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Relational Analysis of the Oil Metabolism.
Exploring biophysical limits to the development of social-ecological systems

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Relational Analysis of the Oil Metabolism

Exploring biophysical limits to the development of social-ecological systems

by

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Sections

Abstract

Fossil energy is ubiquitous in Western societal production and consumption practices. As urban dwellers, we are so detached from the biophysical realities underlying Western societal metabolism, that we lost awareness about the vital role of fossil fuels as enablers of modern societies. Biophysical supply-side constraints and the fragilities of global fossil energy metabolism are systematically neglected when deliberating on energy and climate policies. Listening to the debate about sustainability on the media, the only relevant threat to Western civilization seems to be climate change. Therefore, according to the modern positivistic worldview, every plan devised by Western democratic and capitalistic institutions has been about providing innovative techno-fixes to prevent climate disruption, while maintaining our resource intensive way of life. Unfortunately, this framework is problematic. And in the West, we are realizing it on our own skin.

This dissertation is an exploration into the biophysical limits to the development of social-ecological systems. On one side, endogenous limits within the social sphere. These limits consist of biophysical constraints hidden inside the internal dynamics of a society. Recognizing the existence of endogenous limits introduces a new perspective in sustainability analysis, that currently is totally neglected. Much has been said about overpopulation: too many people, that on average consume way too much, on a finite pool of resource. In fact, despite the huge human population, in the near future we may experience systemic shortages of human time inside individual countries, to the degree of potentially choking global economic growth. Human time is required, both inside and outside the market, to produce and consume the goods and services needed to sustain societal metabolism. The allocation of the available time budget is affected by energy and demographic factors, such as the dependency ratio of a society or the power level at which socio-economic sectors consume energy carriers. The wealthier a society is, the more we observe an evolutionary convergence toward an intensive allocation of human time in consumption activities, and less in producing biophysical commodities. That is, in post-industrial societies, a large share of time is allocated in the reproduction of the dependent population, in the household sector, and in the activities of the service sector. This entails a major reduction of human activity in the primary and secondary sectors of the economy. Indeed, developed societies can operate with negligible fractions of workers in the primary sectors (less than 5% of the work

force in agriculture and around 1 % in the energy sector). This metabolic pattern is sustained by a hypertrophic technical capitalization of the primary and secondary sectors, an immature demographic structure – both boosting labor productivity –, and a heavy reliance on imports. However, if in the first phase of industrialization the demographic structure was still not generating a large overhead of dependent population, over time people get old, and the power level expressed by fossil fuels and associated technologies hits a thermodynamic ceiling. It is increasingly difficult to boost the labor productivity of the shrinking fraction of workers expected to supply the goods consumed by society. When the largest fraction of the time budget of a society is invested in services and final consumption, rather than in supplying the biophysical inputs required by the metabolic process, further growth is constrained. Productivity bottlenecks emerge in the productive sectors. This impasse may be addressed temporary by further increasing capital investment, externalizing the requirement of working hours through imports of goods and services, and importing economically active population through immigration. However, these are not global solutions that can be implemented in a "zero sum game". Without revolutionary energy sources capable of supporting power levels of productivity and metabolic dissipation higher than current fossil ones, a long-term solution remains elusive.

On the other hand, social-ecological systems face exogenous limits within the environmental sphere. These limits emerge not only on the sink side, that is the CO_2 emissions into the atmosphere, but equally relevant on the supply side (availability of resources). Going beyond the traditional concept of Peak Oil, the current set of human activities that compose the societal metabolism must be fueled, in quantity and quality, by proper energy carriers. The supply of those carriers must be compatible with the natural processes taking place in the biosphere over long time scales. Again, in the midst of fossil fuels abundance underground, in the near future we may run into shortages of specific oil products, while experiencing an increasing climate pressure to maintain our current Western way of life. A future scenario dominated by the "unconventional oil revolution" and the considerable depletion of conventional reservoirs may undermine the quality of oil products supply. Diesel and middle distillates may become scarce, especially relative to the European consumption pattern; other regions may face different bottlenecks, depending on the contingent imbalances between their production and consumption profiles. And indeed, whatever the scenario, we should be aware that the CO_2 emission intensity of every barrel supplied will progressively increase, just to maintain the current global energy consumption level, making the plausibility of global low carbon aspirations waver.

Internal and external biophysical limits inevitably emerge from the developmental dynamics of social-ecological systems. They are structural and inescapable, outside direct human control. The urgent threat of climate change seems to generate a systemic denial of the importance of preserving the capacity of the energy sector, and specifically of the oil sector, to provide adequate power flows to modern societies. However, in the short to medium term, preserving the oil metabolism is equally important as preserving the climate stability to guarantee the sustainability of modern social-ecological systems. This trade-off must be addressed in the social discourse on energy transitions, on pain of destabilizing the entire Western social fabric. Based on the insights gained from this work, I propose to turn the point of view on energy transitions upside down: we do not want to change the whole global energy matrix to maintain the same modern social practices; instead, we want to preserve the material achievements of Western culture long enough to foster a bottom-up radical change in the functional organization of Western society – a different set of social practices - to adapt to a radically uncertain, inscrutable future.

The relational framework employed throughout the thesis is the first step towards challenging the ultimate modern belief that the sustainability predicament is a human affair, solvable by sufficient human ingenuity. We must embed again the relation with Nature, in which human societies inevitably subsume, into our collective *weltanschauung*, and look at the future with humility. Only with new eyes, a new thinking, a new language and a new ontology, we may successfully navigate through the inevitable senescence of modern Western societal metabolism.

Resumen

La energía fósil es omnipresente en las prácticas de producción y consumo de la sociedad occidental. Como habitantes urbanos, estamos tan alienados de las realidades biofísicas que subyacen al metabolismo de la sociedad occidental, que perdimos la conciencia sobre el papel vital de los combustibles fósiles en las sociedades modernas. Las limitaciones biofísicas del lado de la oferta y las fragilidades del metabolismo global de la energía fósil se descuidan sistemáticamente cuando se delibera sobre políticas energéticas y climáticas. Escuchando el debate sobre la sostenibilidad en los medios, la única amenaza relevante para la civilización occidental parece ser el cambio climático. Por lo tanto, de acuerdo con la cosmovisión positivista moderna, todos los planes concebidos por las instituciones democráticas y capitalistas occidentales se han centrado en proporcionar soluciones tecnológicas innovadoras para prevenir la alteración del clima, manteniendo al mismo tiempo nuestra forma de vida intensiva en recursos. Desafortunadamente, este marco es problemático. Y en occidente nos estamos dando cuenta sobre nuestra propia piel.

Esta disertación es una exploración de los límites biofísicos para el desarrollo de sistemas socio-ecológicos. Por un lado, límites endógenos dentro de la esfera social. Estos límites consisten en restricciones biofísicas inherentes a la dinámica interna de una sociedad. Reconocer la existencia de límites endógenos introduce una nueva perspectiva en el análisis de la sostenibilidad, que en la actualidad está totalmente desatendida. Mucho se ha dicho sobre la sobrepoblación: demasiadas personas, que en promedio consumen demasiado, sobre un conjunto finito de recursos. De hecho, a pesar de la enorme población humana, en un futuro cercano podríamos enfrentarnos a una escasez sistémica de tiempo humano dentro de algunos países, al punto de asfixiar potencialmente el crecimiento económico global. Se requiere tiempo humano, tanto dentro como fuera del mercado, para producir y consumir los bienes y servicios necesarios para sostener el metabolismo social. La asignación del presupuesto de tiempo disponible se ve afectada por factores energéticos y demográficos, como la tasa de dependencia demografica de una sociedad o el nivel de potencia al cual los sectores socioeconómicos consumen vectores energéticos. Cuanto más rica es una sociedad, más observamos una convergencia evolutiva hacia una asignación intensiva de tiempo humano en actividades de consumo, y menos en la producción de bienes biofísicos. Es decir, en las sociedades posindustriales, una

gran parte del tiempo se destina a la reproducción de la población dependiente, en el sector doméstico, y al sector de servicios. Esto implica una importante reducción de la actividad humana en los sectores primario y secundario de la economía. De hecho, las sociedades desarrolladas pueden operar con fracciones insignificantes de trabajadores en los sectores primarios (menos del 5% del trabajo en agricultura y alrededor del 1 % en el sector energético). Este patrón metabólico se sustenta con una capitalización técnica hipertrófica de los sectores primario y secundario, una estructura demográfica inmadura – potenciando la productividad laboral – y una fuerte dependencia de las importaciones. Sin embargo, si en la primera fase de la industrialización la estructura demográfica aún no generaba una gran sobrecarga de población dependiente, con el tiempo la gente envejece y el nivel de potencia expresado por los combustibles fósiles y las tecnologías asociadas alcanza un techo termodinámico. Cada vez es más difícil impulsar la productividad laboral de la fracción cada vez más reducida de trabajadores que se espera que suministren los bienes consumidos por la sociedad. Cuando la fracción más grande del presupuesto de tiempo de una sociedad se invierte en servicios y consumo final, en lugar de suministrar los insumos biofísicos requeridos por el proceso metabólico, se ve afectada la capacidad de seguir creciendo economicamente. Surgen cuellos de botella en la productividad de los sectores productivos. Este punto muerto puede abordarse temporalmente aumentando aún más la inversión de capital, externalizando el requisito de horas de trabajo a través de la importación de bienes y servicios, e importando población económicamente activa a través de la inmigración. Sin embargo, estas no son soluciones globales que puedan implementarse en un “juego de suma cero”. Sin fuentes de energía revolucionarias capaces de soportar niveles de potencia de productividad y disipación metabólica más altos que los fósiles actuales, una solución a largo plazo sigue siendo difícil de alcanzar.

Por otro lado, los sistemas socioecológicos enfrentan límites exógenos dentro de la esfera ambiental. Estos límites surgen no solo del lado del sumidero, es decir, de las emisiones de CO_2 a la atmósfera, sino también son relevantes del lado de la oferta (disponibilidad de recursos). Más allá del concepto tradicional del Pico del Petróleo, el conjunto actual de actividades humanas que componen el metabolismo social debe ser alimentado, en cantidad y calidad, por vectores energéticos adecuados. El suministro de esos vectores debe ser compatible con los procesos naturales que tienen lugar en la biosfera durante escalas de tiempo prolongadas. Una vez más, en medio de la abundancia de combustibles fósiles bajo tierra, en un futuro cercano podemos encontrarnos con la escasez de productos petroleros específicos, mientras experimentamos una creciente presión climática para mantener la forma de vida occidental actual. Un escenario futuro dominado por la "revolución del petróleo no convencional" y el considerable agotamiento de los yacimientos convencionales puede socavar la calidad del suministro de productos petrolíferos. Los destilados mediano y el diesel pueden volverse escasos, especialmente en relación con el patrón de consumo europeo; otras regiones pueden enfrentar diferentes cuellos de botella, dependiendo de los desequilibrios contingentes entre sus perfiles de producción y consumo. Y de hecho, sea cual sea el escenario, debemos ser conscientes de que la intensidad de emisión de CO_2 de cada barril suministrado irá aumentando progresivamente, sólo para mantener el actual nivel mundial de consumo de energía, lo que hace vacilar la plausibilidad de las aspiraciones mundiales de alcanzar una economía baja en carbono en tiempos rápidos.

Los límites biofísicos internos y externos emergen inevitablemente de la dinámica de desarrollo de los sistemas socioecológicos. Son estructurales e ineludibles, fuera del control humano directo. La amenaza urgente del cambio climático parece generar una negación sistémica de la importancia de preservar la capacidad del sector energético, y específicamente del sector petrolero, para proporcionar flujos de energía adecuados a las sociedades modernas. Sin embargo, a corto y mediano plazo, la preservación del metabolismo del petróleo es tan importante como la preservación de la estabilidad climática para garantizar la sostenibilidad de los sistemas socioecológicos modernos. Este delicado equilibrio debe abordarse en el discurso social sobre las transiciones energéticas, so pena de desestabilizar todo el tejido social occidental. Con base en las ideas obtenidas de este trabajo, propongo invertir el punto de vista sobre las transiciones energéticas: no queremos cambiar toda la matriz energética global para mantener las mismas prácticas sociales modernas; en cambio, queremos preservar los logros materiales de la cultura occidental el tiempo suficiente para fomentar un cambio radical de abajo hacia arriba en la organización funcional de la sociedad occidental – un conjunto diferente de prácticas sociales – para adaptarnos a un futuro radicalmente incierto e inescrutable.

El marco relacional empleado a lo largo de esta tesis es el primer paso para desafiar la fundamental creencia moderna de que el dilema de la sustentabilidad es un asunto humano, solucionable con suficiente ingenio. Debemos reincorporar nuevamente la relación con la Naturaleza, en la que inevitablemente se subsumen las sociedades humanas, en nuestra *weltanschauung* colectiva, y mirar al futuro con humildad. Solo con nuevos ojos, un nuevo pensamiento, un nuevo lenguaje y una nueva ontología, podremos navegar con éxito a través de la inevitable senectud del metabolismo de la sociedad occidental moderna.

Resum

L'energia fòssil és omnipresent a les pràctiques de producció i consum de la societat occidental. Com a habitants urbans, estem tan alienats de les realitats biofísiques que estan subjectes al metabolisme de la societat occidental, que perdem la consciència sobre el paper vital dels combustibles fòssils a les societats modernes. Les limitacions biofísiques del costat de l’oferta i les fragilitats del metabolisme global de l’energia fòssil es negligeixen sistemàticament a l’hora de deliberar sobre polítiques energètiques i climàtiques. Escoltant el debat sobre la sostenibilitat als mitjans, l'únic aspecte rellevant per a la civilització occidental sembla ser el canvi climàtic. Per tant, en línia amb la cosmovisió positivista moderna, tots els plans concebuts per les institucions democràtiques i capitalistes occidentals s'han centrat a oferir solucions tecnològiques innovadores per prevenir el canvi climàtic, mantenint alhora la nostra forma de vida intensiva en recursos. Malauradament, aquest enfoc és problemàtic. I a Occident ens n’estem adonant a la nostra pròpia pell.

Aquesta dissertació és una exploració dels límits biofísics per al desenvolupament de sistemes socioecològics. D'una banda, límits endògens dins de l'esfera social. Aquests límits són restriccions biofísiques inherents a la dinàmica interna d'una societat. Reconéixer l'existència de límits endògens introdueix una nova perspectiva en l'anàlisi de la sostenibilitat, que actualment està totalment desatesa. S'ha dit molt sobre la sobrepoblació: massa persones, que de mitjana consumeixen massa, sobre un conjunt finit de recursos. De fet, malgrat l'enorme població humana, en un futur proper podem experimentar una escassetat sistèmica de temps humà dins alguns països, al punt d'asfixiar potencialment el creixement econòmic global. Cal temps humà, tant dins com fora del mercat, per produir i consumir els béns i serveis necessaris per sostenir el metabolisme social. L'assignació del pressupost de temps disponible està afectada per factors energètics i demogràfics, com la taxa de dependència d'una societat o el nivell de potència al qual els sectors socioeconòmics consumeixen vectors energètics. Com més rica és una societat, més observem una convergència evolutiva cap a una assignació intensiva de temps humà en activitats de consum i menys en la producció de béns biofísics. És a dir, a les societats postindustrials, una gran part del temps es destina a la reproducció de la població dependent, al sector domèstic, i al sector de serveis. Això implica una reducció important de l'activitat humana en els sectors primari i secundari de l'economia. De

fet, les societats desenvolupades poden operar amb fraccions insignificants de treballadors als sectors primaris (menys del 5% del treball en agricultura i al voltant de l'1% al sector energètic). Aquest patró metabòlic se sustenta amb una capitalització tècnica hipertròfica dels sectors primari i secundari, una estructura demogràfica immadura –potenciant la productivitat laboral– i una forta dependència de les importacions. No obstant això, si a la primera fase de la industrialització l'estructura demogràfica encara no generava una gran sobrecàrrega de població dependent, amb el temps la gent envelleix i el nivell de potència expressat pels combustibles fòssils i les tecnologies associades assoleix un sostre termodinàmic. Cada cop és més difícil impulsar la productivitat laboral de la fracció cada cop més reduïda de treballadors que s'espera que subministrin els béns consumits per la societat. Quan la fracció més gran del pressupost de temps d'una societat s'inverteix en serveis i consum final, en lloc de subministrar els consums biofísics requerits pel procés metabòlic, es veu afectada la capacitat de continuar creixent econòmicament. Sorgeixen colls d'ampolla a la productivitat dels sectors productius. Aquest punt mort es pot abordar temporalment augmentant encara més la inversió de capital, externalitzant el requisit d'hores de treball a través de la importació de béns i serveis i important població econòmicament activa a través de la immigració. Tot i això, aquestes no són solucions globals que puguin implementar-se en un “joc de suma zero”. Sense fonts d'energia revolucionàries capaces de suportar nivells de potència de productivitat i dissipació metabòlica més alts que les fòssils actuals, una solució a llarg termini continua essent difícil d'assolir.

D'altra banda, els sistemes socioecològics enfronten límits exògens dins l'esfera ambiental. Aquests límits sorgeixen no només del costat de l'embornal, és a dir, de les emissions de CO_2 a l'atmosfera, sinó que també són rellevants del costat de l'oferta (disponibilitat de recursos). Més enllà del concepte tradicional del pic del petroli, el conjunt actual d'activitats humanes que componen el metabolisme social ha de ser alimentat, en quantitat i qualitat, per vectors energètics adequats. El subministrament d'aquests vectors ha de ser compatible amb els processos naturals que tenen lloc a la biosfera durant escales de temps prolongades. Un cop més, enmig de l'abundància de combustibles fòssils sota terra, en un futur proper podem trobar-nos amb l'escassetat de productes petroliers específics, mentre experimentem una pressió climàtica creixent per mantenir la forma de vida occidental actual. Un escenari futur dominat per la “revolució del petroli no convencional” i el considerable esgotament dels jaciments convencionals pot soscavar la qualitat del subministrament de productes petrolífers. Els destil·lats mitjà i el dièsel es poden tornar escassos, especialment en relació amb el patró de consum europeu; altres regions poden enfrontar diferents colls d'ampolla, segons els desequilibris contingents entre els seus perfils de producció i consum. I de fet, sigui quin sigui l'escenari, hem de ser conscients que la intensitat d'emissió de CO_2 de cada barril subministrat anirà augmentant progressivament, només per mantenir l'actual nivell mundial de consum d'energia, cosa que fa vacil·lar la plausibilitat de les aspiracions mundials dassolir una economia baixa en carboni en temps ràpids.

Els límits biofísics interns i externs emergeixen inevitablement de la dinàmica de desenvolupament dels sistemes socioecològics. Són estructurals i ineludibles, fora del control humà directe. L'amenaça urgent del canvi climàtic sembla que genera una negació sistèmica de la importància de preservar la capacitat del sector energètic, i específicament del sector petrolier, per proporcionar fluxos d'energia adequats a les societats modernes. Tot i això, a curt i mitjà termini, la preservació del metabolisme del petroli és tan important com la preservació de l'estabilitat climàtica per garantir la sostenibilitat dels sistemes socioecològics moderns. Aquest delicat equilibri s'ha d'abordar en el discurs social sobre les transicions energètiques, sota pena de desestabilitzar tot el teixit social occidental. En base a les idees obtingudes d'aquest treball, proposo invertir el punt de vista sobre les transicions energètiques: no volem canviar tota la matriu energètica global per mantenir les mateixes pràctiques socials modernes; en canvi, volem preservar els èxits materials de la cultura occidental el temps suficient per fomentar un canvi radical de baix a dalt en l'organització funcional de la societat occidental –un conjunt diferent de pràctiques socials– per adaptar-nos a un futur radicalment incert i inescrutable.

El marc relacional emprat al llarg d'aquesta tesi és el primer pas per desafiar la creença moderna fonamental que el dilema de la sostenibilitat és un assumpte solucionable amb prou enginy humà. Hem de reincorporar novament la relació amb la Natura, en què inevitablement se subsumeixen les societats humanes, a la nostra *Weltanschauung* col·lectiva, i mirar el futur amb humilitat. Només amb nous ulls, un nou pensament, un nou llenguatge i una nova ontologia, podrem navegar amb èxit a través de la inevitable senectut del metabolisme de la societat occidental moderna.

Preface

#1. "Nothing more can be attempted than to establish the beginning and the direction of an infinitely long road. The pretension of any systematic and definitive completeness would be, at least, a self-illusion. Perfection can here be obtained by the individual student only in the subjective sense that communicates everything he has been able to see." George Simmel

"Para mi solo recorrer los caminos que tienen corazon, cualquier camino que tenga corazon. Por ahi yo recorro, y la unica prueba que vale es atraversar todo su largo. Y por ahi yo recorro mirando, mirando, sin aliento." Carlos Castaneda, through Don Juan.

This Ph.D. thesis is born out of pure curiosity. After seven years spent pursuing degrees in engineering, I was bored, and upset, of looking to the world solely through the mechanical lens. What the reader will find here is the testimony of what has been seen, understood and reflected upon during these five years of personal, intense journey. Throughout this whole thesis, I never intend to reveal truths or dispense certainties. The reader will find risky and dubious interpretations, issues left open, shades of gray, nuances and contradictions along the entire manuscript. I just tried my best to describe what I have seen along the path I have been walking through.

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#2. Lately, it seems to me that Science transformed from a playful and explorative collective endeavor of the humankind, into a tyrant that dictates absolute sets of rules and ideas to be worshipped. We all seem interested in coming up with whatever explanation for the complexity of the world we live in, just to keep our psychological and social stress in check, rather than useful framings and models to guide effective action. Everyone, it seems to me, is satisfied with somewhat accurate, but illusory so, mechanical models of reality. It seems that the illusion of knowledge and control is the most potent drug of our times, providing psychological relief to billions of people in the West. If you just question the 'established truth', if you start to question the 'whys', you automatically become an outcast, to be rejected and marginalized. This spoiled attitude is reflected in our daily behavior; in the way we take decisions or deliberate upon important topics; in the way we relate to others; in how we perceive ourselves and conduct our whole lives. If there is one thing that I am grateful to the pandemic, it is for having magnificently exposed the emptiness of meaning that afflict us all in the West.

***

#3. What is MuSIASEM? MuSIASEM is like complexity: insipid. MuSIASEM does not give you definite answers; rather, it is a multiplier of questions. MuSIASEM is an information virus that generates glimmers of light inside the mind of us, metabolic analysts, that approach it. MuSIASEM is a scientific perspective that flows into the spiritual path. MuSIASEM has been for me the first step along the never-ending way to Wisdom.

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Chapter 1. Introduction

1.1 Motivations

"The sky above the port was the color of television, turned to a dead channel" William Gibson, The Neuromancer (1984).

Even for a coarse observer, it does not take long to understand that fossil fuels are at the same time the blessing and the curse of modern societies. They warm the houses we live in; power the cars we drive; fertilize the crops we eat; pump the water we drink. Fossil fuels represent about 80% of the energy consumed by humanity. The supply of "the four pillars of modern civilization", as Vaclav Smil likes to say, cement, steel, plastic, ammonia, without which we would not have built the modern world as we know it, is strictly dependent on fossil fuels, either as energy sources or feedstocks. Production, transport and manufacturing of raw materials, food commodities and industrial products, even those necessary for a "green transition", depend on adequate flows of fossil energy. Furthermore, fossil fuels assure us not only basic survival and reproduction, but they are also the essential factor allowing the broad spectrum of "life possibilities" – e.g., leisure time and activities, commuting practices and vacations, mass education, personal care and hygiene products, modern medicine and social welfare – that we are currently enjoying in our daily lives.

Fossil fuels have been shaping our societal living in the West since the beginning of the Industrial Revolution. Using fossil sources, humans did not need to wait anymore for the natural ecosystems to recycle nutrients for crop growth, or for the plants to transform solar energy into biomass to burn for heat or to get wood for construction. They tapped into a concentrated form of energy, exploitable with relatively simple technologies, easily transportable, clean and abundant, accumulated by Nature over millions of years, that can be used at will. Crops grew faster, and the more abundant food could sustain a larger population; of this population, a smaller and smaller fraction needed to work in primary sectors, at the interface between environment and society, because the improved productivity of land and human work freed up human time and energies to be employed in new modes of production and consumption. Since less peasants were necessary to grow food, thanks to tractors, pesticides and fertilizers, people moved away from rural areas to expanding cities. Industries were born, powered by machines running on fossil fuels, to manufacture more and more sophisticated agricultural and industrial machines, and productivity grew further. Over time, thanks to continuous efficiency improvements, technological innovations and trade, more energy could be consumed at high power levels to support a growing set of human activities; and most of human time shifted from being employed in producing basic stuff, to services and consumption activities outside wage labor. Nowadays, citizens in the West enjoy a service-based, digital economy empowered by huge annual flows of fossil energy and controlled by information technologies, where most of the GDP comes from the service sector – that employs about 70% of workforce. More than half of human population lives in cities, a number that climbs up to 80% for developed countries: Western citizens are not directly involved anymore in the production of the food, raw materials or industrial goods they consume, but they take advantage of pre-packaged commodities made available from someone else. Most of the population has been freed from the need for hard manual labor and a lot of disposable time and money is spent in a wide range of "free choices". Those elements, together with the availability of cheap energy and machines assisting us in practically almost every activity, is what constitute the high material standard of living – and the backbone of moral justification – of modern capitalism. Fossil energy has allowed human societies to access higher levels of power, gradually shifting from being dominated by human and animal muscles, to being powered by endothermic machines *controlled* by humans. They unlocked new societal identities and new cultural paradigms to rationalize an abundant world. Fossil fuels marked the beginning of a large-scale, social-technical transition into Modernity, an historical period characterized by a deep (perceived) separation between Nature and Society in the West collective psyche. Fossil energy transiently broke the biophysical constraints that human societies have been experiencing since the Agricultural Revolution and, along with Science and Technology, seduced humankind with the promise of prediction and control over Nature.

