal product manufacturing	16.74	3,054
	Iron and Steel pipes and tubes (except casting)	970	35	Fabricated metal product manufacturing	8.06	2,737
	Logging, mining and construct-ion machinery	1,094	51	Machinery manufacturing	5.80	3,236
Transportati-on and services	Freight transport-ation arrangem-ent and customs brokering services	383	66	Scenic and sightseeing transportation and support activities for transport	5.63	1,4231
Services	Support services for oil and gas extraction (except exploration)	6,276	32	Support activities for mining and oil and gas extraction	7.44	14,942
	Architect-ural, engineeri ng and related services	1,727	56	Architectural, engineering, legal and accounting services	2.22	2,234
	Office administrat ive services and head office services	1,376	24	Administrati ve and support services	2.50	826
Financial services	Holding company services and other financial investment and related activities	4,175	48	Other finance, insurance and real estate services and management of company and enterprises	3.39	6,794

	Deposit intermediation services indirectly measured (FISIM)	487	40	Other finance, insurance and real estate services and management of company and enterprises	3.39	661

Source: Supply and Use table (2021a), 2002-2016 and Physical-flow accounts (2021b), Direct plus indirect energy and greenhouse gas emissions intensity, by industry (Table 38-10-0098-01). Author's calculations

Embodied energy values must be further disaggregated for the embodied energy of inputs used in the production of syncrude and crude bitumen respectively. This is done by multiplying the total energy value of indirect inputs by the share of the two crude streams from total production. In 2008, 45.73% of oil sands production was bitumen. The share had risen to 61.51% in 2016 (Alberta Energy regulator, Statistical Report #3, 2008; 2016). After the respective share of total production are identified, the embodied energy per type of input is multiplied by crude stream (Equation 23):

Table 25 Estimation of the share of embodied energy in indirect inputs for crude bitumen, 2008, 2016

Category of indirect inputs	Total embodied energy, oil sands, in TJ	Share of bitumen in total oil sands production, in %	Share of total embodied energy, diluted bitumen producing mines, in TJ	Total embodied energy, oil sands, in TJ	Share of bitumen in total oil sands production, in %	Share of total embodied energy, diluted bitumen producing mines, in TJ
	2008			2016		
Financial services	9,149	45.73%	4,184	5,046	61.51%	3,104
Services	35,603		16,281	36,168		22,247
Material and equipment	21,962		10,043	29,302		18,024
Transport	6,548		16,281	15,525		9,382
Total	73,262		37,056	86,041		52,757

Finally, the share of crude bitumen produced via open-pit mining is isolated by identifying the share of total crude produced via open-pit mining and in-situ mining. In 2008, 34.68% of crude bitumen was produced via open-pit mining. The share had risen to 45.38% in 2016. Thus, I use these ratios to further disaggregate, following Equation 24:

Table 26 Share of energy value for bitumen produced via open-pit mining, 2016

	Energy value of the inputs, Oil sands sector (in TJ)		Share of bitumen, oil sands		Share of energy value of the inputs for bitumen (in TJ)		Share of bitumen produced by open pit		Share of energy value for bitumen produced via open-pit (in TJ)	
	2008	2016	2008	2016	2008	2016	2008	2016	2008	2016
Financial services	9,149	5,046	45.7%	61.5%	4,184	3,104	34.68%	45.2%	1,451	1,409
Transport	6,548	15,525			2,994	9,382			1,038	4,257
Material and equipment	21,962	29,302			10,043	18,024			3,483	8,179
Services	35,603	36,168			16,281	22,247			5,646	10,096
Total	73,262	86,o41			37,056	52,757			12,851	23,941

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