However, this enchanted world that we thought we could inhabit forever (Fukuyama, 1992), has begun to fall apart. In the West, we are now facing sustainability issues that cannot be hidden anymore. Economic growth is sludging, climate change is on the front burner of global political agendas, global debt and inequalities are inexorably increasing. The shadow of stagflation hovers over the West, revealed by a secular stagnation in biophysical terms and the explosion of financial leverage to support an only apparent GDP growth. Western stagflation is accompanied by the renaissance of resource nationalism in the rest of the world. Not to forget equally concerning issues, such as continuous biodiversity loss and ecosystems destruction, persistent and pervasive chemical and electromagnetic pollution, alarming soil depletion, new wars, among many others. Even on a strictly individual level, the “best world possible” is succeeding in creating more depression, anxiety, drug epidemics, non-communicable disease and burnouts than ever in human history. People expectations are colliding with the experienced reality: we are not so happy in our own skin, we are starving for ‘meaning’ and we are starting to questioning the fundamental narratives that are at the core of the materialist, positivist, modern predicament. At the end of the day, it is not true, maybe, that our “life choices” are multiplying; maybe, the peak point in increasing connectivity and possibilities for human exploration has already passed. We are now falling into a “dark age” again, on the back of a glittering Technology.

“In our highly urbanized world, an unprecedented number of people live, in material terms, like royalty. While true, that argumentative line categorically neglects the more complicated, worrying aspects of the modern condition: […] urban life comes hand-in-hand with the paradigm of service sector economy, the end of which is to “entertain and distract a population which—though it is busier than ever before—secretly suspects that it is useless” (Gray, 2003, p.160).” (Renner, 2021, p.19)

The set of sustainability issues we are confronted with directly threatens the identity of modern societies and the Christian, expectant psyche of Western citizens. It has been known for long time that “an infinite growth on a finite planet is not possible” (Kenneth E. Boulding, 1966), but plenty of intellectuals during the last sixty years worked to provide relief to the social stress caused by the silent awareness of living in an unsustainable society (Asafu-Adjaye and et al., 2015). They reassured the West that such claims were unfounded, and that thank to human ingenuity and the invisible hand of the market “the world can, in effect, get along without natural resources” (Solow, 1974, p.11). However, at the present time of writing (2022), in the middle of a global energy and food crisis that looms to be the worst of contemporary history, these limits are too evident to be denied. Western economies are mature, and growth cannot go much further, no matter how much money central banks can print. Hence, the establishment is forced into a moral position that "something must be done", with "new"[1] narratives put forward to try to stabilize the social fabric.

Int this situation, politics and civil society turn to scientists to generate reassuring narratives, now that science has taken the place of a dead God (*sensu* Nietzsche) in Western culture. As a result, current science, rooted in reductionist approaches, far from contributing to a real understanding of the sustainability predicament, has been transformed into an "elite folk science". According to Ravetz (1994), the elite folk science is no more about the expansion of human knowledge and the improvement of practice, but it has function to provide "reassurance for a general worldview". It does so by infecting the political and social debate with what Giampietro and Funtowicz (2020) refer to as "policy legends", i.e., *"historical narrative(s) specific to a time and a place, delivered in a conversational mode, representing folk beliefs or collective experience, and reaffirming the group's common values"* (Tangherlini, 1990, p.385). The circularity of the economy, the possibility of decoupling energy consumption and economic growth, or the green energy transition to zero emissions are crystal clear examples of ideological stances, instead of solid science. They can only be acceptable at societal level because the average citizen is completely detached from the physical reality he inhabits and cannot (or does not want) to check the quality of the proposed narratives. In this hyper-urban world, there is no feedback mechanism on the biophysical foundations of wealth (Giampietro and Renner, 2020; Renner et al., 2021). Detached from Nature, surrounded by a digital reality most of their time, citizens of modern societies do not experience the role of the environment in supporting modern economies. They think that food comes from supermarket, energy from the gas station, and money from the automated teller machine, trapped in what Giampietro (2017) again defines as *"the delirium of urban elites*". The physical foundations of the economic process are missed even among those professionals (the economists) who should take care of it. It is not the case that global economy "exploits" the environment to reach its goals, as if it were something separate; instead, global economy is embedded in natural ecosystems. Material wealth is ultimately constrained by the pace of the natural cycles and the energy accumulated in the fossilized biota; the more we drain from them to put into social-economic systems, the more we close the gap with planetary boundaries. Worse than that, trying to relief a great load of emotional burden, policy legends inevitably generate "granfalloon", i.e., *groups of people who affect a shared identity*

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[1] An electrified economy, powered by wind, solar and nuclear energy sources, using hydrogen as energy carrier to store surplus of electricity and for non-electrical end uses, is not really a new idea: it has been wandering around at least since the '80s, with scarce large-scale commercial application that we all can witness nowadays (Rifkin, 2002).

or purpose, but whose mutual association is meaningless (Vonnegut, 1963). Granfalloons fulfil the need of Western citizens to give meaning to their lives, providing it with reassuring promises about a shining, techno-optimistic future. Societies need to believe in socio-technical imaginaries[2] (Jasanoff, S.,Kim, 2015) to reach an agreement on what should be their common good. For modern social-ecological system, declaring that economic growth on a global scale is no longer possible is equivalent to a cultural and societal suicide. In fact, our collective identity has been built around this fundamental principle: the faith in an omnipotent combination of science and capital able to provide prediction and control over Nature. We are still far from accepting the transience of our human condition and the need of undergoing the tragedy of change (Funtowicz and Ravetz, 1994). Our society seems not to be prepared to acknowledge that we must adapt to an uncertain, evolving world. In order to avoid confronting the inevitable biophysical limits to which we have to undergo willy-nilly, we prefer to further deepen the modern separation between Society and Nature, to reach the radical post-modern stance in which the reality we experience is exclusively a social construction[3]. In this way, we childishly reassure ourselves that the irremediable loss of our identity (social and individual), of our values, of our meaning structure and, eventually, of our life, necessary to promote true change and become “something else”, is only partial, transitory and remediable. That we do not die for real. Hence, that “something must be done” has been neutralized by assuring psychological relief instead of real biophysical, psychological and cultural transformation. The damage done by colonizing the future with techno-optimist imaginaries, by the economics of techno-scientific promises (Joly, 2010) has been huge. It will take generations to decolonize our collective socio-technical imaginaries by evanescent expectations of abundance, while provoking a deep sense of emptiness and desperation in all those who cannot accepts the limits of Nature.

1.2 Objectives

The central quest of this thesis is the exploration of the biophysical limits to the economic development of modern societies. Historically, concerned scholars have looked at sustainability issues from both environmental resource and sink sides.

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[2] *“Collectively held, institutionally stabilized, and publicly performed visions of desirable futures, animated by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology”* (Jasanoff and Kim, 2008, p.6).

[3] In the most extreme (current) conceptualization, reality is constructed not even through a collective, multiscale and interactive endeavor, but purely at the individual level. Subjective feelings and perceptions are the solely criteria of truth. “Whose truth?” is taking the place of “*Cui prodest*?”.

Notably, “Silent Spring” by Rachel Carlson and the famous work on planetary boundaries done by Rockström focused basically on the sink side, while the equally famous “Limits to Growth” by Meadows, the neo-Malthusian and Peak Oil communities explored the resource supply side. These works are characterized by a wide-ranging perspective: the sustainability predicament has always been approached as a wicked, multidimensional problem that unfolds across multiple scales. However, now the agenda of global environmentalists and decision makers has been narrowed down to consider only the strategy of green economic growth compatible with climatic boundaries as the solely relevant problem. With this work, I want to contribute to the re-broadening of the debate on the sustainability predicament. I provide an innovative perspective on selected critical fragilities in the current global oil metabolism and unorthodox considerations about internal societal boundaries associated with the allocation of human time. At the end of the day, for the long-term success of human societies, a strategy aimed at preserving the capacity of the global energy sector, and specifically the oil sector, in order to give to the current set of social practices enough time to adapt and transform in response to an altered global societal metabolism, may result equally important as addressing climate issues.

I present arguments beyond the traditional idea of Peak Oil: the quality of oil product supplies has been ignored so far, the coupling between oil products supply and consumption has not been properly integrated into modelling representations and its implications have not been thought through enough in the current sustainability debate. The fundamental problem of Peak Oil is a dynamic one of relative scarcity of refined oil products against their biophysical requirement and affordability across the social practices that we desire to express. Energy use (from extraction to end use) entails *autocatalysis*[4]: a system keeps using an energy sources only if it is convenient in relation to its identity. An appropriate methodological approach must be able to perceive and assess this basic fact. Furthermore, the issue of the quality of oil supplies affects both environmental and societal boundaries. At the scale the global economy is currently running, high quality fossil energy and, thus, a high-performance energy sector are needed not only to solve a problem of external limits, such as supplying energy carriers at scale without hitting local and planetary boundaries on land use, mineral extraction or carbon emissions, but also to solve a problem of internal limits on available human time – i.e., keep a society

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[4] *“An autocatalytic configuration of two or more ecological processes is one in which the processes can be arrayed in a closed cycle, wherein each process in the cycle facilitates the next”* (Ulanowicz, 2008).

with a high level of welfare. A modern society using approximately 97% of his total time budget in consuming activities would not have enough working time to produce (in the primary and secondary sectors) the biophysical commodities it consumes, without the possibility of using primary energy sources of high quality. Thus, I show evidence that, beyond environmental limits, human time is a forgotten societal limit to economic growth. So far, the time constraint has been dealt with by investing in more technology, technical capitalization and use of energy and materials, but this path heavily depends on the high performance of a fossil-based energy sector. A high performance that we cannot take for granted in the near future. Therefore, *degrowers* claiming that we can (and should) work progressively less, while evening out inequalities through consumption reduction, are maybe overlooking the tremendous boost of labor productivity given by fossil fuels, and the huge amount of working time injected into the Western societal metabolism by the international division of labor and migrations. All these concerns are critical when assessing global energy transition plans to a zero-emission economy based on electric renewables.

This thesis is primarily a methodological endeavor. I tried to provide a solid methodology to properly frame the metabolic assessment for the exploration of energy constraints of social-ecological systems. Methodology is not simply a protocol, a to-do-list of items to reach a pre-envisioned goal. The lens we adopt to look at the world directly shapes what we actually perceive. We humans inhabit coherent and structured representations of meanings, i.e., narratives, that are only rarely broken to make space for something radically new. At the present moment in history, economic narratives are dominating the sustainability discourse, stifling the emergence of fresh perceptions. This state of affairs prevents us from effectively framing the sustainability predicament in biophysical terms. From a methodological standpoint, it is not necessary to look into all the possible biophysical constraints that a modern social-ecological system can experience to falsify happy claims about techno-optimist futures. It is enough to show that the viability of crucial parts of the system is under critical pressure. For that, the Multi-Scale Integrated Assessment of Societal and Ecological Metabolism (MuSIASEM) approach, applied in this Ph.D. work, does not aim at an all-encompassing integrated modelling of the complex dynamic interaction between the multiple structural and functional elements of social-ecological systems (like Integrated Assessment Models do). Instead, more humbly, its scope is to craft useful representations tailored on specific aspects and the special context of the system, reflecting the special purpose of the

observer, in order to identify fragilities and inconsistencies in the simulations proposed. By doing so, it can generate a quantitative representation to support societal deliberation over sustainability concerns of interest. Specifically, I have chosen to look at the most fundamental aspects of social life: energy and human time, and how they are intrinsically entangled in the expression of the metabolic pattern associated with the identity of modern societies. Thus, in the following chapters the reader can find an exploration of the oil metabolism – the integrated network of production processes and social consumption practices of oil within the economic process – and how energy, i.e., fossil energy, using humans and machines, shapes the emergent patterns of human time allocation in the societal metabolism. I focused on oil for a simple reason: oil is the most critical among fossil fuels, it still represents 31% of the total primary energy consumed at the global level and it is a critical supply chain component for 90% of all industrially manufactured products (British Petroleum, 2022; Michaux, 2020). If we want to radically reduce or, worse, erase the current oil metabolism, as some environmentalists claim, we must be very careful at the moment of informing action. The risk is to collapse the entire Western civilization, of which at the moment oil represents one of the crucial supporting pillars.
To conclude, the research questions that guided my quest were the following ones:

1. How does energy metabolism stabilize social practices in modern societies? Or in other words, how the profile of allocation of human time - an emergent property of society’s metabolic pattern - is affected by the performance of the energy sector? – this issue is explored in Chapter 3.

2. How can we characterize the structural and functional factors that compose the energy metabolism from a relational and biophysical perspective and assess their performance in relation to the overall metabolic pattern of modern societies? – Chapters 4 and 5 explore this question.

3. How much is the metabolism of developed societies dependent on oil and to what extent, if any, can unconventional oils substitute for the cheap and easy conventional one? – Chapter 5 depicts the methodological framework to answer this question and gives a partial answer.

1.3 Overview

In Chapter 2, I lie the theoretical foundations to understand the methodological applications done in Chapters 3, 4 and 5. It is crucial to make the reader familiar with the relational framework, in order to share a common perception and representation of the economic process and contextualize the linguistic choices, all elements useful for understanding the work that follows. From a relational standpoint, modern societies are living organisms in all respects. The implications of this statement are elaborated at some depth throughout Chapter 2 on the following line. Modern societies' constituent components – i.e., their "organs" – are materially and functionally entailed between each other to secure the reproduction of the whole society – i.e., the whole organism –, their ultimate goal. If successful, the 'fit for purpose' entailment between constituent components becomes the blueprint for the future system identity and permits the reproduction – i.e., the sustainability – in time of the specific metabolic pattern adopted by the society. However, as all living organisms, social-ecological systems must die. Therefore, a process of development, ultimately leading to senescence and renewal (in the sense of Holling, 1986) must take place. If energy builds up complexity, a social-ecological system expands and complexifies in size and organization under the influence of increasing energy flows delivered at progressively higher power levels. However, if the system does not manage to perpetually increase the performance of energy supply systems, the 'complexity burden' becomes unbearable over a certain threshold, eventually leading to partial or total collapse (Tainter, 1988). This is always the case, sooner or later, for Earth social-ecological systems, ultimately bounded by the flow of solar energy, either as stock, i.e., primary fossil energy sources, or as flow, i.e., direct solar radiation. Therefore, we can conceptualize senescence as 'unpreparedness for change', a failed adaptation to possible, different, future environments, and as a "progressive freezing" of the metabolic activity in the current state to maximally preserve what can be sustained by a declining flow of available energy. Eventually, the system loses its coherence and dies, allowing the recycle from the embedding ecosystem to take place.

In Chapters 3, 4 and 5, the reader can find the core exploration of both *endogenous* and *exogenous* biophysical limits to the development of modern social-ecological systems. Those chapters are stand-alone papers published in scientific journals and are reported with minimal modifications. The reader may find some repetitive concept, that however I believe will be helpful for a clearer understanding. In Chapter 3, the focus is on the human time allocation as an emergent property of the overall societal metabolism. The more a system develops (and becomes rich), the more human activity shifts to exploratory, adaptive sectors and less workforce is employed in primary production. The Energy Metabolic Rates (EMRs) of productive sectors need to keep improving to support an increasingly complex societal metabolism, in face of a diminishing availability of human time. Eventually, the initially favorable allocation of human time becomes a socially *endogenous* constraint to further economic growth, circumventable only temporarily with different strategies (i.e., massive reliance on imports through globalization or immigration of adults). After having identified the existence of a biophysical entanglement between human time, energy and the emergent pattern of societal metabolism, and after having described the factors determining the internal constraint represented by the allocation pattern of human time, Chapters 4 and 5 explore the socially *exogenous* constraints put on modern societies by the environment. In Chapter 4, I discuss the declining performance of the global oil sector, and what are the implications on climate agenda. An extended literature on Peak Oil, starting about 10-15 years ago, shows that, overall, new oil fields are discovered at a pace insufficient to replace the natural depletion of existing ones. This means that we are progressively more reliant on mature and/or unconventional fields. However, "not oils are equal": this implies that bringing to the market the same barrel of oil, hence just to maintain the current state of social-economic affairs, will progressively cost more both on the economic and the biophysical side – i.e., more energy investments and CO_2 emissions. In Chapter 5, the analysis of oil metabolism moves at a higher scale. Generally speaking, 'peak oilers' look only at the production side, striving for accurate assessments of the crude extracted. However, modern societies do not want crude oil. They want final oil products. This simple consideration shifts the analytical focus from absolute measurements of global oil production, that have been on a plateau for two decades now (at least the conventional one), to the dynamic coupling between oil products supplied by the oil sector and oil products required by energy consumption practices. This metabolic perspective proposes a fresh vision on energy security, particularly relevant in the context of the current (2022) energy crisis.

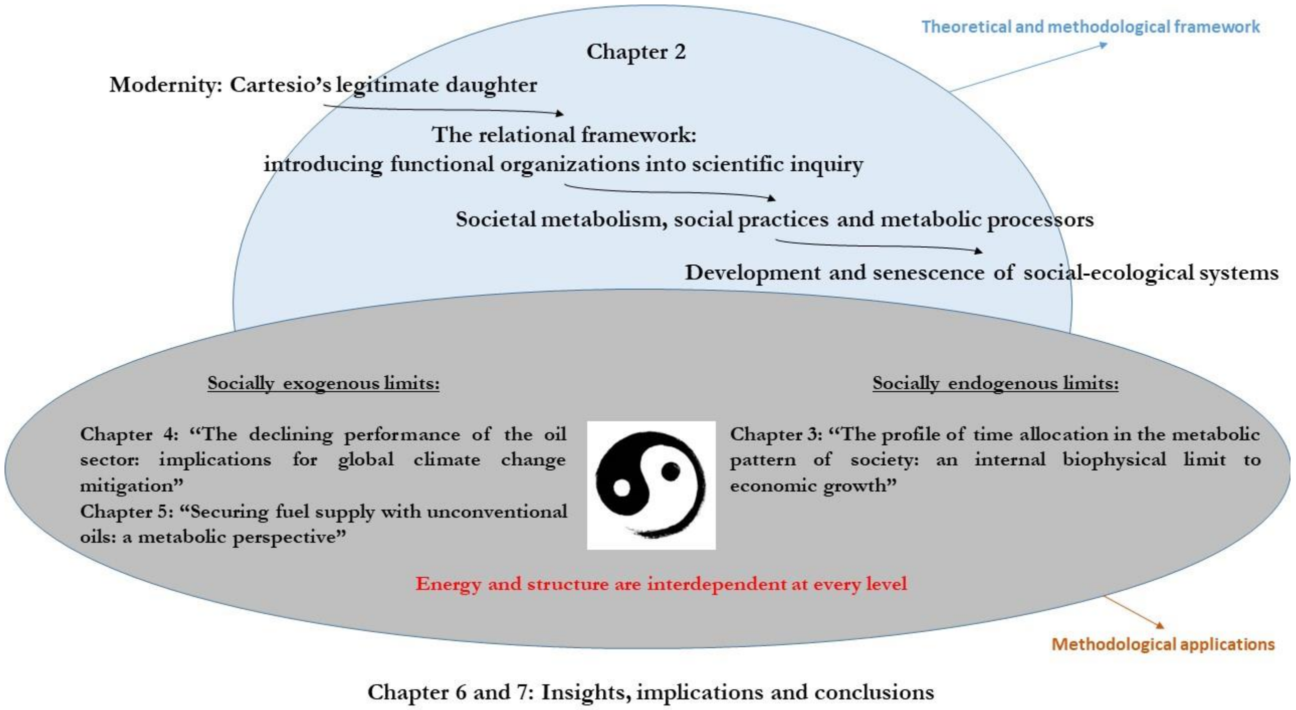

Fig. 1 Conceptual structure of the present thesis

The Multi-Scale Integrated Assessment of Societal and Ecosystem Metabolism (MuSIASEM) is the main methodological framework applied and developed in the current thesis. It has been developed by Giampietro and Mayumi (2012, 2009) as a tool to check the sustainability of social-ecological systems across four main criteria (from Chapter 5):

1. Feasibility: compatibility of the metabolic pattern with external biophysical (environmental) constraints beyond human control.

2. Viability: compatibility with internal biophysical, techno-economic constraints under human control.

3. Openness of the system, e.g., imports and exports required for sustaining the metabolic pattern.

4. Desirability: compatibility of the metabolic pattern with societal expectations.

The methodological applications developed across Chapter 3,4 and 5 were though to check the full spectrum of sustainability criteria across different scales of analysis. In Chapter 3, the methodology is framed to check the constraints on technical viability and social desirability – i.e., the coupling between technical coefficients of the performance of productive sectors and technical requirements from society. Chapter 4 is about the biophysical feasibility, especially the climate pressures, of the oil supply sector. The assessment is done at the level of extraction and refining, without considering the diversified demand of oil products determined by the rest of society. In Chapter 5, this analytical scale is integrated into the metabolic representation. This chapter is about checking the biophysical feasibility and biophysical, technical and economic viability of the oil metabolism across different supply and consumption patterns, typical of different world regions. The model spans the whole oil metabolism, from the extraction up to the interface with the rest of society, but without going into the details of how oil products are used within and between social-economic sectors.

The last part of the thesis discusses the findings and insights provided by exploration of biophysical limits done in the previous chapters, draws the lines of future research and concludes. Here, I paint an integrated picture over the relevant elements that emerge for the metabolic assessment of the oil metabolism, and their relation with the profile of human time allocation (hence social practices), at different scales of analysis and with different purposes. The results are contextualized into the theoretical discussion provided in Chapter 2, humbly trying to grasp what the social dynamics may be in the near future, and why the relational approach developed in this thesis may help to face the challenges that await us. My stated intent is to contribute to the development of a ‘science for governance’ toolkit, specifically tailored to the assessment of the energy sector. This toolkit wants to help to tame the complexity of the world in front of us to a limited, but hopefully useful, extent, allowing to envision a radical change toward an alternative future.

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Chapter 2. Shifting paradigms: from the modern predicament to a relational Weltanschauung

In this chapter, I will provide an overview of the conceptual framework that I adopt throughout the whole thesis. The discussion about the pre-analytical choice of narratives is in general avoided in hard science. In normal science, the points of views and the political ideas of the scientists are not supposed to be relevant. On the contrary, when dealing with sustainability and wicked problems, we are in the realm of Post-Normal Science and, in my view, it is important to inform the reader about the personal worldview of the analyst. Because of this choice, I will get into a theoretical and methodological discussion of the framework adopted, spanning across multiple knowledge domain: (i) the relational framework associated with the analysis of societal metabolism, (ii) the approach of societal metabolism and Social Practices to describe the organization and the functionality of social-ecological systems; and (iii) the concept of evolution (development and senescence) of social-ecological systems. For this same reason, the reader should not expect a rigorous defense of all the points made. The specific methodologies used to generate the quantitative analysis presented in Chapters 3,4 and 5 will be explained in detail in the respective chapters.

2.1 Modernity: Cartesio's legitimate daughter

"Complexity gives us a different approach to engaging with the world – a middle ground between control and chaos." Jean Boulton

The Judeo-Christian culture prepared the ground for the emergence of the Scientific Revolution and the Illuminism. The conception of Time went from being a circular one, marked by the rotation and revolution of the Earth around the Sun, to a linear one. The past is sin, the present redemption, the future salvation. The future becomes with Christianity the most interesting temporal dimension. From being inscrutable and obscure, dominated by Fate for the ancient Greeks – a mysterious entity to which the gods themselves must submit – it becomes the time of human salvation and reincarnation, when Death is definitely defeated. Hope is a central category in the thought and collective psyche of Christian civilization[5], which

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[5] i.e., of Westerners. In the West we are all Christian, whether we believe in God or not: our cultural and psychological structure is intrinsically shaped by Christianity (Galimberti, 1975)

translates, on the practical level, into a transformation of the understanding of man as the "master" of Nature (Genesis): nowadays, the capacity to dominate Nature thanks to knowledge and competence is an idea internalized so deeply to reach the point of being considered a moral obligement. Few important thinkers such as René Descartes, Francis Bacon, Galileo Galilei (among others) revolutionized the conception of Science toward an utilitarian instrument of dominance. The task of scientists was no longer to contemplate Nature to harmonically adapt to her laws, as in ancient times, but to inquire specific natural phenomena using experiments, under stable boundary conditions controlled by the scientists themselves. Using this method, their purpose was to reveal hidden truths, and ultimately use that new knowledge as an instrument of power in favor of human progress. The experiment became the ultimate judge of the validity of scientific knowledge: scientists pre-constructed theories had to pass the test of empirical evidence. In order to do that, scientific objects (variables and constant parameters) had to be measured and measurable, and their entanglement into coherent theories and models must be falsifiable to be properly defined as "scientific" (Popper, 1959). This new *modus operandi* entailed that everything except matter had to be purified from the scientific endeavor: only in a pure material world humans can objectively quantify substantial causal relations over measurable objects; and a universal, geometric order can be constructed. According to the Cartesian machine metaphor, scientists assumed that they can substantially described natural systems in material and formal terms. The machine metaphor assures that there is no horizon of purpose and meaning in the causal relations between natural elements, eliminating those categories from the scientific domain, and that the interactions between the objects that constitute natural systems can be entirely reduced to mechanisms with varying degree of complicatedness[6]. We can refer to Reductionism as the scientific paradigm characterized by the systematic neglection of the liveliest attributes of natural systems[7] from the scientific domain.

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[6] Generally speaking, complicate problems are "hard to solve". Instead, "a complex phenomenon is a phenomenon that requires a simultaneous perception and representation of its various relevant aspects using several non-equivalent narratives and dimensions and scales of analysis" (Giampietro, 2021). For a more in-depth discussion, see (Allen et al., 2018).

[7] "*According to the Aristotelian framework of causality, there are "four fundamental ways of providing an explanation of that which is responsible for some object ("To what is the object indebted?"). Each of the four causes of Aristotle may be considered as an irreducible explanatory resource, essential to answer an inquiry of "Why?":*

- *Material cause is the material or "matter" out of which something is constituted.*
- *Formal cause is the form or "shape" into which the material enters, or the "account of what it is to be".*
- *Efficient cause is the primary agent or source of change realizing or initiating something which is done.*
- *Final cause is the sake for which something is done. It addresses: To what end?"* (Renner, 2021, p.53)

Indeed, Reductionism has been a useful paradigm in a variety of hard sciences, expanding human knowledge and technology to the Moon…literally. Not only that, the technological advancements fostered by scientific discoveries coupled with the use of the abundant, concentrated, cheap and easy to exploit fossil energy permitted to create a huge amount of wealth (at least in some spot in the West), penetrating and cracking even millennial, spiritual and cultural systems such as the Indian or the Chinese. Grounded in the optimistic Christian vision of time and *the Cartesian dream of prediction and control* over Nature (Guimarães Pereira and Funtowicz, 2015), the West has transformed in a few centuries into the dominant civilization, and the richest in human history. The neoliberal capitalism – i.e., contemporary mainstream economics – is the social economic actualization of the current scientific and cultural paradigm: it too is characterized by faith in the future, in techno-science and perpetual economic growth and progress. Those are the ideological pillars of Western market economies, and of all other economies around the globe that are inspired by our model of development. Neoliberal capitalism is the realized *habitable order* (Peterson, 2018) we are currently living in: it has colonized our collective psyche and became the blueprint for the construction and organization of our societies. The tacit belief is that free markets and democratic institutions, innovative business models and technological innovations (human ingenuity) will eventually solve any problem, fueling human progress indefinitely. That is, neoliberal capitalism legitimates and is legitimated by our collectively envisioned and shared socio-technical imaginary of a wealthy future for everyone, promised by Science and Technology – given a sufficient amount of work and time, of course. Therefore, we observe, together with Latour (1993) that the social construction of Modernity as a cultural paradigm and experienced reality is defined by the ontological separation between Nature and Society[8].

"Control, regularity, order, system, techno-culture as our nature: not only are all these fundamental to modernism as Weltanschauung[9], ideology, aesthetic, and

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Reductionism systematically neglects the efficient and final causes, typical of living systems, while preserving only material and formal causes.

[8] "Society" is used in this work as synonymous to habitable order, to indicate the psychological living space for humans conceptualized and perceived as ordered, crafted by human ingenuity and under their control through competence and work.

[9] Definition from Wiktionary: "Noun. weltanschauung (plural *weltanschauungs* or *weltanschauungen*). A person's or a group's conception, philosophy or view of the world; a worldview".

design practice, but they are also (I want to argue) basic to modernity as lived reality."(Edwards, 2003, p.6).

In striking contrast with the chaotic Nature from which Society emerged, humans believe to have created a predictable habitable space through the cultural and scientific fruits of Illuminism and the power of fossil fuels. The ordered space of Society has expanded in the Western collective psyche, to the point that nowadays it has occupied the whole perceived reality, leaving no space for uncertainty and unpredictability. Within this modern worldview, commodification of Nature took place, transforming her into the "environment" (better, "our environment") and seen as a separate, undefined but predictable, stand-alone object under human control, to utilitarianly exploit or maternalistic taking care of.

*"Indeed, humans are ever more alienated from nature. The Oxford Dictionary definition of nature, endorsed by organizations such as the OECD, speaks for itself: "Nature is the phenomena of the physical world collectively, including plants, animals, the landscape, and other features and products of the earth***, as opposed to humans or human creations*** *(bold added)". This definition suggests that "homo economicus" is not part of nature nor evolved on this planet, as if we were instead rational cyborgs, with the sole goal of creating a growing economy independent of nature. (This may well explain the success of the EU circular economy action plan in which human society supposedly will no longer rely on the exchange of inputs and outputs with the biosphere)."*(Giampietro, 2021, p.32).

Nature has been basically reduced to an extension of Society. Indeed, this misleading perception could hold on short time scales, where the environment, even if outside human control, shows stable properties and behaves like an unchanging scenario[10], where humans can act and reproduce. But on larger time scales, human societies have to adapt to external changes, modifying their internal metabolism to survive to new external conditions. Modernity is therefore constructed on this short-sighted perception and the associated belief that Nature, a static object, can be controlled by Society through Technology. However, as soon as we take into account the becoming of Nature, it is clear that the "modernist settlement" (Latour, 1999) falls ruinously. This is exactly the predicament that Climate Change is

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[10] To visualize this point, just think deeply about the idea of "carbon budget", or the "2°C threshold" to avoid climate change…

forcing us to face. Nature and Society co-exist and co-evolve[11], influencing each other, and missing this intimate relation when designing environmental and energy policies leads to ruinously failures, as we can witness with all the climate debate and COPs over the last 30 years (Jackson et al., 2019; Peters et al., 2020; Young, 2016).

As a consequence of the Cartesian reductionist paradigm, the category of finality is left outside the scientific inquiry. Mainstream modelling methodologies commonly adopted in sustainability science to inform policymaking – Integrated Assessment Models (IAMs), Life-Cycle Assessments (LCAs), general equilibrium or econometrics models to name a few[12]– are narrowly focused on the analysis of either structural (e.g., oil extraction processes) or functional (e.g., economic activities) realizations, but miss their entanglement across multiple scales within coherent functional organizations – i.e., the link between the *what-how* and the *what-why* descriptions (see section 2.3). That is, existing quantitative approaches do not allow an integrated analysis of complex social-ecological systems – i.e., the whole set of functional and material entailments between human societies and their structural coupling to an admissible environment. Therefore, when policymakers are confronted with the sustainability predicament of this class of systems (populated by wicked problems[13]), they face the risk of getting trapped into the "silo governance syndrome" – i.e., solving a given problem by setting targets, meaningful only within a given narrative, that ignore negative side effects related to other problems (Giampietro, 2019). Mainstream models usually break down the energy systems into single processes, supply chains or simple dynamics (i.e., formal mechanisms), and look at the most efficient technologies, less emission-intensive products or optimal behaviors to "solve" only the specific problem they artificially created. They reduce the analytical domain to better handle "scientific evidence" defined in terms of input/output analysis, but forget to study the meaning of the overall societal metabolism, a process of autocatalysis in which inputs and outputs, before and after are not distinguishable inside a set of impredicative relations. It is

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[11] Scholars in Ecological Economics and Theoretical Ecology clearly understood this relation and have been conceptualizing human societies as complex adaptive metabolic systems for a long time (Ahl and Allen, 1996; Allen and Starr, 1982; Giampietro, 2004; Giampietro et al., 2012). Actually, Ecological Economics was born because of the need to bring back Nature, in the form of ecological systems, into both neoliberal and Marxist economics narratives. Even if they disagree about how to distribute the generated income, neither liberals nor Marxists explicitly recognize the role of Nature in the economic process (Georgescu-Roegen, 1971; Herman Daly, 2004; Martínez Alier and Naredo, 1979).

[12] See Capellán Pérez (2016) for a more detailed discussion.

[13] *"A wicked problem is a problem that is difficult or impossible to solve because of incomplete, contradictory, and changing requirements that are often difficult to recognize. It refers to an idea or problem that cannot be fixed, where there is no single solution to the problem; and "wicked" denotes resistance to resolution, rather than evil. Another definition is "a problem whose social complexity means that it has no determinable stopping point"*. From Wikipedia.

this choice of reductionism in the analysis that promotes an illusion of control. Questions like "why do we use energy? why do we need to emit CO_2?" are systematically neglected[14]. Asking "why?" forces scientists to recognize that human societies are purposive organizations toward the goal of reproducing themselves; the implication is that, when talking about sustainability issues, matter is always tied with meaning and value for contingent observers. Furthermore, for neoliberalism to be consistent, it needs to systematically neglect the biophysical, entropic roots of the economic process (Georgescu-Roegen, 1971). The Cartesian duality between mind and body leads to the conceptual negation of biophysical limits outside human control, and to abstract representations of the world (Saltelli and Funtowicz, 2015) – for instance, untied from energy constraints. Economic narratives and modelling – focused only on abstract categories like money, interest, productivity, debt – foster the ideology of perpetual growth and human progress, and generate "policy-based evidence" to reinforce the *status quo*, by their simple adoption as unique methodological lens on the world (Saltelli et al., 2020). Their monopolistic use artificially creates and reproduces the separation between Society and Nature, and reinforce the misleading idea that more market and technological silver bullets will fix any sustainability issue[15].

2.2 The relational framework: introducing functional organizations into scientific inquiry

However, the optimistic, ordered and abstract modern world crashes in front of the complexity of living systems. The very foundation of the scientific method, the experiment, turns out to be an act of radical abstraction (an expression borrowed from Robert Rosen) when applied to the study of living systems. In a living context, in order to create the experimental set, scientists assume boundary *ceteris paribus* conditions and eliminate all the possible interactions of the object of analytical interest: (i) with the other constituents of the living system; and (ii) with the

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[14] The mainstream social-economic narrative unquestionably adopted is that of perpetual economic growth and human progress. Hence, the usefulness of common models relies in the capacity to generate information to provide that goal, biasing the pre-analytical selection of the relevant information space to generate "evidence based" knowledge. The underneath socio-technical imaginary is never discussed by science for governance.

[15] *"Wassily Leontief (1982) once criticized the dismal performance of academic economists who could not "advance, in any perceptible way, a systematic understanding of the structure and the operation of a real economic system". According to Leontief, since economists have not been subjected to the harsh discipline of systematic fact-finding, traditionally imposed on and accepted by the natural sciences, they have a predilection for deductive reasoning. This results in mathematical models full of formalism nonsense without serious empirical content."* (Mayumi et al., 2010, p.1-2).

system's admissible environment. That means to kill the living system and, again, reduce it to its material substance and formal description as a mechanism.

"Destroying the organization of a complex system prior to the analysis of its constituents is equivalent to breaking the chicken-egg paradox. This realization sheds new light to the pretentious claim of reductionism that after a system of interest has been sufficiently fractionated into its constituents and those constituents sufficiently studied on an individual basis, the original system can be meaningfully reconstructed from its parts. The sum of the parts is the whole! Once an analyst assumes as unquestionable a narrative, there is no going back to explore alternatives — the breaking of an impredicative loop is a one-way street". (Renner, 2021, p.55-56).

In contrast, according to Renner, social-ecological systems are *"metabolic networks in which constituent components*[16] *stabilize each other in an impredicative (self-referential) set of relations"* (Renner, 2021, p.44). That is, social-ecological systems are living systems: their parts are functionally entailed, meaning that each one has the goal to reproduce and stabilize each other, with the overall purpose of reproducing the whole organism. At the same time, they are materially open, that is energy and materials to feed the system must necessarily come from its admissible environment[17]. *"Such a representation [of social-ecological systems (ed.)] allows for the generation of characteristics such as the relative size of constituent components, their expected metabolic rates, and, more in general, a definition of societal identity"*. The awareness of the organizational unity[18] of social-ecological systems, encompassing both the social and natural spheres, is what allow the shift from a reductionist paradigm to a relational framework in sustainability science:

"Rosen (2005, p.119) summarizes the reductionist approach with the mantra: throw away the organization and keep the underlying matter; and the relational approach

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[16] From the jargon of relational biology, 'constituent' refers to the structural dimension, while 'component' indicates the functional aspect. Therefore, in the context of societal metabolism, constituent components are the societal sectors, the parts of the system.

[17] For an in-depth exploration of this concept, see Renner (2021).

[18] A substantial definition of 'organization' is elusive. Here we can rely on Renner's words for an intuitive understanding, referring to his work for more details: *"any human organization, such as a scientific society, a corporation or a military unit, has a structure in an abstract space. […] "Organization is that attribute of a natural system which codes into the form of an abstract block diagram"* (Rosen, 2005, p.126).*[…] From a topological point of view any organization chart is a graph, usually an oriented graph."* (Renner, 2021).

in the mantra: throw away the matter and keep the underlying organization" […] Where the murmur of the reductionist approach is "structure implies function", the murmur of relational approach is "function dictates structure" (Louie, 2009, p. xx). The approach of the relational scientist is to start with an organizational unity in the world of formalism, constructed of inferential entailment, and explore how that organizational unity is realized by natural phenomena." (Renner, 2021).

When we adopt a relational standpoint, the modern cultural separation between Society and Nature dissolves: societal metabolism – metabolic from the Greek word *μεταβολή, metabolē,* "change" through "ex-change" of energy, matter and information with the admissible environment – can be conceptualized as a relational (organized) network of social practices with the purpose of reproducing the whole over time. I will define what social practice are in the next section. Here it is important to elucidate the concept of wholeness put forward by a relational perception and representation of the world, by introducing a set of ideas that will be used extensively in the following. Adopting a relational approach, we observe with Giampietro et al. (2012) that modern societies are complex metabolic systems. This class of objects is populated by dissipative, hierarchical and adaptive systems fed by "negentropy" (Prigogine, 1980). Dissipative, because the societal metabolism of human societies degrades favorable gradients of external energy flows to build up new structures and functions; hierarchical, because their organization and operational dynamics unfold over multiple components interacting across different spatial and temporal scales; and adaptive, because they are able to evolve in response to external or internal perturbations through feedback loops. According to Giampietro, metabolic systems must be capable of keeping coherence in time over the heterogeneous set of metabolic constituent components across hierarchical scales, to stabilize and reproduce the specific identity of the parts together with the identity of the whole to which they belong. Hence, it is important that a metabolic system is capable of establishing meaningful relations among: (i) the metabolic processes taking place within its parts; (ii) the metabolic processes taking place within the various parts and the whole; (iii) the metabolic processes taking place in the whole in relation to its admissible environment. This requires:

1. A definition of the identity of the metabolic system itself as a whole and the identity of its parts – i.e., its specific organizational relations over constituent components, the particular viable and desirable configuration of the societal metabolism to be expressed.

2. A formal definition of the set of specific metabolic processors capable of expressing the expected profile of transformations, required by each one of the constituent components (parts), for the reproduction of the identity of the whole.

3. The expected associative context, i.e., the set of boundary conditions determined by processes outside the control of the metabolic system that is required for the supply of useful primary inputs and for the absorption of wastes – the specific structural coupling with the admissible environment.

The conceptualization of human societies as metabolic systems explicitly reinstates Nature into the representation. Nature is considered an essential part of the economic process and it is explicitly recognized that the sustainability of the societal metabolism depends on the establishment of: (i) feasible relations with a suitable environment; (ii) a viable internal network of relations over constituent components; (iii) desirable functions expressed by the constituent components for the common good of the whole (Giampietro et al., 2012). Nature is still perceived and represented as admissible environment with which the society is structurally coupled. However, the label of admissible environment flags the fact that the structural coupling depends on processes operating outside the control of the societal system. Thus, social-ecological systems should be considered as the result of a complex entity (metabolic system plus admissible environment) that cannot be substantially modelled. Therefore, Nature is not simply a space where we find commodities to be exploited at will, but a boundary object that co-evolves (in unpredictable ways as ecosystems usually do) with society in time. According to the wisdom of Georgescu-Roegen, the methodological foundation of Ecological Economics is the acknowledgment that the economic process is an entropic process, embodied in natural ecosystems, and regulated by the laws of thermodynamics (Georgescu-Roegen, 1971).

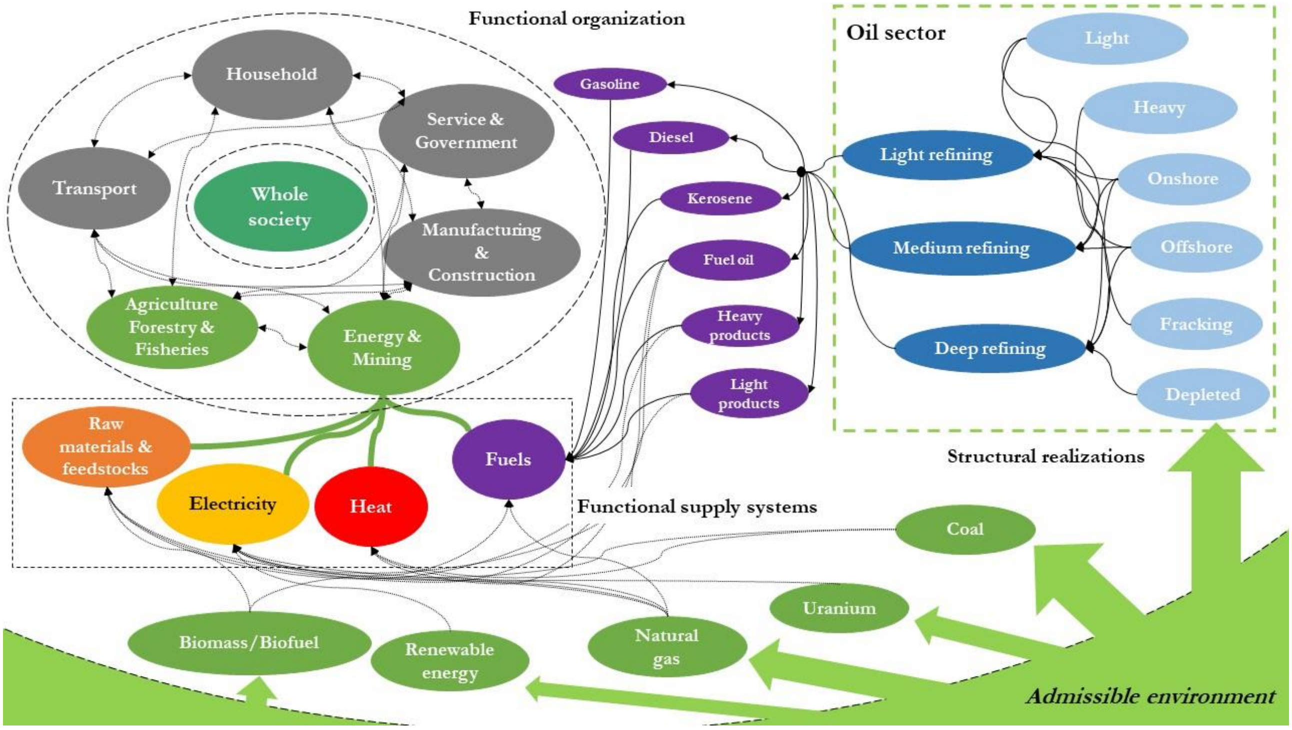

Fig. 2 A visual representation of a modern human society as a societal metabolism, embedded in an admissible environment. Emphasis is put on the hierarchical constellation of practices across the multiple scales involved in the oil exploitation process. Focusing on the oil sector (top-right), purple ovals are functional processors – fuel supply –, blue and light blue ovals are structural processors – extraction and refining processes (see section 2.3 for the definition of metabolic processor). On the top-left, constituent components, expressing metabolic functions at the level of the whole society, are represented in light green and grey. Grey constituent components – 'Transport', 'Household', 'Service & Government' and 'Manufacturing & Construction' – are dissipative sectors, light green – Agriculture, Forestry & Fisheries – are productive ones (see section 2.4 for definitions). Light green ovals in the lower part of the figure represent other subsectors of the energy sector at the interface with the admissible environment (thick green arrows). The black arrows are indicative of both material and functional entailments (this distinction is not emphasized in this figure).

However, breaking the logical impredicativities (chicken-egg paradoxes) among the relations that constitute social-ecological systems is necessary to identify and describe, qualitatively and especially quantitively, the relevant direction of causality over events and act in the world according to the chosen narrative – do we produce gasoline to fuel cars, or do we drive cars because of gasoline availability? Humans need to encode the space of possible perceptions into a reduced space of formal representations to take decisions[19] in their bounded time-space dimension. The narrative is the tool that fill this gap. Essentially, narratives are beliefs about the relevance of an expected cause-effect relation that may result useful for the purposes of the believer. The pre-analytical choice of a narrative necessarily determines a specific direction of causality. *"Narratives are necessary epistemological commitments that serve to create manageable hierarchies, order and unity of experience"* (Renner, 2021). The problem is that several non-equivalent narratives may be valid to explain the same event (Giampietro et al., 2006). For this reason, it is vital that believers and storytellers are aware of the implications of the epistemological frame they are working in. Otherwise, the sin is an excessive reliance on de-contextualized models and weak knowledge claims, generating the illusion of possessing a universal truth.

In the following, I will regard the '*ordered universe populated by rational and ingenious agents guided by the invisible hand of the market towards endless progress'* as a legend. The work that I present in this thesis questions the belief that technological innovations – e.g., technical transition to wind and solar energy, hydrogen, biofuels, fourth generation nuclear, energy efficiency – new business and behavioral models – e.g., circular economy, energy-GDP decoupling –, implemented over a plethora of rational economic agents, will fix our current sustainability issues without considering the key role played in human societies by affective relations and simply by relying on the 'invisible hands' of 'free' markets. The neoliberal narrative is justified only within the modern predicament, from an epistemological point of view, and realized solely thanks to the illusory and transient power given to humanity by fossil fuels, from a biophysical stance. To make my point, I propose an analysis based on the adoption of a relational *weltanschauung*, where human societies are unavoidably entangled with natural ecosystems by a continuous exchange of fluxes of positive entropy and negentropy (Schrödinger, 1944). They are living systems expressing a societal metabolic pattern constantly adapting to the environment, while altering it. Within this vision of the world, human societies continually need energy to stay balanced on the edge of chaos. And as every living entity, social-ecological systems are dominated by evolutionary time[20]: they must be born, grow, mature and die. Accordingly, we

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[19] Every decision is an "act of madness": since we need to eliminate any alternative possible causal entailment in the formal model to guide our action, we must bear the responsibility of the tangible consequences that that chosen framing generates in the real world. Nothing to do with "evidence-based, optimal solutions".

[20] the need of using different time scales to study relevant attributes through the cycles. This has been called complex time by Giampietro (2004).

cannot rely solely on the conventional methods inherited from the Cartesian paradigm, but we need innovative methodologies to study the sustainability of complex metabolic systems. The relation between Society and Nature should once again placed at the center of the sustainability debate.

2.3 Societal metabolism, social practices and metabolic processors

In the previous section, I defined the societal metabolism as a relational network of social practices. ‘Relational’ refers to the functional organization of the network as a whole, representing the communication matrix where the constituent components of the system exchange energy, matter and information. Instead, the concept of social practice comes from practice theory (Schatzki, 1996a, 2010a, 2010b; Shove et al., 2012). Social practices are active integrations of:

1. Material arrangements.
2. Know-how and routines (competences).
3. Teleo-affective structure, domain of symbols, meanings and beliefs.

expressed by a group of agents over multiple space-time and organizational levels of the social structures. According to Schatzki, social practices constitute the “site of the social” (Schatzki, 2010b). “*Social practices ordered across space and time should feature as the basic unit of social inquiry”* (Giddens, 1985). Social practices resemble what Edwards calls, in another jargon, “infrastructure” (Edwards, 2003), or the Castells’ “space of flow” (Castells, 1996):

“Infrastructure knowledge is a Wittgensteinian “form of life”, a condition of contextuality in which understanding any part requires a grasp of the whole that comes only through experience (Edwards, 1996; Wittgenstein, 1958). In this sense, infrastructures constitute society.” (Edwards, 2003).

Hence, now I can more precisely state that social practices hierarchically organized in multi-scale structures, materially, formally and functionally entailed with their admissible environment and sharing the same purpose – the reproduction of the societal whole – are the building blocks that constitute the societal metabolism of socio-ecological systems.

Schatzki continues:

"Accounting of change is not a matter of abstracting sets of forces or systems, but of how social practices, and bundles of constellation of practice, hang together, and of identifying the material and other arrangements amidst which they transpire, and which they also sustain and reproduce. […] Social practices are recognizable blocks or patterns of activity that are filled out and enacted by practitioners, […] who reproduce, transform and perpetuate the practices they carry" (Schatzki, 2010a).

What Schatzki is describing fits perfectly with the concept of 'metabolic processor' in the societal metabolism literature, and especially in MuSIASEM, the backbone methodological framework for the present thesis. Metabolic processors are epistemic tools first introduced in relational biology and then borrowed by MuSIASEM to quantitatively represent social-ecological systems. They put together expected input and output profiles of flows and funds[21] (material arrangements and know-how) with a specific function (the purpose of the processor defined inside the teleo-affective structure) at the specific scale of the societal metabolism where agents express that specific function (Cadillo-Benalcazar et al., 2019; Di Felice et al., 2019; González-López and Giampietro, 2017; Renner, 2021). In other words, metabolic processors bridge together structural and functional representations of:

(i) *what the system* (or process, or sequential pathway, or functional sub-system) *is* and *how* it does what it does – the structural description, answering to the question "WHAT-HOW" at the same scale of the observer or lower. The structural view is concerned with material infrastructures and input/output flows associated with the necessary know-how – i.e., the technical coefficients that formally characterize how those material flows and infrastructure are arranged and transformed – used to execute specific functions inside the network.

(ii) *what the system does and why* it does what it does – the functional description, answering to the question "WHAT-WHY" at a higher scale than the observer. The functional view is concerned with *expected* patterns of functions

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[21] A brief description of the Georgescu-Roegen's flow-fund model is given in section 2.4.

(meanings and beliefs) to be expressed by specific agents needed for the reproduction of the whole network[22].

Managing to realize an instance that matches the expectations of the upward and downward causation is called *coarse graining* (Flack, 2017). Since complex socio-ecological systems are hierarchically structured (Allen and Starr, 1982; Pattee, 1973), keeping coherence between different levels is vital to check the consistency of the representation given (non-contradictory) – an essential requisite to operate an effective system of control – and to grasp the meaning of different components inside the system (the big picture). Indeed, using processors, it becomes possible to scale the representation of the system inside and across the different constituent components, maintaining coherence between them. That is, it is possible to track what is produced and consumed, at what biophysical and environmental costs (the associated biophysical production function) and in relation to which societal purposes. In this way, the dangerous simplifications of reductionism can be avoided, maintaining different non-equivalent descriptions of the observed system and managing to generate the emerging complexity of the representation. The relational assessment of the sustainability of social-ecological systems – i.e., the use of metabolic processors for the semantic and formal representation of the social practices expressed by the societal metabolism – allows an integrated representation of production processes (of energy, materials and services) and consumption patterns across the multiple scales that compose modern societies. It provides a broad descriptive power in an apparent simple formalization.

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[22] More precisely, the 'upward causation' responds to the question WHAT-HOW: what the node (in tangible terms, biophysical processes), because of its formal cause (blueprint) can do. It is the actual profile of inputs and outputs expressed by tangible objects up to the observation scale. Whereas the 'downward causation' responds to the question WHAT-WHY: what the network niche of the node, defined in notional terms within the network, defines what the profile of inputs and outputs should be from a scale higher than the observer. *Holons* emerge when these non-equivalent descriptions coincide (Allen and Giampietro, 2014).

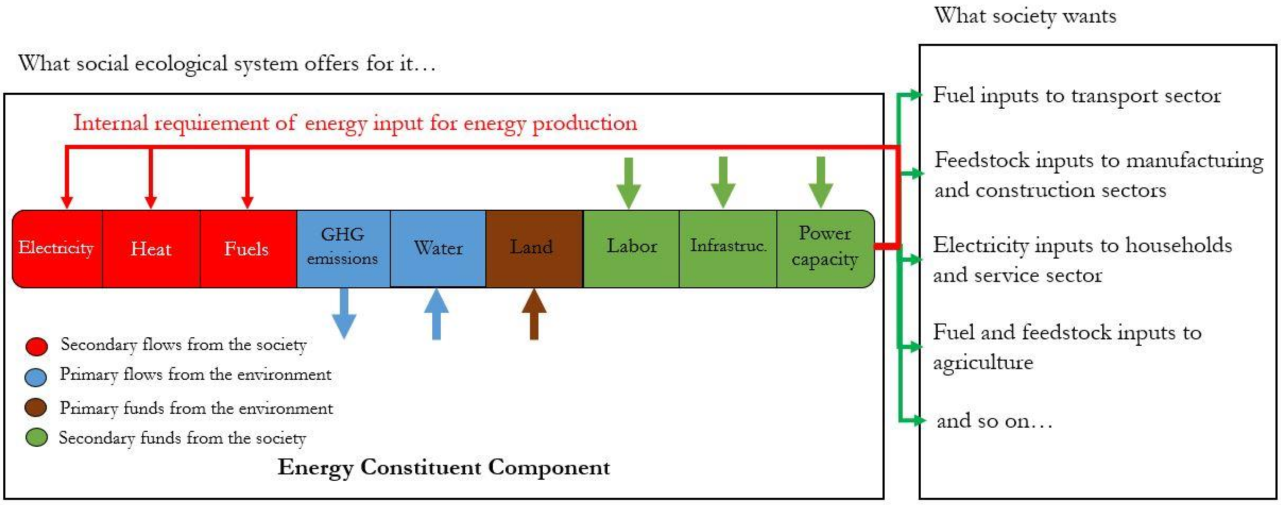

Fig. 3 Biophysical demand placed by a social-economic system on its constituent component "Energy" represented as metabolic processor (on the right), and biophysical pressures of the Energy processor on the social-ecological systems in which it is embedded (on the left). In metabolic processors, technological coefficients are bounded with societal and environmental pressures: primary flows and funds between society and environment are tracked in the bottom side – the Environmental Matrix in MuSIASEM jargon (Giampietro et al., 2021); on the top are represented secondary flows and funds supplied from inside the society – the End Use Matrix (Pérez-Sánchez et al., 2019; Velasco-Fernández et al., 2018). Scaling up metabolic processors across levels allows the integrated metabolic representation given in Fig. 4, specifically tailored for the oil sector. Adapted from (Renner, 2021).

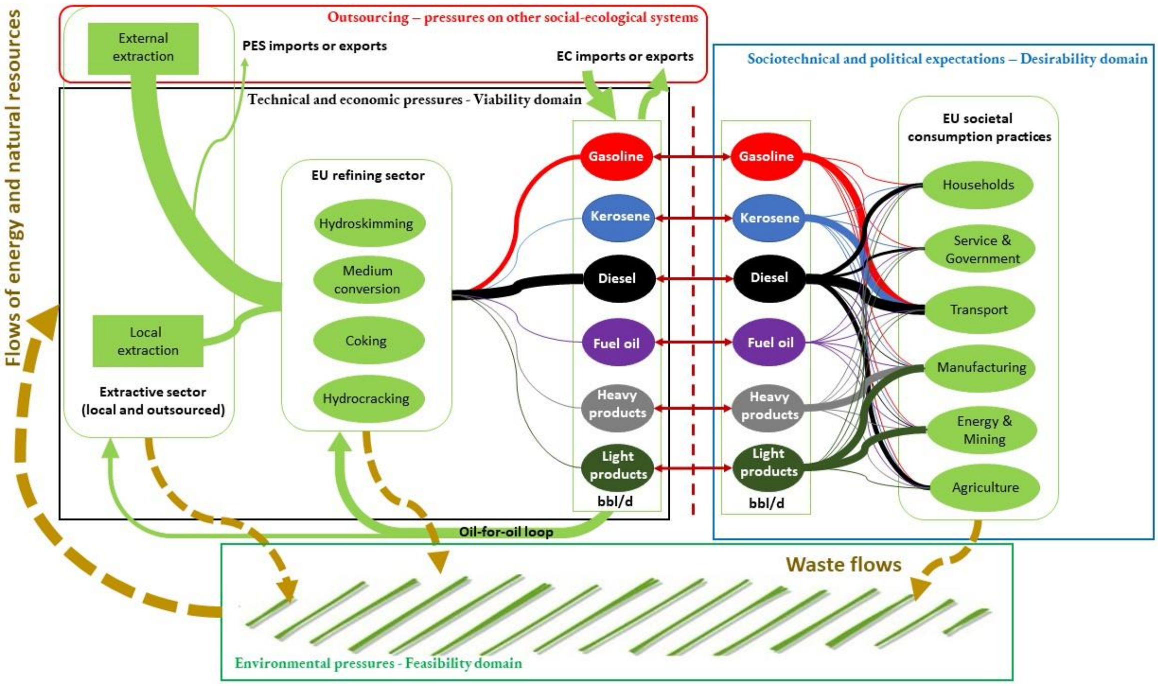

Fig. 4 Integrated metabolic representation of the oil sector. Boxes and ovals in light green represent metabolic processors associated with different functions (fuel production and

consumption) at different scales. Depending on the observation scale, each processor – a network niche – executes a specific function (it has a purpose) and expects specific functions to be executed from the others (beliefs about the whole system) to functionally and structurally reproduce the whole network

Specifically contextualizing this general discussion for the case of energy systems, and the role of energy inside social-ecological systems, first and foremost it should be said that energy availability, power availability and power density are determinant attributes that shape the physical infrastructures of the modern world and the complexity of the societal metabolism (Lotka, 1922; Odum and Hall, 1995; Odum and Odum, 1994; Smil, 2015). Therefore, the role of "energy" in modern societies is not just of a simple commodity, tradeable as any other good and perfectly interchangeable with other forms (for instance, fossil fuels vs renewables), but *"a [fundamental] ingredient of the social practices and complexes of practice of which societies are composed"* (Shove and Walker, 2014). According to Shove,

> *"The analysis of energy starts with and is inseparable from an analysis of the dynamics of social practice. Understanding energy is first and foremost a matter of understanding the sets of practice that are enacted, reproduced and transformed in any one society, and of understanding how material arrangements, including forms of energy, constitute dimensions of practice"* (Shove 2012).

Because "energy" is an open semantic category and not a substantial one – gasoline is energy for a car but not for horse – and we need a pre-analytical semantic structure, a 'grammar', in which we can implement and give meaning not to energy *per se* (that does not exist), but to specific energy transformations for contingent end uses. *"Energy analysis must always be contextualized. It can only be carried out in relational terms, i.e., by looking at the expected characteristics of the interaction of a special open dissipative system with a special context"* (Giampietro and Bukkens, 2022). From this perspective, an integrated representation (supply and consumption *simultaneously*) of energy systems becomes necessary to understand the purpose and meaning of the energy sector inside modern societies. We need to define pre-analytically what are the *primary energy sources* (PES, that is primary stocks and funds outside human control, e.g., coal, oil, wind, solar radiation) available in the admissible environment for the system to be transformed into *energy carriers* (EC, that is secondary flows under human control, e.g., gasoline, industrial heat, electricity) to satisfy the set of energy *end uses* (EU, e.g., mobility, heating, lighting) required to express desired social functions. The whole set of those energy transformations are embodied by contingent social practices. The energy sector is not an isolated primary sector that just produce disposable commodities, but an essential functional subsystem of the whole society, entangled with all the other sectors it contributes to reproduce – to a degree that is not reflected by its share of global GDP, since energy is the pre-condition upon which the more lucrative sectors (manufacturing, services) can build their activities. This underestimation depends on the fact that primary energy sources, making possible the metabolic pattern in the first place, are freely and generously generated by Nature, while the accounted costs for human societies regard only the exploitation processes.

Box. 1 Biological analogy between human and societal metabolism

A biological analogy can be useful to understand the complexities exposed in the previous paragraph. The energy sector – and the oil sector, as far as I am concerned in the rest of the present work – resembles human metabolism in many ways. Let's give the example of protein requirements for tissue growth. Like societal metabolism needs energy carriers, human metabolism needs, among other things, a specific amino acid spectrum to properly express its whole set of functions. The expected physiological requirement must be met with an adequate and varied food supply. If only one amino acid is lacking or not supplied in the proper amount, either in absolute quantity and in relation to the others – notably the case of lysine in grains or methionine in legumes – it becomes the limiting factor for the correct functioning of the whole metabolism. As a consequence, food intake needs to be manipulated, either in quantity (e.g., eating more food in general) or quality (e.g., eating relatively more meat or a balanced combination of grains and legumes) to match physiological requirement (demand) with external food intake (supply). This unescapable dynamic coupling sets constraints to the great variety of possible human diets: you can eat a vegetarian or carnivore diet, but thriving exclusively on green vegetables or grains, although possible for a short time, it is not feasible in the long term. Alternatively, you have to change the protein requirement (possible only to some degree), by slimming down or reducing muscle mass. When dealing with the oil metabolism, we find the same situation. Primary food items are represented by the different types of Primary Energy Sources and the different amino acids needed in the body are represented by different types of energy products (gasoline, diesel, lubricants). These are needed in the right quality and quantity to fuel the whole set of societal functions.

Modern societies express a specific set of functions – social practices – that requires an adequate supply of a variety oil products, e.g., gasoline and kerosene for motorized transport, petrochemical feedstocks and heavy distillates for industry, asphalts for roads and so on. The overall combination of the energy carriers supplied must match the overall requirements in the end uses, i.e., the different uses of fossil energy carriers across the various activities of the society (industrial machinery, buses, home appliances) translates into the definition of specific requirements of energy carriers (gasoline, diesel, electricity). In order to match the demand with an adequate supply, the energy sector uses a mix of sequential pathways, represented by a chain of functional units semantically identified by “extraction → transport → refinery → distribution” levels (in the case of oil sector). As a matter of fact, petroleum is extracted worldwide in different forms – light and heavy gravity, onshore or offshore, conventional extraction technology or fracking, and so on – and transformed into a relatively small and homogeneous array of desirable useful products – gasoline, diesel, kerosene, fuel oil, coke, light and heavy products. Depending on the set of geological-environmental constraints - e.g., types of oil fields, land and water available –, techno-economic capacities and contingent environmental pressures – e.g., technology, capital, labor, net water consumption, CO_2 emissions – there is a restricted space of feasible and viable sequential pathways that can produce a set of possible product slates.

Once established the desired socio-economic structure expressing different typologies of end uses, we can draw the requirement of oil products. Then, only specific combinations of sequential pathways will be able to match the required supply and generate a stable metabolic state. Each possible metabolic state would be characterized by specific biophysical, economic and environmental pressures (density and intensity of flows), associated with metabolic processors aggregated at different scale of analysis – at the level of isolated processes, sequential pathways, entire functional subsystems, whole oil sector. As for human metabolism, the coherence between the oil products required and supplied must be obtained. If it is not possible to generate a feasible combination of supply pathways to fit the required profile of oil products over time, developmental changes emerge to re-establish the required structural coupling. This can happen on the supply side, by adjusting the combination of the sequential pathways used in production and/or expanding the set of primary energy sources exploited by the energy sector. This means choosing among a new set of feasible sequential pathways – analogous to changing diet to get the required aminoacidic spectrum. In alternative, the set of end uses on the consumption side can be transformed, changing the material and formal arrangements, and the agents expressing social practices – e.g., sharing public cars instead of private ones for private urban mobility, rationalizing energy products or prioritize one economic sector over another. Both solutions will change the identity of the original metabolic pattern. This entails that if we want to explore the constraints that the oil sector imposes on the development of social-ecological systems, we need to develop an integrated supply-consumption representation of the whole oil metabolism. For that, the relational framework is crucial because it considers the whole functional organization: supply structures are meaningful only in relation to societal consumption practices, and viceversa. As Giampietro and Bukkens stated it clearly (2022), "*to analyze the performance of energy transformations within dissipative structures it is essential to adopt the concept of end-uses.*"[23]

The conceptualization I have been depicting above, of human societies as relational networks of social practices, gives us the possibility to dismantle the second important dichotomy of the modern predicament, embedded in current sustainability narratives: the one between Society and Technology. In this view, the social dynamic is seen as separate from technological development: the social is considered the immutable background where technological innovations are deployed by firms, governments, institutions and individual agents to achieve desired purposes. Policies that push for large-scale transitions to low carbon economies based on electric vehicles and renewable energy, along with policies advocating for more energy efficiency and biofuels, are crystal clear examples of policies based on that separation thinking (Di Felice et al., 2021; Giampietro and Mayumi, 2009; Lund and Mathiesen, 2009; Mathiesen et al., 2015). Those green narratives are all flawed by the Cartesian abstract assumption of *ceteris paribus* conditions: technology changes, while all other socio-economic and ecological aspects remain constants. Put it in another way, the aim of these policies is to change the material and formal arrangements of the energy production practices, while maintaining constant socio-economic agents – i.e., firms and governments through

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[23] Integrating set of end uses into modelling representation is problematic using IAMs and LCAs. IAMs usually model end uses as "demand", i.e., GDP growth and/or increasing energy requirements. LCAs completely disregard the functional description, since their focus is on object/process and the aim is usually to compare different processes used for to achieve the same task

market mechanisms – and the societal functions – i.e., respective end uses[24]. However, this approach is problematic. The dichotomy between Society and Technology leads to the idea, among others, that energy supply and consumption can be addressed exogenously and separately. On the contrary, they are unavoidably entangled into a complex multi-scale network of social practices inside society. In fact, it is common knowledge that, whenever a policy induces a local change in one part of the system, not only local but systemic adjustments take place, because of multi-scale "side effects" of the introduced measures – a phenomenon known as Jevons Paradox (Giampietro and Mayumi, 2018; Polimeni et al., 2012). In contrast to the *ceteris paribus* assumption, according to practice theory, the social sphere and technology co-evolve, establishing complex relations over time that affect the "space of life" – the "horizon of intelligibility"– for humans living in those systems (Schatzki, 2010a). The material and technical aspects shape, and at the same time are shaped by, cultural categories and societal functions that every society specifically develops over time, defining its own metabolic identity. For this reason, the process of transition to low carbon societies cannot be addressed only focusing on the substitution of individual technologies or the attempt to change individuals' behaviors. The modernist settlement is a conceptual artifact that undermines serious sustainability assessments and real transformation of social-ecological systems.

2.4 Development and senescence of social-ecological systems

Following the framework proposed by Ulanowicz in theoretical ecology (Ulanowicz, 1997, 1986), societal metabolism is composed of what we can label, from a biophysical standpoint, as *productive* and *dissipative* sectors. *Productive* sectors, *hypercyclic* compartments in Ulanowicz jargon, are the constituent components of the economy that provide a surplus of biophysical flows (fuels, electricity, raw materials, food, etc.), net of their internal consumption for maintenance and repairing needs. The hypercyclic process refers to a process of

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[24] Modern energy supply systems and consumption practices have been co-evolving in time for centuries now. If the free market is the best tool known to humankind to efficiently allocate resources over large social-economic systems (as neoliberal economists claim), Western societal metabolism should be in the best situation possible to express and empower the most efficient and productive set of social practices. It happens to be the case that, for the social practices currently expressed (and likely desired), fossil energy is the best primary source from a market perspective. That is exactly the reason why we are confronting sustainability troubles, hence more efficiency ("more of the same", we have been improving efficiency forever) is unlikely to address sustainability concerns. On the other hand, pushing a green transition through manipulation of the markets (subsidies to renewables, carbon tax and so on), without addressing changes in social practices, should be problematic to justify from a neoliberal perspective, because it means to question the optimal allocation of resource established by financial markets.

autocatalysis in which biophysical flows are consumed in the exploitation process of primary sources, to produce a net supply of biophysical flows. Agriculture and the energy sector are clear examples: they produce food and energy carriers in excess to what they consume internally – e.g., for the energy sector, to drill crude oil, transport, refine and distribute it to final users; for agriculture, to feed animals and farmers or to reproduce seeds – and so they provide feed and fuels for the rest of society. They operate at the interface between the environment and the social-economic system. *Dissipative* sectors are the constituent components that metabolize secondary flows, made available by the productive sectors, to express societal functions. The household sector reproduces humans, the service and government sectors reproduce institutions and administration, manufacturing and construction sectors reproduce the power capacity associated with machines, the built environment and the material infrastructures. They use the secondary flows metabolized in the first place by productive sectors as production factors. Thus, they operate internally to the social-economic system: manufacturing, service and transport sectors, households cannot directly use crude oil or wind or cows, but they need productive sectors to transform those primary sources into useful inputs. Therefore, a network of forced relations emerges between the whole set of constituent components, representing the impredicative material and functional entailments that characterize the societal metabolism of modern societies. The purpose of each sector is to make the others functioning over time: flows of food and energy carriers are simultaneously the outputs of the productive sectors and the necessary inputs for both the dissipative and productive ones, without which they cannot operate; at the same time, the outputs of dissipative sectors provide control over the whole society. They represent a metabolic network expressing group autocatalysis.

"In modern societies, the final causes of dissipative sectors map to the efficient causes of each other and to the various hypercyclic sectors (i.e., productive., ed.) of the economy. The dissipative sectors provide a system of control for the hypercyclic sectors. The final cause of the hypercyclic sectors, on the other hand, is more and more to provide exosomatic flows of biophysical material to dissipative sectors. [...] ***It should be clear that the set of hypercyclic sectors, in their provisioning of material flows to dissipative sectors, present a biophysical constraint on each other and on the dissipative sectors*** *(bold added)."* (Renner, 2021).

Textile factories produce clothes; that are used to keep humans warm, so they can work in the service sector and regulate the transactions needed to operate textile industries; they eat food farmed by the agriculture sector; burn diesel to operate machinery assembled by other mechanical industries; and so on, and so forth. Those relations are impredicative because the direction of causality cannot be substantially defined. A simple direction of causality can be defined only in relation to a pre-analytical choice of contingent contexts, analytical goals and timescales: for instance, on a short timescale, the energy sector provides fuels to manufacturing, hence the former is the 'efficient cause' of the latter. However, on a longer timescale, manufacturing provides machineries to extract and refine fossil fuels, hence it is the efficient cause of the energy sector. In other words, we have to recall the wisdom of Georgescu-Roegen, described as *"the economy does not produce goods and services but rather reproduces the fund elements producing and consuming goods and services to guarantee adaptability and a desirable state"* (Giampietro and Pastore, 1999, p.438). This statement brilliantly resumes the essence of the bioeconomic perspective about the nature of the economic process. This entails also that social practices (and policies to change them) should be considered in relation to the role they play in productive or dissipative sectors.

According to Georgescu-Roegen's *flow-fund model* (Georgescu-Roegen, 1971), *flows* are entities that change their identity during the chosen analytical timeframe. They become something else between the beginning and the end of the assessment, e.g., gasoline is burn for motorized mobility, electricity is consumed for lighting, food is fed to humans. Funds, on the other hand, maintain their identity during the analytical timeframe and represent the agents that metabolize flows. Machinery, power plants, rigs, refineries (i.e., power capacity, available MW), human labor (i.e., the available number of hours) "survive their use", at least during the time relevant for the assessment, and use flows (e.g., energy carriers) to express some function at a higher level – within the social practice in which they are used as biophysical production factors (e.g., oil extraction and refining, manufacturing, electricity transformation). Funds represent what the system is materially made of. Furthermore, back to the previous statement by Georgescu-Roegen and keeping in mind the above introduced conceptual distinction between flows and funds, we observe that *"we are what we eat"*: flows are partially embodied into funds on larger time scales (Diaz-Maurin, 2016). Steel factories burn coke to produce steel. Some of the energy required in the production process is dissipated, but some is embodied in the chemical structure of the steel itself. Energy is thus embodied into organized matter. That steel is then used to build up other infrastructures, that can be seen as higher scale embodiments of energy. Eventually, cities and the whole human environment can be understood as natural flows embodied in organized artificial structures. As a consequence, for proper sustainability assessment (that by definition unfold over large time scales), we need to be aware of the "age" of the social-ecological system: it is not only relevant how many flows of food or energy carriers societies are producing each year; equally important is the distribution of funds across the constituent components and the 'metabolic rates' of food, material and energy flows metabolized in relation to the size of those constituent components. This implies that specific demographic structures and/or technical capitalizations across social-economic sectors reflect the history of the metabolic system and its evolutionary trajectory Those factors determine the bundles of social practices that emerge from the social-economic development over time, that in turn determine the material standard of living of modern societies (more on this point in Chapter 3).

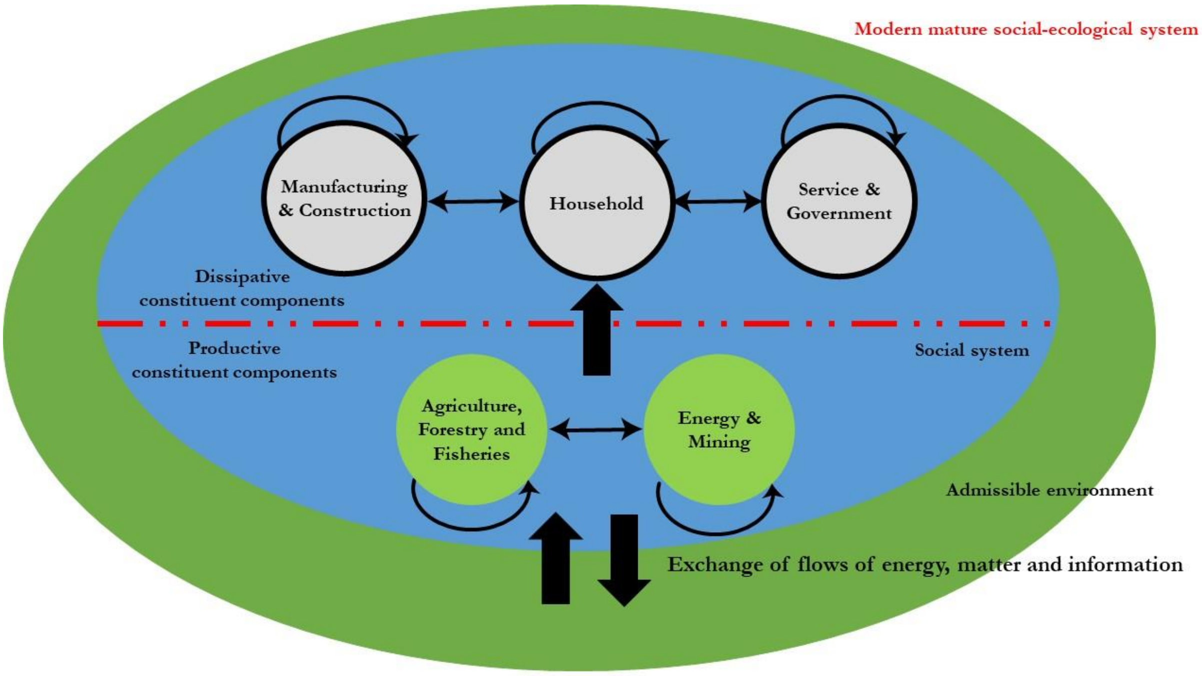

Fig. 5a Illustrative representation of a modern ***mature*** *social-ecological system. On top are represented dissipative constituent components – 'Household', 'Service & Government' and 'Manufacturing & Construction' –; at the bottom, the productive ones – 'Agriculture, Forestry & Fisheries', 'Energy & Mining. The size of the social-economic funds and the production pace of biophysical flows required by the social system are compatible with the biophysical capacity of the*

ecological funds in the admissible environment

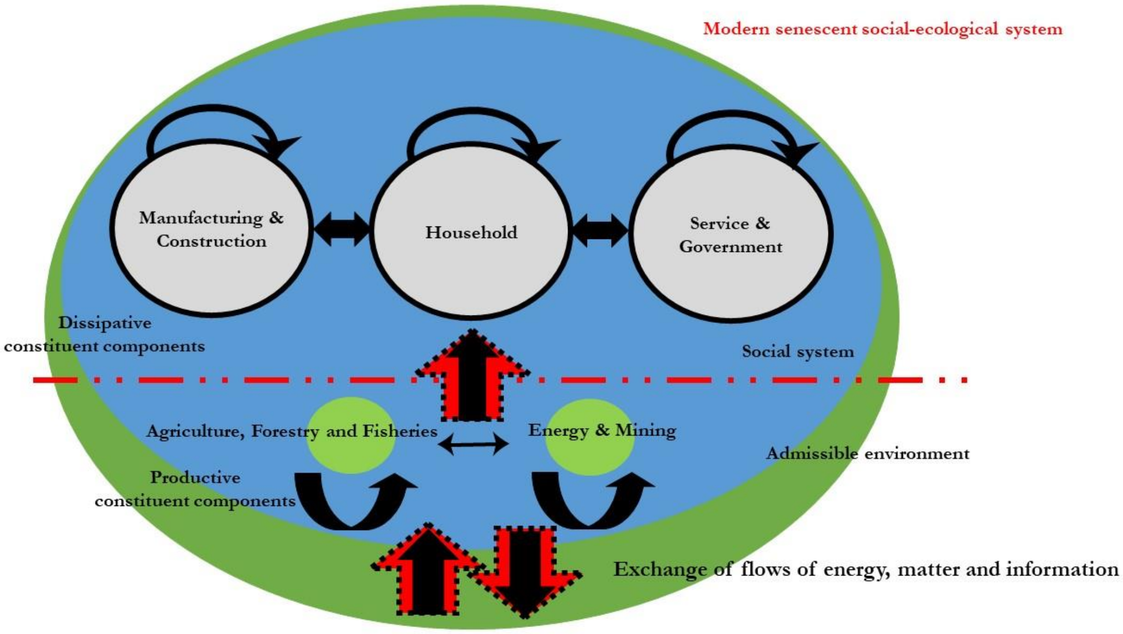

Fig. 5b Illustrative representation of a modern ***senescent*** *social-ecological system. The size of the social-economic funds and the production pace of biophysical flows required by the social system are incompatible with biophysical capacity of the ecological funds in the admissible environment. The dissipative sectors are hypertrophic, requiring biophysical flows at a power level too high (red arrow with black dotted contour line inside the blue oval) relative to the production capacity of productive sectors (black arrow inside the red arrow). At the same time, the internal biophysical requirement of productive sectors increased (thicker self-referent arrows at the bottom). The combination of these two factors exacerbates the pressures on the admissible environment that cannot be buffered by ecological funds (mismatch between available supply/sink capacity and required supply/sink capacity – black arrows inside the red arrows at the bottom). Therefore, the productive sectors shrink in size and metabolic activity due to the process of senescence, leading to an unstable (or better, metastable) configuration of the social-ecological system, depending either on imports or depletion of internal buffers, that need to change (in either adaptive or destructive ways)*

Concisely summarizing the conceptualization introduced above, it is the flow of energy throughout complex metabolic systems that generates complexity. The set of social-economic funds – technical and human assets using an economics jargon – determine the power level at which the metabolic dissipation of energy occurs. However, the level of metabolic dissipation is necessarily constrained by the regeneration pace and the size of ecological funds: available land, aquifers, forests, livestock, etc. Ecological funds have to provide the primary flows needed for the complexification of human societies, either in a renewable way – if the exploitation pace is compatible with their capacity to regenerate (flow-fund exploitation) – or in a non-renewable way – if the exploitation pace is higher than their capacity to regenerate (stock-flow exploitation), ultimately depleting the ecological fund. Here it is where fossil fuels broke the natural constraints: they provided concentrated and easy to extract energy from depletable fossil stocks. Humans did not need to wait for natural cycles to provide the resources they need; they just had to tap into geological reservoirs and mines, accumulated over millions of years, at the rate determined by the available technology – at least for the initial, immature and advantageous phase of exploitation – and collect how much they need in the form of energy carriers to boost industrial and agricultural production. The better the technology, the larger the energy that flows through the system, the more the trophic network of the system grows in size and connectivity, i.e., *ascendency* (Ulanowicz, 1997, 1986).

“One way of depicting ascendency is to regard it as "organized power", because the index represents the magnitude of the power that is flowing within the system towards particular ends, as distinct from power that is dissipated naturally. Almost half a century ago, Alfred J. Lotka (1922) suggested that a system's capacity to prevail in evolution was related to its ability to capture useful power. Ascendency can thus be regarded as a refinement of Lotka's supposition, that also takes into account how power is actually being channeled within a system.” (Edited from Wikipedia).

However, the building up of ascendency in time is not homogeneous throughout the whole social-ecological system. It can be empirically observed that wealthy societies progressively invest more flows and accumulate more funds into dissipative sectors. Rostow noted this dynamic back in the ‘50s and proposed his backbone theory of the stages of economic growth (Rostow, 1960). The workforce in agriculture must progressively shrink if an economy wants to be richer, while the majority of GDP and jobs need to be created in manufacturing (between 20-30% of the total workforce) and service (about 70%). The same holds true for power capacity: today in the Western world most of the energy is consumed, and therefore most of CO_2 emissions are generated, in the dissipative sectors (International Energy Agency (IEA), 2021). Elaborating on the same line, Matutinović et al., (2016) argue that we are now in the mature stage of capitalism, leaving behind the ‘immature’ phase of exponential economic growth and entering one of mature plateau. Recalling the biological analogy used earlier, only immature biological systems have the potential for accelerated growth. When considering metabolic characteristics of children, for example, their size is small, but their energy throughput per unit of mass is higher compared to adults. This entails that they recover faster from stress and grow rapidly. Later in life, the energy throughput declines, but still remaining sufficient to adequately recover from perturbations, the size and organization of the system reaches their final form (the adult human organism) and greater stability is guaranteed. Finally, the metabolism enters the senescent stage, when the energy throughput per unit of mass gradually drops below functional requirements. The absolute energy and matter throughputs are still high, but declining, and the internal stability is hindered by the typical senile inflexibility due to the accumulated burden of complexity (Salthe, 2001).

"It is only in what I would call the immature stage of the cell cycle that cycling cells can be regulated by outside influences (Pardee, 1989), just as it is only in diastole that the muscle cell communicates with its surroundings. ***Senescent systems are increasingly involved only in the private self they have organized*** *(bold added)".* (Salthe, 1993, p.24).

Generally speaking, we can say that cheap fossil energy and 'growth social practices and institutions' mark the immature stage of the development of social-ecological systems. Agriculture, energy and mining, manufacturing and construction sectors are quickly capitalized and their productivity grows at fast pace. People move from rural areas to cities (urbanization) and start the process of industrialization. The demographic structure has a sharp pyramidal shape, with high availability of workforce: young people on average spend little time in education and start to work early; the retirement overhead is light. Maximizing the profitable use of fossil fuels in key industrial infrastructures is all you need to fuel the modernization process of strongly homeorhetic immature systems. At the beginning, the world was still 'empty' (Daly, 2005), hence the integrity of ecological funds and quality of fossil stocks in the admissible environment was still high. That makes the production of biophysical flows used in the economic process easy and cheap. Ascendency was low. The mature phase kicks in when the growth pace of the ascendency of dissipative sectors overcomes that of productive sectors. The social-economic system progressively moves towards its final configuration: allocation of human time and power capacity, distribution of GDP across economic sectors and geographical regions (to assure the best economic efficiency), energy consumption per capita and level of productivity stabilize around a typical state of equilibrium

(Matutinović et al., 2016). The construction of the welfare state and debt accumulation we have been witnessing unfolding approximately since the ‘80s and exploding in the first of the third millennium are good examples of the maturity of Western economies. Established social practices and institutions are still legitimate and (partly) adequate to the functioning and reproduction of the societal metabolism: small incremental changes manage to comply with the developmental trajectory, adapting and reinforcing the societal identity. The quality of the admissible environment is degrading, but more technological innovation is able to partially buffer negative effects on both the resource and sink sides – e.g., technologies to improve chemical pollution and waste treatment, better extraction and refining techniques, greater efficiency in conversion devices, such as engines or combined power plants. Senescence begins when the ascendency of the productive sectors starts to decline. The senescent stage can be seen as a process of “progressive freezing” (Zotin, 1970): the developmental process becomes self-limiting when the biophysical cost of maintaining and expanding societal ascendency is too high in relation to the exploitation pace of natural gradients. Back to the previous quote by Renner, in this phase the performance of productive sectors determines a biophysical constraint on the whole societal metabolism. Increasing production performance, by building up funds in productive sectors over time, has been providing biophysical flows at an increasingly power level and size, able to maintain, and further expand, the progressively more expensive dissipative sectors. The accumulation of funds in the dissipative sectors improves the adaptability, flexibility and long-term sustainability of the whole social-ecological system, giving a clear evolutionistic advantage and a better standard of living. However, this virtuous circle can be established and sustained only if natural gradients are ever expanding too, since the admissible environment is the ultimate source of all flows metabolized by social-ecological systems, providing the supply and sink capacity necessary for the stabilization of the metabolic pattern. Due to the first principle of thermodynamic, humans cannot create natural gradients out of nothing; even worse, due to the second principle of thermodynamics, extraction of natural resources is subjected to diminishing returns (Hall and Klitgaard, 2001), while human societies need increasing returns on production to expand wealth (Reinert, 2007). Furthermore, human population is also a natural gradient, subject to degradation over time. During the developmental process, the share of young, active and healthy population shrinks. Fertility rates become very low and less than mortality rates; therefore, population growth rates become negative. The demographic structure shifts from a pyramid-shape, typical of immature systems, to the *constrictive* pyramid-shape, a pyramid with a narrow base known as *urn* or *bulb* shape, reflecting the challenge of an aging population and a high dependency of elderly people in wealthy, highly educated countries, up to the *kite* shape, typical of senescent systems (Saroha, 2018). Therefore, in the long run, the burden of complexity in the dissipative sectors becomes unbearable, and the system gets senescent and ready for renewal. The effect of external limits can be hidden for a while by relying on imports and debts. In this way, it is possible to externalize biophysical pressures on other social-ecological systems, while generating added value in the financial sector. However, when enlarging the scale of operation to reach the planetary scale, the globalized economy becomes a zero-sum game. In this situation, both internal (shortage of human activity) and external limits (shortage of primary and secondary flows) to the metabolic pattern of post-industrial societies become evident – this will be discussed in detail in the following chapters.

Following Prigogine's conceptualization of becoming systems (Prigogine, 1980), we observe that the above depicted developmental trajectory is irreversible. Indeed, the very definition of development is "*predictable irreversible change"* (Salthe, 2003). However, the development of social-ecological systems is not to be viewed as a deterministic process, but for sure it sets the ultimate constraints to what the social-ecological system might eventually become. That is, it expresses a potential. After all, if we agree that social-ecological systems are alive, no living system grows indefinitely in nature, and all living systems eventually must die. However, it should be noted that human systems are reflexive – meaning that they are aware of themselves, hence able to influence their own developmental path by creating their meanings, purposes, beliefs, and anticipatory models of action. This entails that whether and when the system will eventually reach its ultimate potential depends on the choice of adaptive social and cultural practices; that is, it depends on the actual evolution of the system – the contingent, path-dependent, non-predictable trajectory of individuation (change), *"irreversible accumulation of historical information"* (Salthe, 2003). The evolution is the actualization of the developmental potential, and it is the tangible, observable dynamic unfolding in time in the world. Mockingly enough, the same process of complexification that get us wealthy in the first place, that allows human societies to expand and individuals to enrich their "life possibilities", is the same that breaks down the stability of the societal metabolism. As stated by Schumpeter, *capitalism will be destroyed by its own success*[25].

At the present historical moment, ascendency of dissipative sectors at the global level is still growing, fueled by globalization, the Chinese industrialization over the past three decades and the quick growth of those nations belonging to the poorest parts of the planet. This implies higher biophysical requirements on the production pace of flows that have to be supplied by social-economic and ecological funds of global productive sectors to construct, maintain and repair that added complexity. Something that translates into an increasing pressure on the environment. This combination of stressors, both on the status quo among social systems and on the health of ecosystems, has started a process of destabilization of the network of interactions between countries, and between the social and ecological spheres. In the following chapters, I will provide insights to show that: (i) despite the largest human population in history, we may run into a shortage of human time to invest appropriately in social metabolism (Chapter 2); (ii) despite continuous technological innovation and climate commitments, the extraction and refining of each barrel of oil will emit more CO_2 over the next decades (Chapter 3); and (iii) despite huge oil reserves, we could run into shortages of specific oil products (Chapter 4). The oil sector will suck more resources from the societal metabolism, leaving less for the other sectors. Not only that, its output of oil products will gradually generate mismatches in relation to societal requirements. This combination may lead to heavier environmental pressures, posing significant threats to the feasibility of the global economy in relation to external (environmental and climate) conditions (Chapter 3); and to the viability of internal, social-economic relations between the constituent components of society (Chapter 2 and 4). The assessments provided in the next chapters do not want by any means provide a definitive proof of the senescence of Western capitalism, nor are to be considered accurate and complete assessments encompassing all the analytical dimensions relevant for a holistic description to predict the developmental trajectory of global

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[25] *"Schumpeter believed that the enormous productivity of capitalism would easily churn out the goods needed for basic consumption, freeing up labor from the fields and factories to enjoy a leisurely life in the new modern intellectual class of academics, journalists and bureaucrats. This class would be so separated and removed from the actual process of entrepreneurship and production, they would turn against the very philosophical foundations and institutions of the economic system that made their lives possible. Not understanding the roots of their own condition, they spend their daily efforts deliberately working to undermine the systems of private property, private contracting, decentralized decision-making, entrepreneurship and voluntary exchange. They condemn capitalism as a foregone conclusion and view any pro-capitalism position as crazy and anti-social. […] In Schumpeter's view, the continual flow of product innovation becomes something people take for granted, entrenched in the routine operation of large firms. Progress is no longer so visibly attributed to innovative entrepreneurial individuals"* (Sobel, 2021). *Schumpeter's argument differs from the one presented in this thesis, yet the two views are compatible.*

economy. As mentioned earlier, when dealing with the evolutionary trajectory of complex adaptive systems it is impossible to predict the future, due to the irreducible uncertainty in the sustainability analysis of social-ecological systems. Instead, the reader should understand the content of following chapters as methodological applications, aimed at developing more effective scientific tools, hopefully useful to deal with the ‘governance in complexity’ more than ‘governance of complexity’. At best, they can provide clues to properly orient us to the challenges ahead in the near future. Contextualized within the relational *weltanschauung*, it is my hope that those insights will generate awareness of the organizational unity of the metabolism of modern societies.

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Chapter 3. The profile of time allocation in the metabolic pattern of society: an internal biophysical limit to economic growth

This chapter is the transcript of the paper: "Manfroni, M., Velasco-Fernández, R., Pérez-Sánchez, L., Bukkens, S.G.F., Giampietro, M., 2021. The profile of time allocation in the metabolic pattern of society: An internal biophysical limit to economic growth. Ecol. Econ. 190, 107183. https://doi.org/10.1016/j.ecolecon.2021.107183", with only minimal modifications. The language and the structure used reflects the fact that this chapter was conceived as a stand-alone paper to be published in the scientific literature.

1. Introduction to the issue

The famous quote of Kenneth Boulding (United States-Congress- House, 1973) "anyone who believes exponential growth can go on forever in a finite world is either a madman or an economist" typifies current discussions about the (un)sustainability of continuous economic growth. These discussions are systemically concerned with an expected shortage of external resources, i.e., the Malthusian trap. Indeed, the limits to growth (Meadows et al., 1972) are currently understood to be exclusively external. Several methods have been used to quantify these external limits, both on the supply side – e.g. the availability of net primary productivity (Vitousek et al., 1997a, 1997b), water (Hoekstra, 2017), land (Giljum et al., 2013), materials (Wiedmann et al., 2015), oil (Kerr, 2011) and other fossil fuels (Heinberg, 2007) – and on the sink side – e.g., GHG emissions in the atmosphere (Pachauri and Meyer, 2014), pollution and destruction of habitats and biodiversity (Brondizio et al., 2019). In all these studies, society is invariably seen as a black box and the environment as the factor limiting its expansion by constraining the availability of resources and environmental services. Not surprisingly, policymakers are obsessed with technical innovations and business models that are expected to decouple economic growth from natural resource requirements. The bio-economy, circular economy, and net-zero carbon transitions are examples par excellence (Giampietro, 2019; Giampietro and Funtowicz, 2020; Parrique et al., 2019).

However, economic growth can also be limited by *internal biophysical* constraints. Current analyses of sustainability tend to overlook the existence of these internal constraints because they are observable only by looking at the social practices taking place inside the black box. This neglect is surprising because, for example, in the field of human metabolism it is well known that growth is not only determined by food (external factor). Age (internal factor) also limits the growth of individuals by changing the characteristics of the metabolic system. This suggests that the analysis of the growth of any metabolic system should address both external and internal constraints. In this paper, we seek to fill this gap. We analyze the factors that determine the profile of human time allocation in contemporary society and explain how forced relations between time and energy allocation can generate a phenomenon of senescence in the metabolic pattern. We illustrate our arguments with practical examples.

The paper is organized as follows: Section 2 summarizes past research relevant for the semantic framing of our analysis. Section 3 presents the conceptual framework for analyzing the impredicative constraints between the profile of human time allocation and the organization of energy end-uses (metabolic pattern) inside society. Section 4 illustrates the relevance of the results with three practical examples: a comparison of time allocation and labor productivity between the EU and China, the role of trade in easing internal biophysical constraints, and the effects of immigration. Section 5 concludes.

2. The profile of human activity as a limiting factor of growth

Spanning several scientific disciplines, the literature on societal metabolism and human time allocation is abundant. In this section, we exclusively focus on previous research relevant for the semantic framing of our analysis. For a broader overview of the literature on societal metabolism, see (Gerber and Scheidel, 2018; Giampietro et al., 2012; Haberl and Fisher-Kowalski, 2007; Manuel and Toledo, 2014). For previous research on social practices and human time allocation in the field of ecological economics, see (Druckman et al., 2012; Jalas and Juntunen, 2015; Røpke, 2009; Schatzki, 2010; Shove et al., 2012; Smetschka et al., 2019; Yu et al., 2020). Other entry points for the analysis of human time allocation have been explored (e.g., gender, race, class) by, among others, (Carrasco and Mayordomo, 2005; Fisher and Robinson, 2011; Folbre and Bittman, 2004).

As early as 1941, Zipf (1941) analyzed in a holistic way the concept of human time allocation at the level of society. He was the first to suggest that the diversity of socio-economic activities is a key factor in shaping the emergent property of a ‘bio-social organism’. Reflecting on the roots of the Great Depression that hit the USA from 1929-39, Zipf associated the onset of the economic crisis with the saturation of its ‘consumptive capacity’. He pointed at the insurgence of an internal constraint to economic growth determined by the existing profile of human time allocation. For the US economy to continue growing, Zipf argued that its existing economic structure had to give way to a radically new one, in which more hours could be allocated to consumption:

“.. in 1929 the United States discovered a new "raw material": leisure time, which in a way is just as much a "raw material" as coal, oil, steel or anything else, because for many types of human activity, leisure time is an essential prerequisite [...], any change in kind or amount of goods or of processes within a social-economy will necessitate a restriation within a social-economy itself" (Zipf, 1941, p.324).

With the term ‘restriation’, Zipf intended a different pattern of allocation of human activity, matter and energy flows – that is to say, a new set of social practices inside and outside the paid-work sector – in order to generate a different pattern of societal organization and metabolism. Zipf’s insight is fundamental to our argument: in order for a society to produce more (economic growth), it has to consume more. When a society has access to new resources, it has to get out of the structural lock-in and move human activity from the primary sectors to services and final consumption.

Along this same line, Meier (writing in 1959) proposed that the enlargement of the option space of possible human activities represents an indicator of economic growth:

“Thus, if it can be shown that more people are choosing to use their time for a wider range of activities, one has as significant an indicator of socioeconomic growth as increased per capita income [...] A steady growth of per capita income over the long run does imply wider choice in time allocation: and the inverse is equally true” (Meier, 1959, p.29-30).

Indeed, an expansion of the diversity of social practices associated with modern life styles is a powerful driver for the creation of new labor roles, especially in the service sector. The continuous generation of new activities for consumers boosts the GDP. According to this rationale, economic growth is directly related to the diversity of activities expressed. However, as the overall amount of human time at the level of society is given (8,760 hours/year per capita), a larger fraction of human activity invested in consumption and a concomitant larger demand for services is likely to entail a reduction of the workforce in the productive sectors (we have a zero-sum game at societal level in closed systems).

Cipolla (1978) confirmed the latter hypothesis through a historic analysis of structural changes of the economy. He used the percentage of the active population employed in agriculture as a proxy of the level of industrialization of societies between 1750 and 1950. The percentage was more than 40% at the beginning of the industrial revolution, between 21-40% during its expansion, and less than 20% in its consolidation phase (Cipolla, 1978). In developed countries, the active population employed in agriculture has dropped further, to less than 5%, and in most of them to even less than 2% (Arizpe et al., 2011; Giampietro, 1997). Thus, the dramatic reduction in the share of the workforce employed in agriculture provides a robust indicator for characterizing the evolutionary pattern of the industrial revolution, one of the most remarkable events in human history (Cipolla, 1978; Smil, 2017). The existence of this trajectory of structural change has been confirmed by the analysis provided by (Giampietro et al., 2012).

However, (Tainter, 1988) pointed out that a perpetual complexification of society can also be ‘too good a thing’. Too much growth of final consumption and services can lead to a collapse of the productive sectors, as was the case in the Roman Empire. Tainter documents several examples of past empires collapsing due to a systemic excessive complexification. The continuous swelling of the final consumption and service sector, associated with the reinforcement of the identity of the empire, ended up strangling the primary sectors of these economies (i.e., farmers and rural communities) through a continuous increase of taxation. At a certain point, farmers simply could not produce enough surplus for appropriation by the tertiary sector.

The idea of the existence of internal constraints to a perpetual complexification has also been explored in conceptual terms in the field of infodynamics – the study of the evolutionary patterns of complex adaptive systems – from the perspective of information theory and thermodynamics (for an overview, see (Salthe, 2003)). The phenomenon of senescence is here explained in terms of an information overload, i.e., a growing fraction of resources invested as overhead in the building of adaptive capacity leads to a progressive reduction of the internal investment in the primary productive sectors. Maturity is reached when the vast majority of available human activity is needed to control the process of self-organization in the consumptive or anabolic part of the metabolic process rather than to produce the inputs required by the productive or catabolic part of the metabolic process.

This mechanism has been neatly illustrated in theoretical ecology by (Ulanowicz, 1997, 1986) in his seminal work on the evolutionary pattern of ecosystems. The limits to ecosystem growth are determined by the relative sizes of the dissipative compartment (detritus feeders, herbivores and carnivores) providing control and the hypercyclic compartment (primary producers) generating a net surplus of resources for the system. In mature ecosystems, the dissipative compartment limits the activity of the compartment generating the surplus. The balance between the activity and the relative size of the dissipative (anabolic) and hypercyclic (catabolic) compartments is determined by the closure of nutrients in the ecosystems (the balance between what is produced and what is consumed internally).

In this paper, we frame the analysis of the phenomenon of senescence in the realm of human society and argue that post-industrial societies have outgrown the solution described by Zipf, and are approaching the situation described by Tainter. The time invested in the dissipative compartments of society (consumption and control) has passed from being "too little" to becoming "too much" to sustain economic growth. Post-industrial societies are therefore steadily heading toward senescence: the growing requirement of goods and services has to be produced by a continuously shrinking work force in the productive sectors. The approach presented in this paper is original in that we use Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) to establish a coherent representation of the entanglement between patterns of human time allocation and exosomatic[26] energy end-uses across the various structural and functional components of society.

3. The entailment between time allocation, energy metabolism and societal organization

The perspective of societal metabolism permits us to view a given profile of human time allocation as a specific combination of social practices both inside and outside the paid work sector within a given option space (Giampietro et al., 2012; Renner et al., 2021). This bundle of social practices is expressed simultaneously across different levels of societal organization and can only be 'observed' using an

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[26] Exosomatic means outside the body. Exosomatic energy metabolism refers to energy conversions by power sources outside the human body, but operated under human control, such as machine or animal power. Endosomatic means inside the body. Endosomatic energy metabolism refers to the conversions of food energy taking place inside the human body.

analytical framework that integrates the different factors shaping the social life. The idea that the stability of the metabolic pattern is determined by a dynamic equilibrium between the supply and the requirement of energy carriers (and material and technology) as well as human time, is at the core of the concept of metabolic pattern of social-ecological systems (Giampietro et al., 2013, 2012). Indeed, the entanglement between the time requirements in social practices inside and outside the paid work sector is exactly what generates an internal constraint, i.e., the biophysical opportunity cost of human time at the societal level.

To study the profile of human time allocation, we need a categorization of the functions expressed by the social practices inside and outside the paid work sector, as well as a characterization of the socio-economic and demographic structure (e.g., types and sizes of socio-economic sectors) in relation to the expression of these functions. The various functions and structures must then be associated with different typologies of energy end-uses. The quantity of exosomatic energy used per hour of human activity will depend on: (i) the nature of the task (function) to be expressed; and (ii) the technology and the power available to express the task. The coupling of the profile of allocation of human activity and that of exosomatic energy end-uses gives rise to the energy metabolic rates of the metabolic elements in society. More specifically, the energy metabolic rate of a structural or functional element is defined as the amount of exosomatic energy throughput in the element i (ET_i) divided by the hours of human activity in that element i (HA_i), according to the relation $EMR_i = ET_i/HA_i$ (measured in MJ/h).

Both the economic process and the demographic structure are described at the level of society, which is above the level at which we observe the agency of individuals. Hence, in the analysis of the societal metabolic pattern, individual choices are ‘invisible’. We can only discern patterns of time allocation describing social practices at the level of functional elements of society (average amounts over categories). Nonetheless, individual choices are important in that they shape the pattern. Individuals can decide whether or not to supply their time to certain jobs or how to invest their time outside of paid work. This is relevant for the stability of the metabolic pattern. In fact, in the paid work sector the activity of individuals is required for the realization of specific functions (associated with ‘jobs’ i.e., social practices inside the paid work sector), while outside the paid work sector it is essential for the reproduction of the agency of human beings. Thus, the allocation of human activity across the various compartments of society represents an expected pattern that has to be expressed by instances of structural types of citizens.

3.1 The time allocation pattern in society

Fig. 1 represents the taxonomy of human time allocation in relation to the societal organization in the form of a dendrogram. The Total Human Activity available in society (THA) – observed at level n – is limited and amounts to: “population size × 8760 h/y” (24 h/d × 365 d/y). If expressed per capita, the THA_n is simply 8,760 h/y. At the level *n-1*, we split the human activity between: (i) the hours allocated to social practices inside the paid work sector of the economy (‘job roles’) – indicated by the label ‘Paid Work’ (PW), and (ii) the hours allocated to social practices outside the paid work sector – indicated by the label ‘Societal Overhead’ (SO). The label ‘societal overhead’ reflects that this is the amount of human time society requires for making available the required net supply of human activity (hours of human time) for the paid work sector. Most post-industrial societies will manifest a time allocation pattern similar to that of Spain, shown in Fig. 6: less than 10% of the total human time is allocated to paid work, i.e., between 650–800 h per capita per year. Note that for each level of the dendrogram, the allocation of human activity to the selected set of categories must be mutually exclusive (time can only be accounted in one activity at the time) and exhaustive (all time must be accounted for), in order to provide closure in the accounting. Thus, at every level *i*, the following relation must be observed: $THA_i = [\sum HA_i]$.

A second split in the dendrogram, at level *n-2*, allows a more detailed analysis of the profile of time allocation (see Fig. 6), both for the societal overhead and the paid work sector. As regards the societal overhead (left side of Fig. 6), we distinguish between disposable time (DT) and non-disposable time (NDT). Disposable time refers to the activities carried out by people currently requiring nurture and care within the option space shaped by socio-cultural and economic constraints (such as income). Time allocation within this category is not strictly forced on individuals by their context, but at the same time it does not only depend on their ‘attitudes, behaviors or choices’ (Shove, 2010). Cultural traditions, income, education and the demographic characteristics of the household do affect the choices determining the formation of standardized typologies of social practices. The disposable time (DT) is further divided (at level *n-3*) into ‘household chores and commuting’ (R&M – Residential and Mobility) and ‘leisure, culture and study’ (LCS). Note that the former includes unpaid household work. As for the non-disposable time, this includes the physiological overhead of all individuals (PO) – i.e., sleeping and personal care – and the remaining time of the population Requiring Nurture and Care (RNC) (at level *n-3*). Note that the largest share of the available time (about 50% at societal level), goes in sleeping and personal care (PO). Note that in this taxonomy work is defined both inside (PW) and outside the paid work sector (R&M).

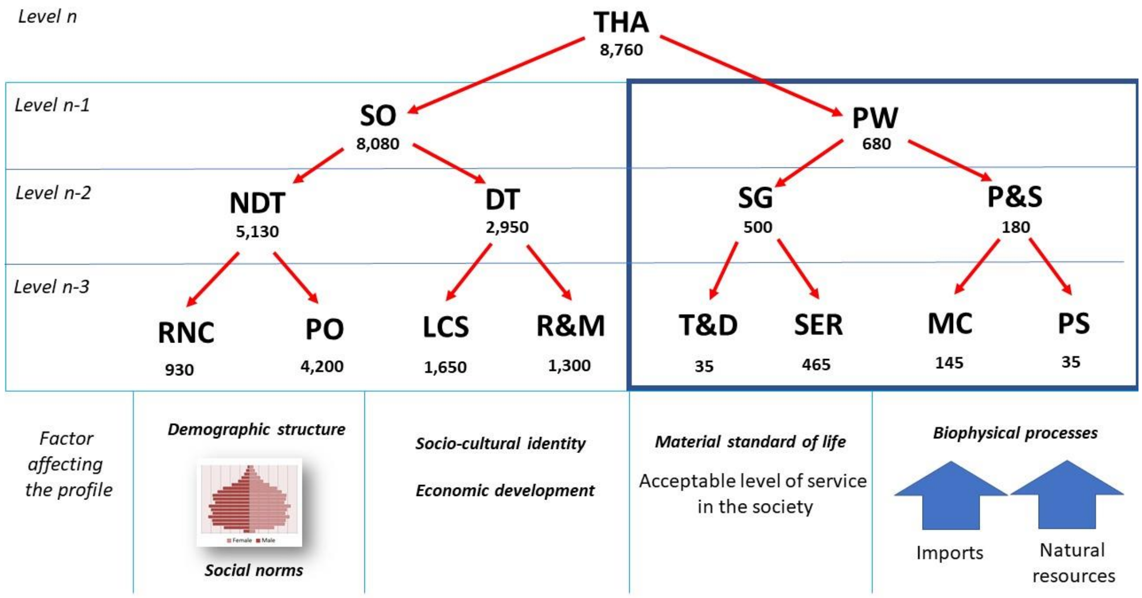

Fig. 6 Dendrogram characterizing the profile of time allocation (in h per capita per y) associated with the expression of a given metabolic pattern (Spain, year 2012). For abbreviations, see Box 2; for data sources and calculations see Appendix, section A2.

Box 2: List of acronyms

Acronym	Explanation
BEP	Bio-Economic Pressure: the amount of energy carriers consumed by society per hour of paid work in the primary and secondary sectors
DT	Disposable Time of the ‘population currently not requiring nurture and care’ (for more details, see Appendix, section A2)
EMR_i	‘Energy Metabolic Rate’: the exosomatic energy throughput per hour of human activity of the metabolic element i of society
ET_i	‘Energy Throughput’: the exosomatic energy metabolized by the metabolic element i of society
GDP	Gross Domestic Product
HA_i	Human Activity: time allocated to the metabolic element i of society
LCS	‘Leisure, Culture and Study’ (for more details, see Appendix,

	section A2)
MC	‘Manufacturing and Construction’, subcategory of Primary & Secondary sectors (P&S)
NDT	Non-Disposable Time – the combination of physiological overhead of the entire population and the time of population requiring nurture and care
P&S	‘Primary & Secondary’ sectors: comprehensive of economic activities with the purpose of producing goods.
PO	Physiological Overhead: personal care and sleeping
PS	Primary Sectors: agriculture, forestry, fisheries, mining and energy sectors, subsector of Primary & Secondary sectors (P&S)
PW	Paid Work: time spent on paid work
R&M	Residential & Mobility: household chores and commuting (for more details, see Appendix, section A2)
RNC	Time of the population Requiring Nurture and Care
SEH	Strength of the Exosomatic Hypercycle: the amount of energy carriers supplied to society per hour of paid work in the primary and secondary sectors
SER	Other services: subcategory of Service and Government sector (SG)
SG	Services and Government sector: comprehensive of all typologies of societal and economic services, administration and institutional activities
SO	Societal Overhead: the time spent outside paid work
T&D	Transport & Distribution: subcategory of Service and Government sector (SG)
TET	Total Energy Throughput: total exosomatic energy metabolized at the level of society on a year basis
THA	Total Human Activity available in society on a year basis

On the side of the paid work sector, we adopt the standard accounting categories used in statistics. In the example given in Fig. 6, we see that around 25% of the hours in paid work go to the ‘primary and secondary production sectors’ (P&S) and 75% to the ‘service and government sector’ (SG). At a lower level (*n-3*), the tertiary sector SG is subdivided into ‘transport and distribution’ (T&D) and ‘other services’ (SER), whereas the primary and secondary sectors are split into the secondary sector ‘manufacturing and construction’ (MC) and the primary sectors ‘agriculture, forestry and fisheries’ and ‘energy & mining’ (PS). Note that only 5% of the time allocated to paid work (less than 50 h per capita per year) is allocated to the primary sectors of the economy and about 19% (less than 200 h per capita per year) to the secondary sector.

While data on time allocation for the paid work sector is readily available from national and international statistics, this is not the case for the societal overhead. The time allocated to the sub-categories of societal overhead in Fig. 6 has been estimated from available data from surveys on time use. Classification, data sources and calculations are detailed in the Appendix, section A2. Time use in the informal economy (also known as shadow economy) has not been considered in Fig. 6.

Fig. 6 conveys an important (implicit) message: the overall profile of human time allocation is affected by four main factors (illustrated in the bottom row of the figure):

1. The demographic structure of the population – This factor determines the percentage of dependent population, i.e., the population under 15 years and over 65 years. For instance, in the example of Spain (Fig. 6), it is about 32% (Table 1).
2. The socio-cultural identity of society – This factor shapes the social practices outside the paid work sector and determines the participation of women in the formal economy, the, the size of the households, the accessibility of higher education, the legal working and retirement age, etc.
3. The level of economic development of society – This factor determines the demand for services in society. The expectations about a minimum standard of living defines a certain bio-economic pressure, i.e., the need for investing a certain fraction of the work force and energy carriers in the SG sector of society. This mechanism is explained in detail in the following section (section 3.2).

The boundary conditions – This factor determine the productivity of the biophysical processes taking place in the primary and secondary sectors. The boundary conditions reflect both: (a) the amount and the quality of the natural resources available for exploitation by the primary sectors (agriculture, energy and mining); and (b) the option of importing resources and goods. The latter option saves on the requirement of resources and the human activity needed for their exploitation.

Note that, within this analytical framework, numerical relations over the categories of time allocation are expressed on a per capita basis. This makes the population size an ‘invisible’ attribute. What matters in this set of relations is a change in any of the four factors listed above (demographic structure, socio-cultural identity, standard of living, boundary conditions). Indeed, with an increasing standard of living and life expectancy, less work hours are available in the market economy (less time in PW in Fig. 6), whereas more work hours are needed in the service sector (more time in SG) and more goods are consumed. This leads to a progressive shortage of labor in the productive sectors (less time in P&S). In such a situation, developed countries have only three options to avoid a stagnation in their economy: (i) (further) increasing the use of energy and machines to boost the labor productivity in the productive sectors, provided resources are available; (ii) externalizing the production of goods by exploiting the (temporary) availability of labor surplus in other countries, thus overcoming internal shortages of labor in the primary and secondary sectors; and (iii) using immigrant workers to (temporary) increase the relative size of the workforce (compared to the dependent population) in society.

These three options are further analyzed in the form of examples in section 4. The conceptual framework explaining the mechanisms underlying these three solutions is described in the following sub-section (section 3.2).

3.2 Entanglement of human time and energy allocation patterns

The previous section (section 3.1) focused on the taxonomy of human time allocation according to functional categories. In this section, we address the implications of the need for energy carriers in the expression of those different activities. Indeed, the performance of a task invariably involves the realization of an energy end-use and requires a specific mix of human activity, energy carriers and power capacity (technology). Therefore, we couple the dendrogram of human time allocation to that of exosomatic energy allocation (Fig. 7). On the right-hand side of Fig. 7, the total energy throughput (TET) of society is subdivided over the same set of accounting categories, thus describing the profile of allocation of energy carriers at lower-level nodes (ET_i). Even in the case of energy end-uses, closure of the accounting is required at each level i of the dendrogram: $TET_i = [\sum ET_i]$.

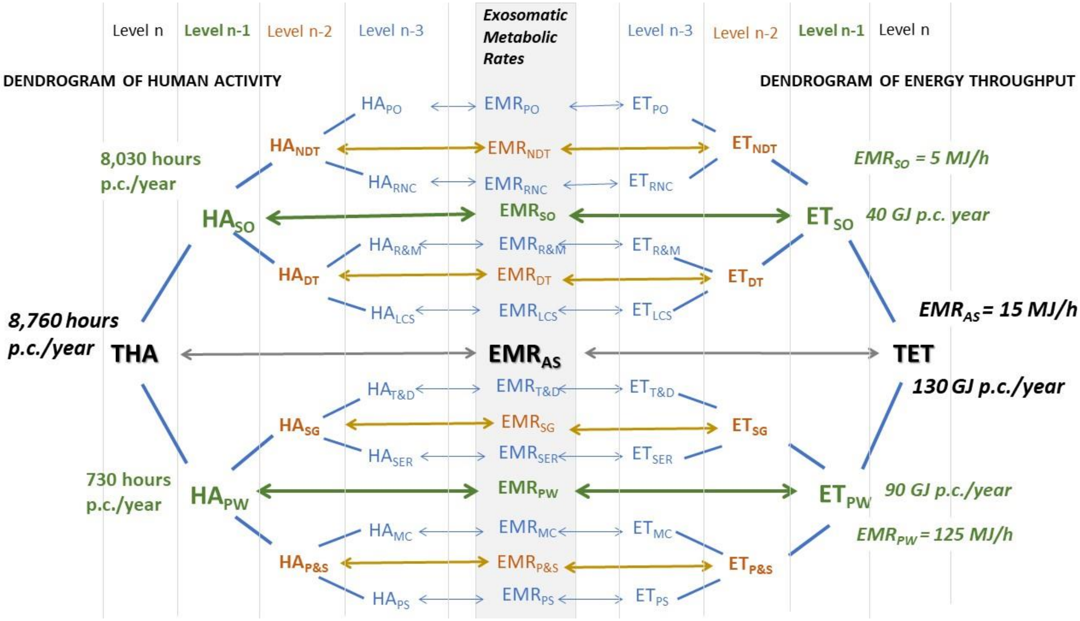

Fig. 7 Coupled dendrograms of human activity (HA, left) and energy throughput (ET, right) for the EU. Subscript abbreviations are explained in Box 2. Data from (Velasco-Fernández et al., 2020).

The representation in Fig. 7 allows us to characterize, in an indirect way, the level of technical capitalization of the activities. The level of technical capitalization is a proxy of power capacity and refers to the quantity of technical devices used for the expression of a given activity. It can be approximated by the value of the energy metabolic rate (EMR_i) for that activity. Thus, the EMR_i's measure the specific rate at which exosomatic energy is used per hour of human activity in the various social practices inside and outside the paid work sector, i.e., the end-uses of energy. They represent important benchmark values for the study of the societal metabolism (Velasco-Fernandez et al., 2018).

The coupled dendrograms of time and energy allocation, shown in Fig. 7, permit the analyst to identify forced patterns of time allocation in relation to the feasibility, viability, desirability and security (openness) of the metabolic pattern of society (Giampietro et al., 2021). Particularly useful in this regard is the concept of Bio-Economic Pressure (BEP), a biophysical indicator of economic development (Giampietro et al., 2012; Giampietro and Mayumi, 2000). BEP is defined as the required (or desired) total energy throughput (TET in J) of a society (used for the production and consumption of good and services) divided by the total hours of human activity allocated to the primary and secondary sectors of its economy ($HA_{P\&S}$ in h), both expressed on a year basis (see equation [1]). It can be calculated from the set of relations shown in Fig. 7, and is measured in MJ/h. BEP is considered a 'pressure' because it reflects the amount of energy and materials that must be made available by the productive sectors of the society (P&S) to meet the desired standard of living. BEP can also be expressed in terms of the average energy use in society (EMR_{AS} in MJ/h) and the time (in h) allocated to the consumptive (dissipative) compartments ($HA_{NDT} + HA_{DT} + HA_{SG}$) (see equation [1]). The larger is the value of BEP, the higher the material standard of living. It has been empirically proven (Giampietro et al., 2012; Pastore et al., 2000) that BEP correlates well with conventional indicators of development and material standard of living. This confirms that economic development entails an increase in societal energy use, coupled to a simultaneous increase in the share of human time invested in its consumptive (dissipative) compartments.

$$BEP = (TET / HA_{P\&S})_{\text{required}} = EMR_{AS} \times THA / [THA - (HA_{NDT} + HA_{DT} + HA_{SG})] \quad [1]$$

The surplus required by society from the primary and secondary sectors to meet the BEP must be consistent with what the primary and secondary sectors can possibly supply. We refer to the latter capacity as the Strength of the Exosomatic Hypercycle (SEH) (see equation [2]). SEH mirrors BEP and is also expressed in MJ/h. It depends on the available resources (boundary conditions), technology and imports. The dynamic equilibrium between SEH and BEP (equation [3]) entails a constraint over the relations of the coupled dendrograms shown in Fig. 7, which is formalized by equation [4]. Note that in equation [4], the EMR_{AS} on the left is defined as the average rate of *supply* of energy carriers to society (TET per year), whereas the EMR_{AS} on the right side refers to the average rate of *consumption* of energy carriers (TET per year). Any discrepancy between internal supply and consumption must be compensated by trade.

$$SEH = (TET / HA_{P\&S})_{\text{supplied}} = EMR_{AS} \times THA / (HA_{P\&S}) \quad [2]$$

$$SEH \leftrightarrow BEP \quad [3]$$

$$EMR_{AS} \times THA / (HA_{P\&S}) \leftrightarrow EMR_{AS} \times THA / [THA - (HA_{NDT} + HA_{DT} + HA_{SG})] \quad [4]$$

Equation [4] is useful to study the conditions of congruence required for achieving a dynamic equilibrium between SEH and BEP. These conditions will define the feasibility, viability and desirability of a given profile of human time allocation, and, importantly, the extent of openness of the system (Giampietro et al., 2012;

Pérez-Sánchez et al., 2021). Note that, even if formally identical, SEH and BEP are defined over different scales and using non-equivalent descriptive domains. BEP is concerned with the internal viability of the distribution profiles of energy throughputs and human activity among societal components; it can be assessed by looking at the characteristics of the purely dissipative compartment of society in relation to the characteristics of the whole (EMR_i per hour across levels). SEH is related to the labor productivity in productive sectors, guaranteeing the feasibility of the metabolic pattern; it depends on boundary conditions (external primary energy sources) and technological capital and know-how (TET of the whole society and $HA_{P\&S}$).

4. Applications

4.1 Comparing changes in time allocation between the EU and China

In this first example, we show the existence of an attractor in the evolution of the metabolic pattern of societies. The presence of such attractor was first suggested by (Giampietro et al., 2012) in a longitudinal analysis of the metabolic pattern of EU countries, in which the energy metabolic rates (EMR_i) of the various sub-sectors of the paid work compartment were plotted against the corresponding sub-sectoral gross domestic product (GDP_i, calculated per hour) for the period 1992-2005. In the example presented here (see Fig. 8), we examine how the various compartments of the paid work sector of China (left pane) and the EU (right pane) changed during the period 2000-2016. Fig. 8 also shows the difference between China and the EU for the selected economic sectors at the different points in time. In this example, changes are represented in a purely biophysical Cartesian plane (no monetary indicators). The sectoral EMR_i are represented on the vertical axis (in MJ/h, averaged over one year), the sectoral HA_i on the horizontal axis (in h per capita per year). The energy throughput per capita (ET_i pc) of the different economic sub-sectors are represented by the relative size of the bubbles. The scope of this example is to show that economic development entails: (i) an increase in the EMR_i of the primary and secondary sector; and (ii) an increase in the HA_i allocated to the service & government sector.

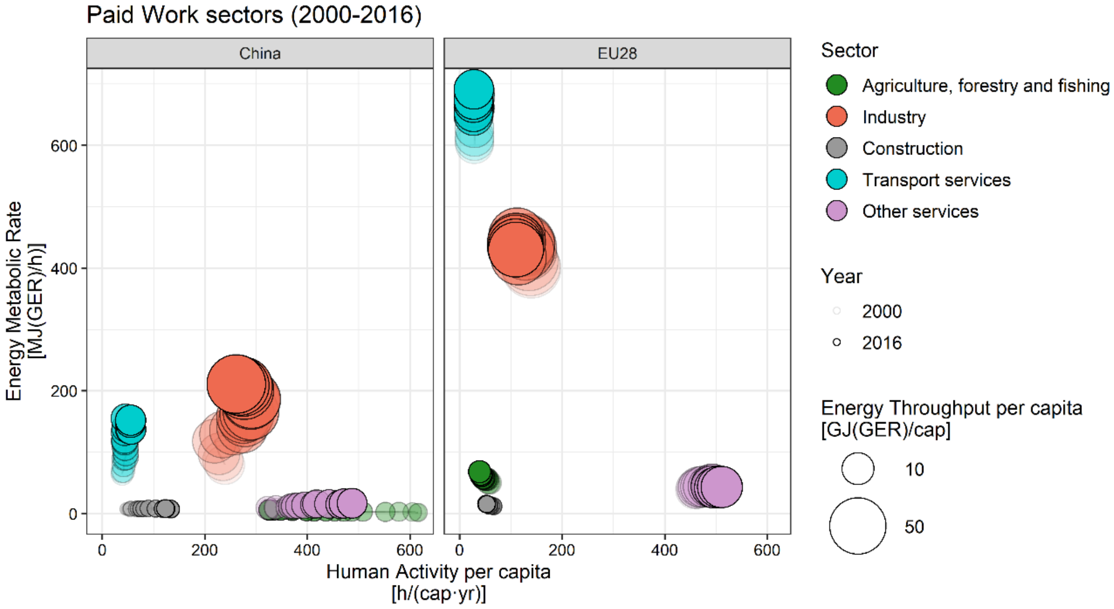

Fig. 8 A diachronic analysis of the metabolic pattern of China and the EU over the period 2000-2016, after (Velasco-Fernández et al., 2020).

A comparison of the two graphs in Fig. 8 shows that sectoral EMR_i values for China are consistently lower than those of the EU, the difference being most marked for the sectors of transportation, industry and agriculture. In the EU, the level of technical capitalization appears to be stable (with the exception of the transport sector, whose EMR_i is still increasing in time), thus indicating a situation of maturity. For China, on the other hand, values are steadily heading toward the EMR_i levels recorded for the EU. This pattern is especially evident for the transportation and industry sectors.

Important differences between China and the EU also exist for the investment of human time in the various economic subsectors (HA_i, Fig. 8). The number of hours per capita allocated to the 'other services' sector has been rapidly increasing in China over the past 20 years (the purple bubbles move to the right with time) and is approaching EU values. This development originates from China's modernization process that has implied a progressive and steady reduction of farmers (the green bubbles moving to the left, partly covered by the purple bubbles). This pattern confirms the existence of an attractor in the evolution of the time allocation profile and the hypothesis of Zipf, Meier, and Cipolla (discussed in section 2) that economic progress leads to a progressive reduction in time allocated to agriculture and a simultaneous increase in time allocated to final consumption. Nonetheless, China has not yet reached the 'maturity' observed for the EU: although the time invested by China in the agricultural sector declined, in 2016 it still was about 10 times that of the EU. For the industrial sector, the Chinese time investment in 2016 was more than twice (almost triple) that of the EU (Velasco-Fernández et al., 2020). Note that the low investment of human time in the EU agricultural sector is achieved not only through technical capitalization (boosting the labor productivity of farmers) but also through a massive import of agricultural commodities (mainly feed for animal production) (Cadillo-Benalcazar et al., 2020; Renner et al., 2020). Such a solution is currently out of reach for China, as capitalization is still focused on industry and urbanization. It is also questionable whether enough agricultural commodities would be available in the global market to cover a significant amount of China’s enormous food requirement. Another interesting feature of China’s metabolic pattern is the rapidly growing investment of hours in its construction sector. This reflects its incredible pace of urbanization: China consumed in 3 years (2011-2013) more cement than the USA in one century (1901-2000) (Smil, 2014).

In Fig. 9, we zoom in on the EU for the year 2012, adopting the same plane as in Fig. 8, but a different scale. For the sake of visualization, we represent a heterogeneous sample of 12 European countries only (Spain, Greece, Bulgaria, Italy, France, Sweden, UK, Finland, Czech Republic, Romania, Netherlands and Germany). As can be seen from Fig. 9, the industrial sectors of these countries exhibit markedly different EMR$_i$ values, depending on the industrial production processes performed. For instance, the high EMR of the industrial sectors of Finland and Sweden can be attributed to the relative importance of their energy-intensive pulp and paper industry (Velasco-Fernández et al., 2019). On the other hand, time allocation to the industrial sector (i.e., the HA$_i$ values) is fairly similar among the selected EU countries. The same applies to the agricultural sector. This chart confirms that there is an evolutionary attractor toward reducing the time investment in the productive sectors. Eventual mismatches between the demand and supply of industrial and agricultural products are solved through trade, rather than domestic production, when too high an investment of human time is required (see section 4.2). The variation in time allocation observed for the SG sectors of these EU countries reflects small gradients in their economic development and their different reliance on imports.

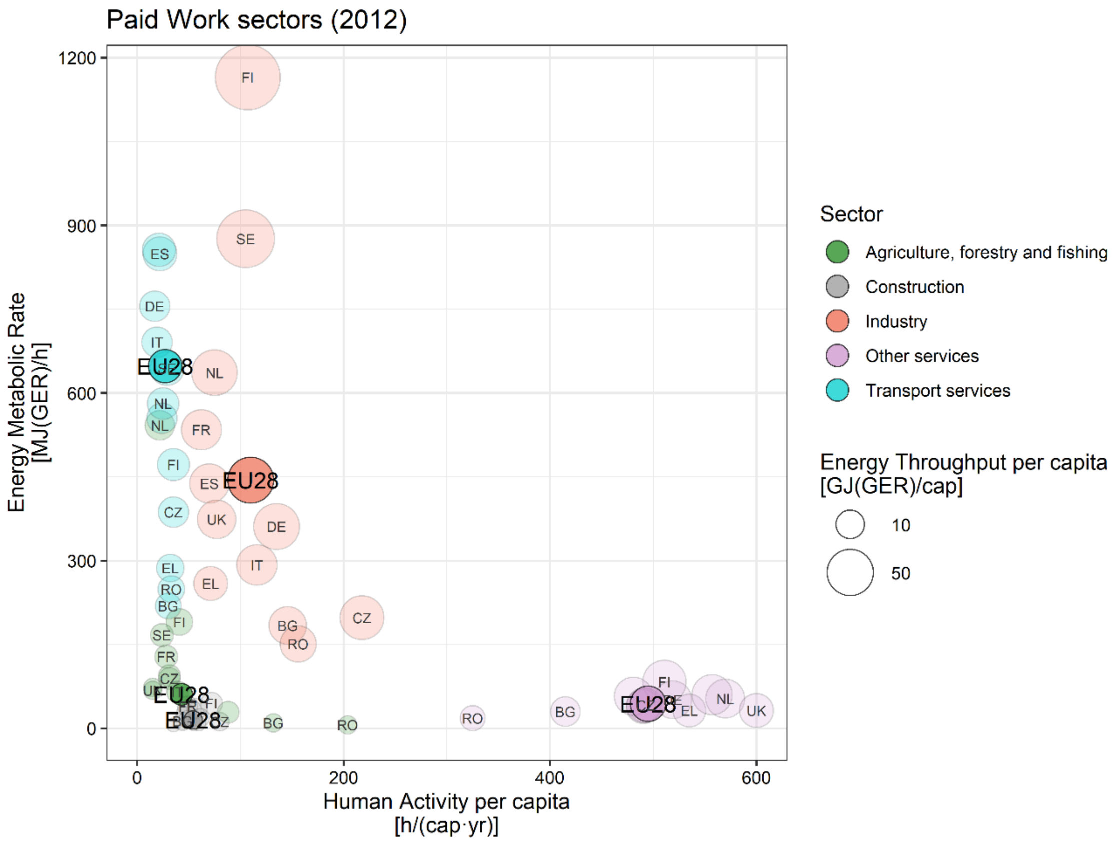

Fig.9 A synchronic analysis of the metabolic pattern of a sample of 12 European countries in 2012. Data are from the same study reported in Fig. 8 (Velasco-Fernández et al., 2020)

Table 1 shows time allocation for China, the EU, and the 12 individual European countries from Fig. 9, along with dependent population, workload, average energy metabolic rate and BEP. Obviously, values reported are necessarily approximated. As can be seen from this table, the ratio between the societal overhead and the time allocated to the paid work sector is markedly different between China (6/1) and the EU (11/1). This difference is explained by (i) the lower percentage of elderly (over 65 years) in the population of China, i.e., 10% compared to 18% in the EU, and (ii) a higher workload per worker (almost 2300 h/worker/y in China versus 1710 h/worker/y in the EU). Note that the labor force participation rate in China of the population 15y+ is higher than that in the EU for both males and females, the difference being more marked for male than female workers (The World Bank, 2021). Thus, the assessment of time allocation on a per capita basis clearly illustrates that the larger amount of HA_{PW} in China (1300 h p.c./y) is basically due to its demographic structure and workload regulations. The higher percentage of adults in the population gives China an important (temporal) economic advantage over the EU.

Studies on the time invested in the paid work sector (the formal economy) in other countries report values closer to that of the EU (730 h p.c./year) than that of China (1300 h p.c./year), suggesting the situation in China is unique. For example, (Eisenmenger et al., 2007) report 990 h for Brazil, 870 h for Chile, and 870 h for Venezuela, all values referring to 2000. (Velasco-Fernández et al., 2015) found a stable value of around 880 h for India between 1990 and 2010. Similar values have been reported for Australia (790 h in 1990 and 870 h in 2010), Canada (700 h in 1990 and 830 h in 2010, the increase in time probably due to immigration), as well as the USA (880 h in 1990 and 2008) (Chinbuah, 2010). Other EU countries, not included in our sample, have values like those reported in Table 1. For example, Hungary 670 h and Poland 740 h (Iorgulescu and Polimeni, 2009). All values reported as hours per capita per year.

The unique situation of China is also reflected in the relatively low value of its bioeconomic pressure. In 2012, the BEP of the EU was 669 MJ/h compared to 97 MJ/h for China – a difference of more than 6-fold. In that same year, the EMR_{AS} of the EU was 16 MJ/h while that of China was only 9 MJ/h (a difference of less than 2/1). Note that these values represent the average metabolic rate for the whole society, calculated over the mix of energy carriers across end-uses and are expressed in Gross Energy Thermal equivalent (Velasco-Fernández et al., 2020). The ratio between the THA and $HA_{P\&S}$ in China was 11/1, whereas that of the EU was 42/1 – a difference of almost 4 times (recall that the value of BEP depends not only on the level of energy use in society, but also on the profile of time allocation – see equations [1] to [4] in section 3.2). Hence the difference in the value of BEP between China and EU cannot be explained only by the observed increase in labor productivity in the primary sectors of the EU (larger values of EMR_i). To explain the discrepancy, it is essential to consider the effect that global trade has on the requirement of paid work in the different economic sectors (changes in the values of $HA_{P\&S}$). This analysis is illustrated in the next example.

Table 1. Population, demographic structure, time allocation, workload, average societal energy metabolic rate (EMRAS) and bio-economic pressure (BEP) for the EU, China and 12 European countries for 2012. Values for time allocation and workload are expressed on a per capita and per year basis. Data sources: "Population on 1 January by broad age group and sex", "Population on 1 January by age and sex" (Eurostat, 2018a, 2018b) and Tabulation on the 2010 Population Census of the P.R.C. (NBSC, 2018) for total population and demographic structure; "National accounts employment data by industry", "Full-time and part-time employment by sex and economic activity" (Eurostat, 2018c, 2018d) and China Labor Statistical Yearbook (NBSC, 2019a) for time allocation in paid work; Energy Balances for the EU (Eurostat, 2019) and for China (NBSC, 2019b). EMR and BEP sources: our calculations.

		Demographic structure			**Time allocation**							
2012	**Population**	**Adults**	**<15**	**>64**	**Societal overhead**		**Paid work**		**P&S sector**	**Workload**	**EMR$_{AS}$**	**BEP**
	millions	*%*	*%*	*%*	*h*	*%*	*h*	*%*	*h*	*h*	*MJ/h*	*MJ/h*
Bulgaria	7.3	68	13	19	7,990	91	770	9	328	1,920	12	317
Czechia	10.5	69	15	16	7,900	90	860	10	338	1,840	20	513
Finland	5.4	66	16	18	7,995	91	765	9	235	1,665	31	1144
France	65.3	64	19	17	8,120	93	640	7	141	1,620	19	1174
Germany	80.3	66	13	21	8,025	92	735	8	202	1,515	19	820
Greece	11.1	65	15	20	8,000	91	760	9	196	2,290	12	532
Italy	59.4	65	14	21	8,040	92	720	8	214	1,900	13	546
Netherlands	16.7	67	17	16	8,015	91	745	9	154	1,495	23	1308
Romania	20.1	68	16	16	7,980	91	780	9	428	1,820	8	172
Spain	46.8	68	15	17	8,080	92	680	8	161	1,760	13	711
Sweden	9.5	64	17	19	7,985	91	775	9	198	1,580	25	1110
UK	63.5	65	18	17	7,985	91	775	9	155	1,670	15	867
EU	504	67	15	18	8,030	92	730	8	207	1,710	16	669
China	1350	75	15	10	7,460	85	1300	15	814	2,295	9	97

4.2 The effect of global trade on time allocation patterns

The second example is based on an analysis of (Pérez-Sánchez et al., 2021) on the externalization of labor time requirements associated with international trade. We use the findings of this study to illustrate the relevance of considering simultaneously intensive variables (the profile of human time allocation inside the society, expressed as a fraction of the total – a qualitative attribute) and extensive variables (the size of the population, expressed as the actual number of people) to check the effects of (and the limits to) the externalization of requirements of human labor through trade.

In Fig. 10 we summarize again the main factors determining the supply of working hours for the EU and China: (i) population size; (ii) demographic structure; and (iii) the yearly workload. Immediately below, the time allocated to the entire paid work sector, and to the service sector in particular, are shown for the EU and China. The latter figures make it evident that in absolute terms the time investments in the service sector are similar for the two societies. However, the relative investment of working hours in the service sector (as % of the total HAPW) in the EU (68%) is much larger than in China (34%) and leaves little room for time investments in the other economic sectors.

In the bottom part of Fig. 10, the flows of embodied hours of work associated with trade are shown. According to the data of (Pérez-Sánchez et al., 2021), the EU imports 566 hours p.c./year and exports 101 hours p.c./year, whereas China exports 158 hours p.c./year and imports 88 hours p.c./year. In order to make sense of these data, they need to be contextualized in relation to the characteristics of these two societies and the size of the global market.

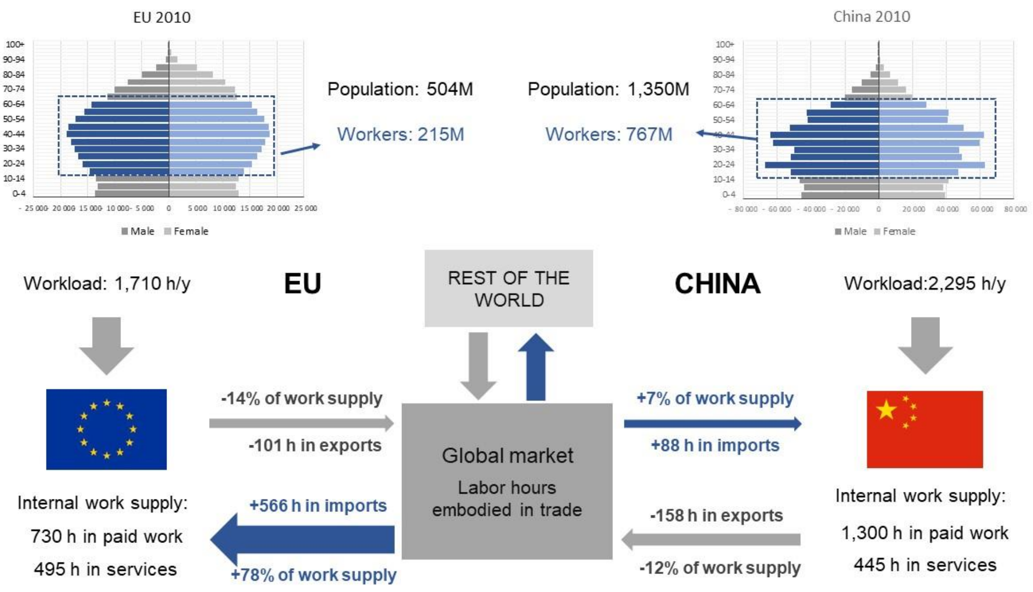

Fig.10. The pattern of time allocation at the societal level for China and the EU, using extensive and intensive variables. All values for time allocation, work load, and import and export of labor time are expressed on a per capita and per year basis. Year of reference: 2011 Data from (Pérez-Sánchez et al., 2021).

In the EU, the exported working time concerns the manufacturing of products with high added value, while the imported working time is associated with lower value chains. In this way, the EU can boost its internal work supply by 78%, using the equivalent of an inflow of more than 167 million workers (calculation based on EU workload). If this work were to be achieved with 167 million immigrant workers, it would entail, in the long term, a significant increase in the size of its dependent population associated time requirements of nurture and care (Fig. 6). From the data reported in Fig. 10, it is evident that Europe is importing goods also from other countries, besides China. On the contrary, China has a slightly negative net trade of working hours per capita (-5% in relation to its paid work sector), exporting more hours than it imports. All the same, given its huge workforce (and workload), China is a large supplier of human time to the rest of the world.

In relation to the global market, this analysis casts doubt on the possibility of extending the pattern of economic growth adopted by the EU (and the USA) to population giants such as China, India and Brazil. If the latter countries would adopt the strategy of sustaining their increasing BEP by externalizing the labor requirements of the productive sectors (manufacturing, agriculture, energy and mining) to other countries – reaching a level of dependence on imported labor similar to that of the EU and USA – we would run into a problem of planetary boundaries. Besides the problem of scarcity of primary resources (an external limit), there would not be, at the global level, sufficient surplus of labor hours, nor technical capital, infrastructure, skilled workers etc. (internal limits). Moreover, a systemic externalization of work by rich countries to poor countries would impede an increase in the material standard of living of the poor countries playing the role of net exporters of paid work hours. This solution would lock them into an economy based on primary sector activities, with diminishing returns (Reinert, 2007). Needless to say, that at a global level the solution of externalizing labor requirement to "others" does not exist. The given budget of human time entails a "zero sum game" at the global level. This internal constraint at the global level determines the option space of the profile of human time allocation of individual societies. Thus, the openness of the metabolic pattern of post-industrial societies requires an enlargement of scale of the analysis, to the global level and weaken the control on their own metabolic pattern of trading societies. In relation to this point, Ulanowicz (1997, 1986) explicitly addressed the relevance of considering the level of openness of the metabolic pattern of ecosystems. Ecosystems that rely on nutrients derived from 'outside', have a weaker "metabolic identity". In fact, the stability of their metabolic pattern depends on the stability of their boundary conditions which are determined by their context. This observation points at the importance of considering the "metabolic security" of modern economies.

4.3 Can immigration ease internal labor constraints?

In this section we look at the effects of immigration on internal labor constraints through an alteration of the demographic structure of the population. We refer to the time allocation pattern presented in Fig. 6 and the BEP discussed in section 3.2 The age structure of the population of immigrants is known to markedly differ from that of the hosting population. This is shown in Fig. 11 for Spain for the period 2011-2012. We select Spain as a case because in the period 2002–2014, it had an accumulated immigration inflow of 7.3 million and a net flow of 4.1 million, making it the second-largest recipient of immigrants (in absolute terms) among OECD countries, after the USA. As a result, the total foreign population in Spain rose from 2% in 2000 to about 12% in 2011 (Romero, 2015).

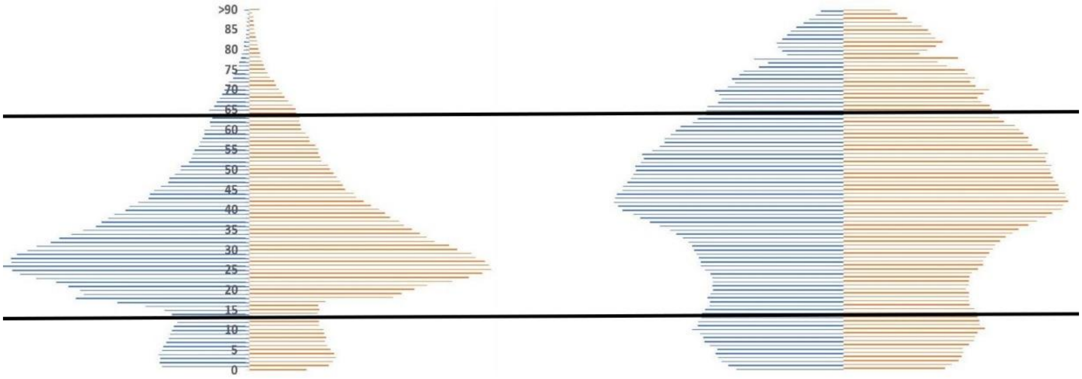

Fig.11 Comparison of the demographic structure of the Spanish residents in 2012 (pyramid on the right) with that of immigrants coming to Spain (pyramid on the left) throughout 2011. Data from INE[27]

The age structure of immigrants shown in Fig. 11 suggests that 79% of the immigrant population belongs to the work force, compared to 67% of the resident population. A similar figure (65-86%) has been found for the immigrant population in most other EU and OECD countries for 2011-12 (OECD, 2015a, Table 2.A1.1). This entails that the budget of human time of 1 million immigrants could potentially supply 1.35 billion hours per year of paid work for society (1,710 x 0.79 x 1,000,000) – provided all immigrants find employment. In comparison, the average net supply of paid work hours of a same-sized population with the demographic structure of Spain (67% of the population in the workforce), would be 1.15 billion hours. Assuming the same workload, this makes on average 1350 paid work hours per capita per year for immigrants and 1150 for residents.

As is evident from the dendrogram of Fig. 6, the immigrant population has a lower per capita societal overhead because relatively little time is implied for the dependent population – children and dependent elderly (in the category 'Requiring Nurture and Care' in Fig. 6). By relying on immigrants to boost the available time in the PW sector, the overhead associated with their dependents (temporarily) remains in their country of origin, thus generating the so-called global care chains (Pérez-Orozco, 2016).

Immigration does not only lower the societal overhead of paid work (SO in Fig. 6), but tends to also reduce the labor demand in the service & government sector (S&G in Fig. 6). Compared to the hosting (native) population, immigrants in the EU have a relatively low income (OECD, 2015b), consume less goods and services (e.g., (Borch et al., 2019)) and are more likely to live in overcrowded homes (OECD,

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[27] *https://www.ine.es/dynt3/inebase/index.htm?type=pcaxis&path=/t25/e447/a2009-2010/p02/&file=pcaxis&L=1*.

2015c). This reduces the BEP at societal level, but represents evidently an undesirable situation.

Immigrants thus potentially provide an immediate relief on the pressure to maintain the dependent population by (temporary) increasing the relative proportion of working hours in society, while not always receiving in return the due amounts of public services. However, what will happen in the long run?

The long-term effects of immigration depend on the differential in fertility rates between immigrant and native population, the stability of this differential in time and the integration of immigrants in society. In the period 2008-15, foreign births made up on average 20% of total births in Spain, while immigrants made up about 11% of the total Spanish population during this period (data from INE). The younger age and relatively high fertility rates of the settled immigrants counteract the aging process of the Spanish population, but also increase the human time in the category “Requiring Nurture and Care”. Moreover, immigrants will eventually retire. At that point, the initially positive effect of the original injection of immigrants, in terms of hours of labor supply versus societal overhead, may be largely nullified (Giampietro et al., 2012, p.33-36).

The potential solution of immigration to the relative shortage of labor hours has received much attention in recent years. In 2001, the United Nations (UN) published an influential study on ‘replacement migration’ in response to increasing concerns about the effects of population aging in developed countries (United Nations, 2001). The report presented estimates of the replacement migration needed by developed countries to: (a) maintain the size of the total population, (b) maintain the size of the working-age population (aged 15 to 64), and (c) uphold the potential support ratio (PSR), defined as the ratio of persons aged 15–64 / 65+ (the inverse of the old age dependency ratio). An inevitable diminution in the potential support ratio emerged from the study, with a plausible number of migrations unable to halt (or revert) this progression. Many variants of the study have been published since. Notably the use of a more dynamic definition of the labor force participation and/or a more elaborated definition of the support ratio have resulted in more nuanced estimates and conclusions (e.g., Bijak et al., 2007; Craveiro et al., 2019; Marois et al., 2020; Rees et al., 2013; Wu and Li, 2003, see also the Appendix, section A2). Surprisingly, most studies define the support (or dependency) ratio solely in relation to old age, only few (e.g., Marois et al., 2020; Wu and Li, 2003) also consider the need to support children (<15). Some studies factor in migrant education level in relation to labor productivity (Marois et al., 2020) or potential effects on the demand side through variables such as household size (Rees et al., 2013), albeit exclusively in monetary terms. Nonetheless, given the multitude of factors involved, projections about the effects of replacement migration on the support ratio in the host society have remained inconclusive.

Giampietro (1998) proposed that the stabilization of a given population size is linked to the establishment of a metastable equilibrium between BEP and SEH, building on the empirical knowledge that demographic changes are related to changes in the metabolic pattern of society as a whole. According to the classic theory of the demographic transition, in a situation of high fertility and high mortality rates, we may have a stable population size with BEP matching SEH at a low value. In this equilibrium, the majority of human time is invested in producing food and other primary inputs, an activity with low labor productivity. This limited production (supply) keeps the level of consumption low and prevents a further expansion of human activity (population size). In a transitional period, in which the value of SEH consistently exceeds that of BEP (e.g., in response to the industrial revolution), society experiences a simultaneous increase in the EMR_i in PW and the time allocated outside the P&S sectors (the expansion described by Zipf). Finally, a new equilibrium can be reached when BEP matches SEH at a higher value. This translates into a society with low fertility and low mortality rates, i.e., an aged society with a high productivity of labor, investing much of its time in consuming. However, as observed by Giampietro (1998) the existence of this second metastable equilibrium does not necessarily solve the problem of Malthusian instability (potential problems generated by population growth) (Layzer, 1988). If a gradient in economic growth exists among different societies (different BEPs) with global economic transactions, the formation of “immigration pumps” is inevitable: human activity produced in countries with a lower BEP will move to countries where the SEH is stronger.

Note that the ’solution’ of replacement immigration presupposes a surplus of active population at the global level. As is the case with the import of goods and services, such a solution therefore presumes that a gradient between ‘poor’ and ‘rich’ countries persists. The effects of international migration on the countries of origin of the migrants have been relatively poorly documented and focused on isolated aspects such as brain drain (e.g., (Remeikienė and Gasparėnienė, 2019), and short-term economic effects such as remittances and relief on unemployment rates (Asch and Reichman, 1994) rather than on the structural transition process to that of a developed economy.

In this paper, we have used data from time use surveys to study the nature of this phenomenon. We combined demographic statistics of Spain with data from the Spanish Time Use Survey 2009-2010 (Instituto Nacional de Estadistica (INE), 2011a), which is consistent with the methodology of reference in Europe and amenable to the categories of accounting shown in Fig. 6 (Instituto Nacional de Estadistica (INE), 2011b) (see Appendix, section A2 for more details). Nonetheless, it remained difficult to relate these data in a systemic way to the conceptual framework proposed in Section 3, especially with regard to the distinction between: (i) the societal overhead and paid work at level *n-1*; and (ii) disposable and non-disposable time at level *n-2*. In Fig. 6, the closure of time allocation is based on a taxonomy of functional categories of time allocation, whereas the data in time surveys refers to a taxonomy of structural types of population (e.g., unemployed, student, part-time worker, men, women). It is therefore complicated to use these data to examine the relations over the different quantities of human time across the different functional compartments of society. The use of such data represents a challenge that needs further research.

5. Conclusions

We have provided a conceptual representation of the profile of human time allocation as an emergent property of the metabolic pattern of society. In this representation, the profile of time allocation is conceived as a specific combination of human activities capable of expressing an integrated set of functions that is needed to reproduce the functional and structural elements of the society across different hierarchical levels of organization. A set of formal relations has been proposed to identify the factors that shape the dynamic budget of human time in relation to society's resource (exosomatic energy) use. Two crucial benchmarks resulted from these formal relations: the bio-economic pressure and the strength of the exosomatic hypercycle. The former is defined by the profile of time allocation and energy expenditure associated with the production and use of goods and services expected by society; the latter defines the biophysical limits to this pressure imposed by the productivity of labor in the primary and secondary sectors. As the available amount of human time is given for a defined population, the expansion of the consumptive sector (time allocated to the services and government sector plus time allocated outside the paid work sector) that typically comes with economic growth, translates into a dramatic increase in the pressure on the labor productivity of the primary and secondary production sector.

Three empirical applications of the conceptual framework have shown that: (1) with economic growth, the societal metabolic pattern evolves toward an increase in labor productivity in the primary and secondary production sectors associated with larger EMR_i, more working hours allocated to the service sector, and more time allocated outside the paid work sector and thus an increase in the societal overhead of paid work; (2) with the labor capitalization process saturated, the EU and its individual member countries currently overcome internal labor constraints through the massive use of working hours embodied in imported commodities, a solution that cannot be extended to the global level; (3) immigration can be a temporary solution to ease labor constraints, but is unlikely to solve the problem of senescence of developed societies in the long term.

History has shown that the time allocation in society is flexible and responsive to changing political, economic and environmental contexts. In crisis situations (e.g., war, famine, pandemic), the acceptability of consumption levels (EMR_i) and social roles inside and outside the paid work sector (profile of HA_i) is readily adjusted so as to guarantee the survival of society. The result is a 'forced' adaptation of the metabolic pattern. The sustainability crisis may represent in the near future one of these forcing phenomena. However, to improve the sustainability of the current metabolic pattern of developed societies, there is also the option of a planned gradual transition to a post-growth caring economy. Our findings suggest it will be no walk in the park either, as it will require radical changes in our social practices. To better inform such a transition, we need analytical tools that provide a richer understanding of the societal metabolism and how it relates to the choices we make in our social practices. This paper has made a contribution into this direction.

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Chapter 4. The declining performance of the oil sector: implications for global climate change mitigation

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This chapter is the transcript of the paper: "Manfroni, M., Bukkens, S.G.F., Giampietro, M., 2021. The declining performance of the oil sector: Implications for global climate change mitigation. Appl. Energy 298, 117210. https://doi.org/10.1016/j.apenergy.2021.117210.", with only minimal modifications. The language and the structure used reflects the fact that this chapter was conceived as a stand-alone paper to be published in the scientific literature.

1. Introduction to the issue

Climate change is on the front burner of the political agenda, given its huge potential impacts on the biosphere and the global economy (Rockström et al., 2009; Vitousek et al., 1997). A rapid decarbonization process is therefore advocated almost unanimously by all national governments and international bodies (IMF, 2020; Independent Group of Scientists appointed by the Secretary-General, 2019). However, in the short term, the energy input required for such a radical transformation will have to be supplied by the current energy matrix, which still consists predominantly of fossil fuels (about 90% of the world energy consumption in 2019) (British Petroleum, 2020; International Energy Agency IEA, 2020). Hence, during the transition period, the energy sector will have to provide not only a sufficient supply of net energy for the daily functioning of the economy, but also for the required extra investments in low-carbon technologies and infrastructures (Sgouridis et al., 2016; Solé et al., 2018). This (largely fossil) energy "overhead" translates into an overhead of CO_2 emissions, which will determine the biophysical pay-back time of the energy investment - i.e., the time required by alternative energy sources to compensate for the extra CO_2 emissions accumulated for building and operating green infrastructures and technologies (Di Felice et al., 2018; Gibbs et al., 2008).

Given the ubiquitous carbon lock-in in the primary and secondary production sectors, it is unlikely that we will be able to radically change our energy matrix and substantially reduce CO_2 emissions in the near future (Janipour et al., 2020; Unruh, 2000). Looking at current fossil fuel end-uses, we find that: (i) transportation is almost 100% petroleum based; (ii) industry is heavily dependent on petrochemical feedstocks and fuels for essential processes like plastic, cement, steel and glass production; (iii) agriculture completely depends on ammonia and machinery; (iv) electricity production is dominated by coal, natural gas and uranium (Smil, 2017, 2015). To this picture we have to add the sunk-cost of the already existing technical capital (Tong et al., 2019), buildings (Röck et al., 2020) and infrastructures (Davis et al., 2010), which generates an important fossil fuel path dependency that is not easy to change. In addition, rapid population growth in some developing countries and the strive for better living conditions worldwide are likely to further increase fossil energy use and CO_2 emissions. Hence, not surprisingly, both fossil energy consumption and emissions continue to rise despite the Paris agreement, UNFCC and IPCC international meetings (Nieto et al., 2018; UNEP, 2019).

At the global level, oil still represents the first primary energy source (accounting for 33% of the total primary sources) (British Petroleum, 2020). Rather than a transition away from fossil fuels, two interrelated drivers of change dominate the oil sector: (i) the progressive depletion (aging) of conventional oil fields (Höök et al., 2009); and (ii) a "fossil transition" from conventional to unconventional sources, entailing a complexification of the supply system (Farrell and Brandt, 2006). The two processes are intrinsically entangled: while conventional oil production is progressively declining, an array of new oils, such as oil sands, tight oil, new heavy and extra-heavy oils, ultra-deep waters oils and oil shales is projected to fill the gap. From 2005 onwards, the world production has been sustained by US tight oil, which accounts for 60% of the global increase in supply. Conventional crude is expected to account for only 60% of liquid-fuel supply by 2040, compared to 80% in 2012 (Gordon, 2012).

Based on the evidence reported in (Höök et al., 2009; Visual Capitalist, 2019), about 60% of the global oil production comes from giant fields, whose major discoveries (in terms of production capacity) date back to the period 1940-1980. The progressive depletion of those fields makes the oil extraction more difficult (Brandt, 2011) and Enhanced Oil Recovery (EOR) techniques of different complexity are increasingly needed to keep up the production. EOR entails more energy carriers (heat, electricity and fuels) and water use (to keep the reservoir in pressure and pump out fluids with increasing water-to-oil ratios), to produce the same amount of net supply. The consequence is a decline of the Energy Return On Investment (EROI) and higher emissions per unit of net supply (Masnadi and Brandt, 2017a, 2017b). The process of aging also affects the crude quality, with older fields often producing heavier and dirtier oils (Parra et al., 2020). Therefore, considering an average age of currently depleted fields around 80 years (Carnegie Endowment for

International Peace, 2018), the effects of this aging phenomenon will become fully evident between 2020 and 2060, which is the critical time window for climate change mitigation, according to the IPCC (Rogelj et al., 2018). At the same time, the worldwide ongoing “unconventionalization” process of oil supplies affects the infrastructures and technologies needed for extraction, transportation and refining. More complex drilling and deeper refining of unconventional sources increase the energy intensity and the related emissions of the changing oil industry (Brandt and Farrell, 2007).

The effects of these two drivers challenge the plausibility of a rapid renewable energy transition and of climate change mitigation scenarios. Therefore, before making ambitious plans for a radical decarbonization of the global economy in 2050 (European Commission, 2018; Rogelj et al., 2018), it is important to assess the wider impacts of the declining performance of the oil sector on our low-carbon future aspirations.

Currently commonly used methodological approaches, such as Life-Cycle Assessment (LCA), strive to produce accurate carbon intensity assessments for specific oil products (or net energy units) to inform policy-making (Brandt et al., 2018; Masnadi et al., 2018). For instance, LCA assessments have been provided for unconventional extraction (Brandt et al., 2016), refining (Jing et al., 2020), and the entire well-to-wheel oil supply chain (Carnegie Endowment for International Peace, 2018). However, the findings of these LCA analyses are valid only within the (narrow) context defined by the assumptions of the analyst. Indeed, LCA results are highly sensitive to system boundaries definition, efficiency benchmarks and the taxonomy of functional units (Farrell et al., 2006): choosing different boundaries or allocation criteria among different products leads to significantly different assessments for the same fuel pathway (Heijungs and Suh, 2002; Wang et al., 2011). In practice, these assessments generate questionable ‘optimal’ solutions for narrow policy domains (e.g., the California Low Carbon Fuel Standard, LCFS), rather than a multi-dimensional knowledge space for an informed discussion.

The same narrow optimization scope, but using highly-aggregated, general equilibrium models, is pursued by the IPCC’s assessments of climate change mitigation pathways (IPCC, 2014; Rogelj et al., 2018). These models represent the current state-of-the-art of the Integrated Assessment Modelling (IAM) for climate change mitigation options, and push for innovation and efficiency towards a clean energy transition (Bloess et al., 2018; Rissman et al., 2020; Zappa et al., 2019). Nonetheless, these IAMs of energy and CO_2 emissions pathways have been widely criticized (Rosen and Guenther, 2015; Scrieciu et al., 2013), in particular the basic assumption of energy-abundance (Höök and Tang, 2013). Several studies, using different economic (Capellán-Pérez et al., 2016) and geological models (Berg and Boland, 2014; Brecha, 2008) to relate CO_2 emissions and supply projections, have shown that a decline in fossil fuel production will constrain mitigation options and future climate impacts. Surprisingly, the structural implications of the fossil transition within the oil sector (aging of conventional oil fields and the transition to unconventional oils) on required energy investments and GHG emissions, and the resulting consequences for climate change mitigation pathways, are yet to be comprehensively investigated.

The purpose of this paper is to gain better insight into the effects of the aging and "unconventionalization" processes of the global oil sector, so as to support the assessment of the option space for plausible decarbonization pathways. By using relational analysis, we first characterize the biophysical performance of the global oil sector across multiple scales and dimensions, using data from seventy-one oil fields and associated refineries world-wide, representing about 25% of global production. Subsequently, we simulate a progressive aging of existing oil fields and an increasing exploitation of unconventional oil sources, and assess the related changes in the consumption of energy carriers and CO_2 emissions. For each simulation, we focus on the change in emissions and energy requirement per barrel, where the barrel is a weighted average of viable sequential pathways of oil extraction and refining. We then use the forecasted level of oil supply worldwide of the IEA "Stated Policies Scenarios" (International Energy Agency (IEA), 2019) to provide a rough estimate of the absolute magnitude of the increase in CO_2 emission that may be expected from the fossil transition in the oil sector.

The rest of this paper is structured as follows. Section 2 explains the methodology and data sources. Section 3 describes the results of the analyses. Section 4 discusses the strength and shortcomings of the approach. Section 5 provides some policy indications and concludes.

2. Materials and Methods

2.1 Relational analysis of the oil sector

Our analytical framework is grounded in Rosen's theory of relational analysis (originally born as 'relational biology') and represents a relatively novel approach for characterizing the performance of complex systems, such as the energy sector (González-López and Giampietro, 2018; Parra et al., 2020).

In brief, in relational analysis an energy system is described as a metabolic network of structural and functional elements (Fig. 12). The study starts from an identification of functional elements for which it is possible to identify expected relations. Only in a second phase, the characteristics of structural elements are studied (Louie, 2017; Rosen, 2005). The distinction between structural and functional strictly depends on the scale of observation and the distinction between tangible (instances) or notional (types) elements considered in the representation. Structural elements are 'tangible elements' such as oil fields or refineries - e.g., the Ghawar field, Fig. 13. These structural elements are associated with structural typologies sharing a common set of metabolic attributes (inputs and outputs profile) - e.g., "Light watery offshore" fields in Fig. 13 or "Medium conversion" refineries in Fig. 12. Different structural elements can be combined together in order to express a functional element – i.e., a 'notional element' described in terms of expected profiles of inputs and outputs. In this case, the metabolic characteristics of functional elements - that are not tangible – can be assessed by calculating the characteristics of the particular mix of structural types making up the functional type. The use of notional elements is essential to describe the performance of the energy system. Examples of notional (functional) elements in Fig. 12 are "Light watery offshore" extraction or "Deep conversion – coking" refining. Both structural and functional elements can be described in quantitative terms as profiles of inputs and outputs through the use of metabolic processors (see section 2.3). The quantification of structural types is derived from the observations of equivalence classes of given instances of structural elements, while functional elements are observed as nodes in the network and calculated as combinations of the characteristics of mixes of structural elements (or functional elements at higher levels).

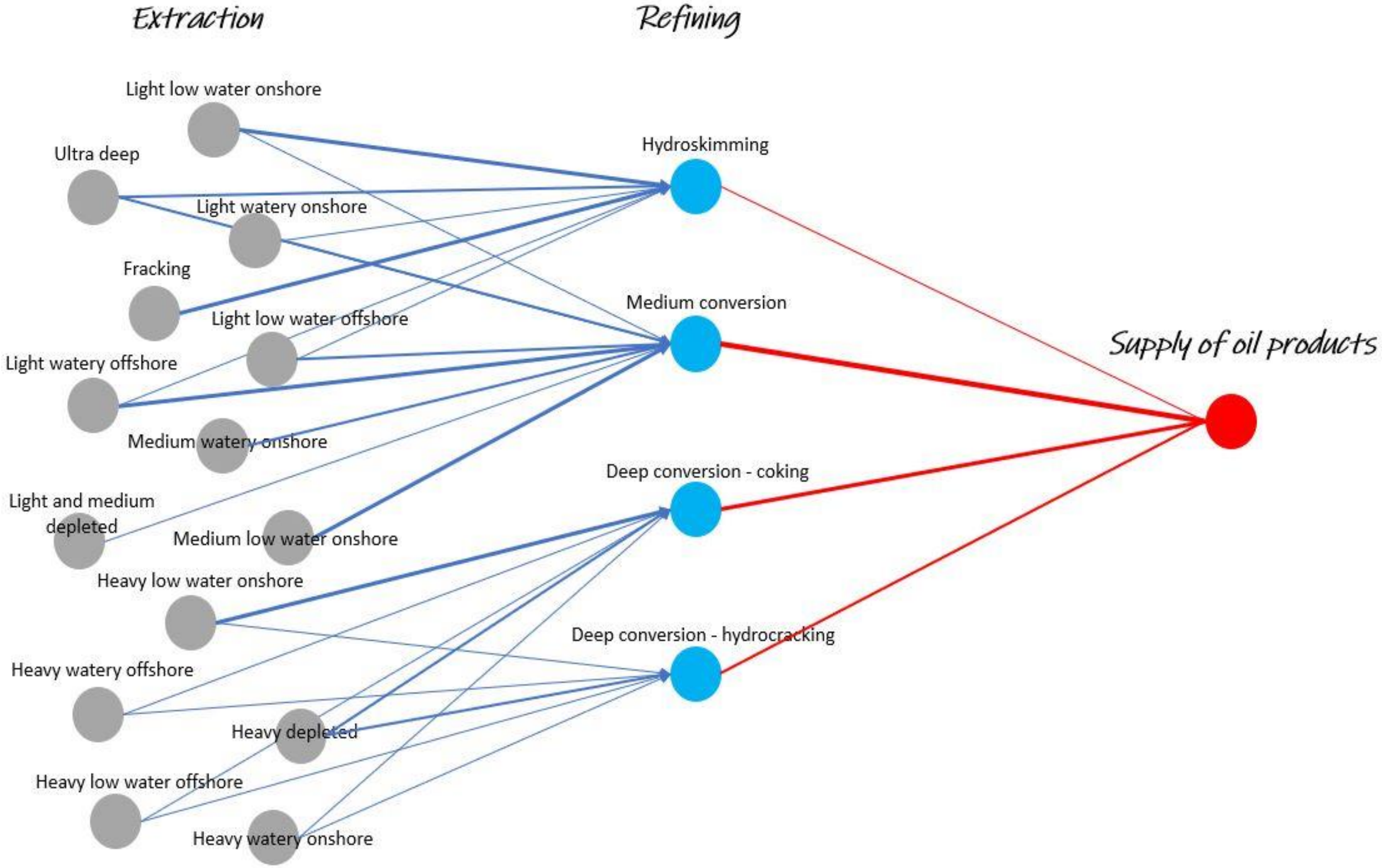

Fig. 12 The oil sector as a metabolic network. Extraction typologies are represented in blue, refining typologies in green. Components are related by the functional entailment of producing fuels (red) at the superior scale. For the sake of simplicity, only functional elements are shown.

The relations over the nodes in the network (the *identities* of "metabolic processors" in the jargon of relational analysis) can be scaled in two different ways (see Fig. 13):

1. Parallel composition, when different profiles describing different classes of functional elements (i.e., different types of extraction or refining) are composed, according to their relative contribution (i.e., percentage in the mix), into an aggregated metabolic profile of the functional element defined at a higher level of analysis. This is illustrated by the undirected edges between nodes across levels in Fig. 13.
2. Sequential pathway, when different structural or functional elements are linked by a material entailment, i.e., the output of a node is the input of the next node. This is illustrated by the directed edge between 'Extraction' and 'Refining' (on the same level) in Fig. 13.

First, structural elements at *level n-3* are combined together in a parallel composition to form structural types at *level n-2*. In other words, different instances (fields) of oil extraction, such as the "Ghawar field", are combined together into different types of extraction, such as "Ultra-Deep". Then, those structural types are combined into the functional element "Extraction" at *level n-1*. At that level, different functional elements – i.e., Extraction and Refining – can be combined into a sequential pathway determining the characteristics of a functional element – i.e., "Fuels Supply" – defined at the superior *level n*. At the end of this chain, a mix of different final oil products (see Appendix, Table A7) is made available for end-uses in the other sectors of society and in the energy sector itself (internal loop of energy carriers to produce energy carriers, i.e., 'energy-for-energy'). The composition of this final mix of oil products depends on the relative composition and specific identities of the structural and functional elements in the metabolic network.

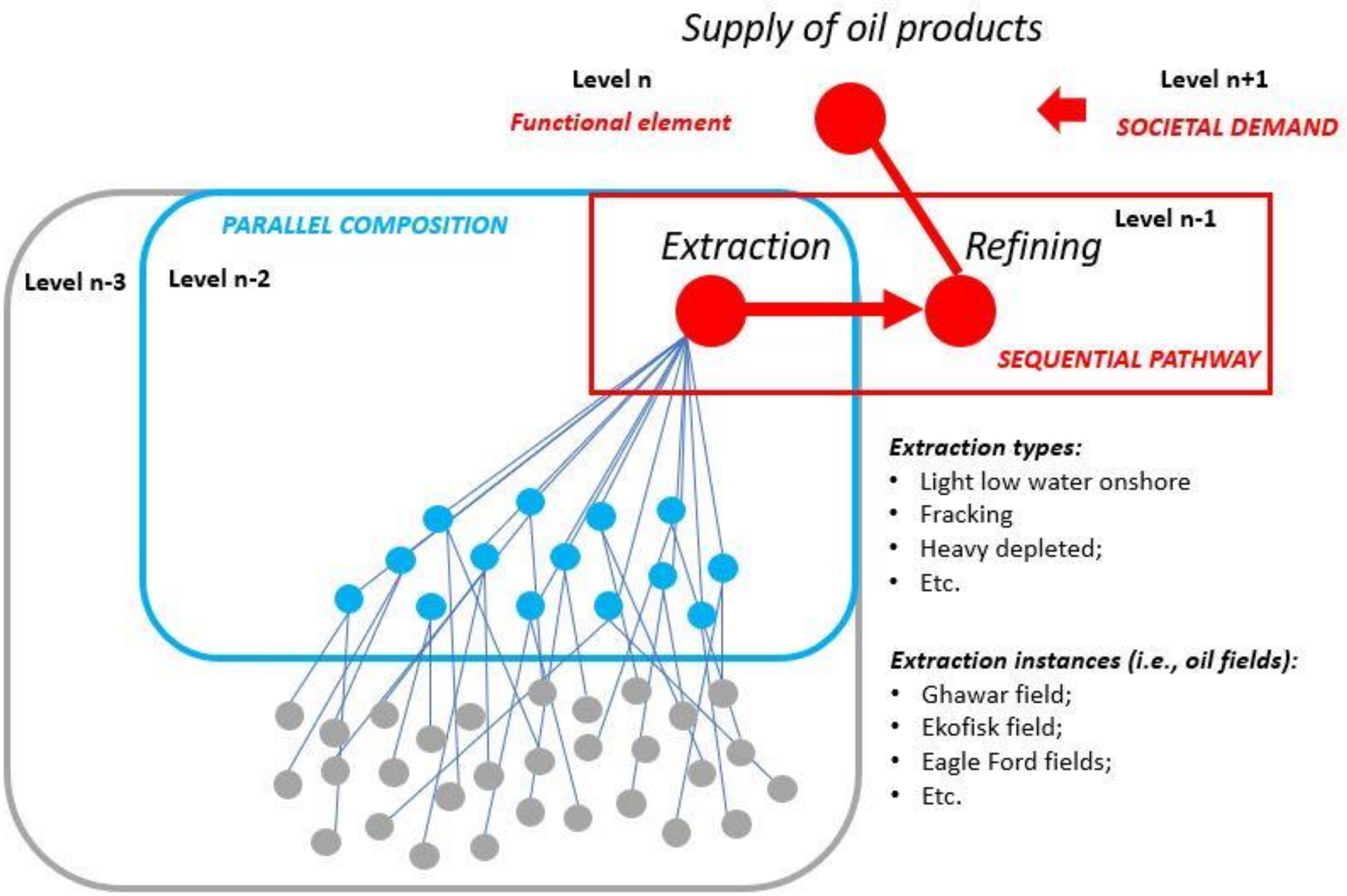

Fig. 13 Examples of scaling: sequential pathway and parallel composition of structural and functional elements. The sequential pathway represents a material entailment (directed edge): the output of extraction is the input for refining. The parallel composition represents a hierarchical entailment (undirected edges) and interrelates two or more levels: the elements are tied together by the same function at higher scales. NB. Elements can be either structural or functional, depending on the scale of observation: they can be functional processes in relation to higher levels, or structural types ('blueprints') for elements at lower levels.

In the present study, a two-stage sequential pathway has been considered: (i) extraction: extraction processes, in-site upgrading and/or transformations and transport to refineries; and (ii) refining. To simplify the analysis and for data availability reasons, the sequential stage of "transportation" has been included in the step of "extraction", as a flat overhead.

2.2 Taxonomy of structural and functional elements

2.2.1 Oil fields and Extraction

The taxonomy of oil fields (typologies of structural elements) and the corresponding extraction processes (typologies of functional elements) has been defined based on the following criteria:

1. API Gravity - 3 categories: (i) light, (ii) medium, (iii) heavy oils;
2. Water content - 2 categories: (i) low water, (ii) watery;
3. Location – 2 categories: (i) onshore, (ii) offshore.

The combination of these criteria results in twelve different typologies of oil fields and corresponding extraction processes (illustrated in Fig. 12). To these, an additional four types were added, namely: (i) "Fracking" and (ii) "Ultra-Deep" crudes, both of which are characterized by distinct technologies of extraction with specific biophysical requirements and environmental burdens; (iii) "Light and medium depleted" and (iv) "Heavy depleted" oils, both characterized by a long history of exploitation and evident signs of aging (depletion).

In this work, only fracking and ultra-deep crudes are referred to as unconventional oils. Given the ambiguity in the use of the label "unconventional" (Gordon, 2012; Ramírez-Corredores, 2017), this semantic choice was made to distinguish them from the categories "heavy" and "heavy depleted". For the purpose of this analysis, heavy and depleted fields, that, under specific circumstances (like advanced EOR techniques or very high viscosity) can be considered unconventional oil, are accounted for separately, in order to enrich the taxonomy and appreciate the effect of time on a greater variety of crudes.

2.2.2 Refineries and Refining

Four different typologies of refining processes (functional elements) have been considered to classify the refineries (facilities, structural elements) in our data base:

1. Hydroskimming conversion;
2. Medium conversion;
3. Deep conversion - coking;
4. Deep conversion – hydrocracking.

The choice of coking versus hydrocracking depends on the refiner. Hydrocracking maximizes middle distillates, while coking maximizes light distillates. The choice entails different input requirements and products outcome. As detailed in Section 2.4, all the deep conversion refining in our simulations is assumed to be coking, even if both typologies have been considered and assessed within the space of viable sequential pathways. Note that the complexity of refining increases with API gravity and sulfur content of the crude oil: more energy and technical intensive processes are required to transform the heavier and dirtier oils.

2.2.3 Identifying viable sequential pathways

Using the taxonomy of typologies of the structural and functional elements defined in the previous subsections, different sequential pathways were constructed according to the metabolic network shown in Figure 1. Note that not all possible combinations of extraction and refining processes are viable: even if technologically possible, heavy oils usually are not processed in hydroskimming refineries due to the low yields of high quality (and high economic value) products such as gasoline and diesel. In the same way, the economic viability of low and medium complexity refineries is increased with the selective processing of light and medium oils. Hence, we have used the following criteria for generating sequential pathways:

- Light, medium and ultra-deep oils are associated with hydroskimming or medium conversion refining depending on their sulfur content;
- Tight oil from fracking always goes to hydroskimming refineries;
- Heavy oils can be refined by medium or deep conversion plants, either by coking or hydrocracking facilities;
- For the purpose of refining, light, medium and heavy depleted oils are assumed to be equivalent (in physical-chemical properties) to their respective non-depleted variant and linked to same refining typology.

The resulting viable sequential pathways are characterized in the results section (see section 3.1 and Table 4).

Once viable sequential pathways have been identified, it is possible to characterize their relative importance (contribution) in the supply chain. In this way, the analyst can scale up the assessment of the requirements of inputs (mix of energy carriers) and the CO_2 emissions produced for the supply of one barrel of products to the *level n*. This quantitative characterization has been done for the actual situation (diagnostic) and for scenarios. Results are reported in section 3.

2.3 The metabolic processor

The metabolic processor is an analytical tool organizing quantitative information in the form of a data array. It can be interpreted as an extended production function in that it defines an expected (functional) or observed (structural) profile of inputs and outputs associated with a specific process, such as oil extraction or refining (González-López and Giampietro, 2017). Metabolic processors allow for a quantitative representation of the relations between structural and functional elements across levels (Fig. 13). In this way, we can quantify the functional units of the oil sector by bridging the relations between processors, either looking at sequential pathways determined by a material entailment or by a parallel composition, when considering a functional entailment (different elements expressing the same function at the higher level). The choice of a mix of functional and structural elements depends both on biophysical (set of typologies of oil fields and refineries available) and socio-economic constraints (set of economically viable products determined by societal demand). The use of metabolic processors for the characterization of the metabolic pattern of social-ecological systems has been described in detail in (Giampietro et al., 2021).

Quantification starts out from data that refer to the characteristics of specific instances of structural elements, i.e., the observed fields and refineries. The inputs and outputs for the metabolic processors used in this study include:

- For extraction processors:
- Net consumption of natural gas (NG) and refinery fuel gas (RFG) (MJ/bbl);
- Net and indirect (associated with imports) consumption of electricity (MJ/bbl);
- Net and indirect consumption of diesel (MJ/bbl);
- On-site and indirect CO_2 emissions ($kgCO_{2eq}$/bbl);

- Daily Production Capacity (bbl/day).
- For refining processors:
- Net consumption of natural gas and refinery fuel gas (MJ/bbl);
- Net consumption of electricity (MJ/bbl);
- Net consumption of diesel (MJ/bbl);
- Net consumption of coke (MJ/bbl);
- On-site CO_2 emissions ($kgCO_{2eq}$/bbl);
- Daily refining capacity (bbl/day);
- Product slate (%).

For a detailed explanation of the data processing based on the OCI Climate Index data base within our relational procedure, see the Appendix.

Figure 14 illustrates the processor of the functional element “Fracking” (extraction). This simplified illustration shows the main features of the organization of the information in a data array. The technosphere, shown in the upper right part of Fig. 3, refers to the conversions (end uses) of flows taking place under human control. This includes: (i) the input requirement of energy carriers (natural gas, diesel, electricity and coke) to produce oil (the energy-for-energy loop); and (ii) the output of barrels of crude (that then becomes the input consumed by refineries). Note that the internal energy loop for natural gas is usually closed at the level of the extraction processor, while diesel, electricity and coke are coming from ‘outside’, i.e., either from a higher level of the oil sector (after refining) or from imports (nonetheless, for some oil fields also natural gas is imported). The information in the technosphere is relevant for the economic and technical viability of the process and to assess the correct output of oil products (Table A7). In the lower left part of Fig. 14, inputs and outputs that are relevant for studying processes outside of human control (in the biosphere) are shown. These include: (i) the supply capacity of oil (and associated gas) stocks (i.e., oil fields); and (ii) the sink capacity of primary biophysical flows (CO_2 emissions in this study).

The same structure of inputs and outputs is used to quantify relations between structural and functional elements across all levels of the entire metabolic network, thus allowing the generation of an integrated quantitative representation. Note that metabolic processors can be expressed either as extensive processors (based on a given size of the flows) or unitary processors (benchmarks, per unit of throughput) (González-López and Giampietro, 2017). Further explanations on the construction of metabolic processors for the characterization of the performance of the oil sector are available in (González-López and Giampietro, 2018; Parra et al., 2020).

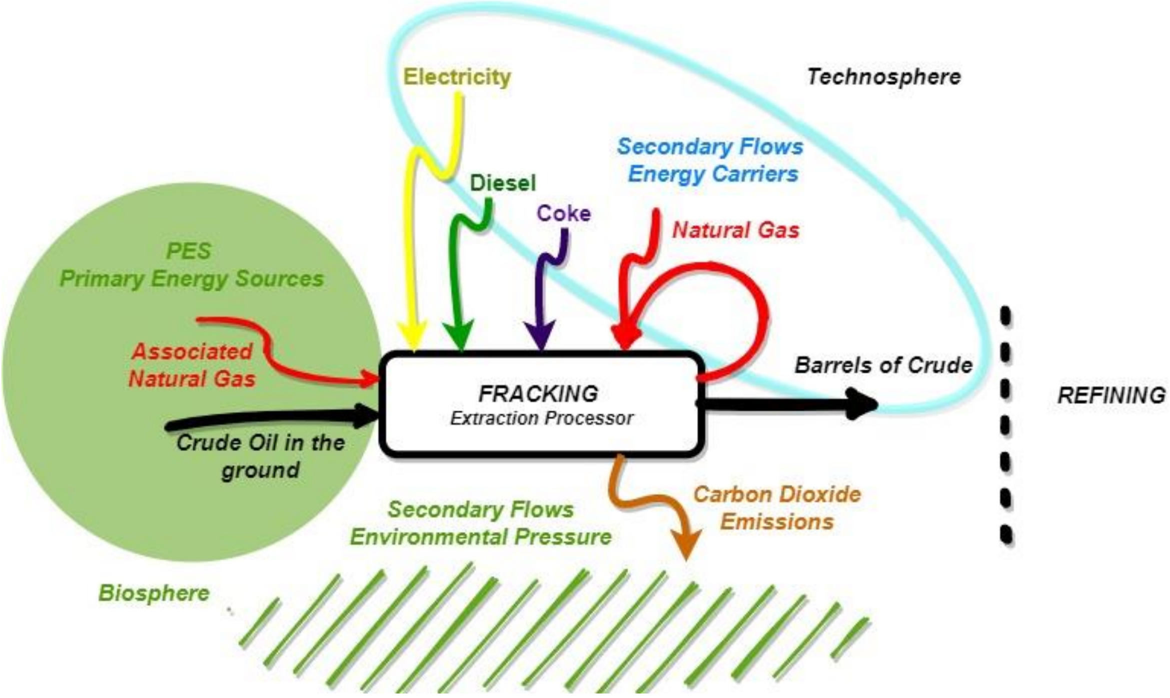

Fig.14 Metabolic processor for the functional element "Fracking"

2.4 Data Sources and Assumptions

2.4.1 Diagnosis of the current situation

The relational analysis has been implemented using raw data from seventy-one oil fields and associated refineries world-wide, representing 25% of global production, from (Carnegie Endowment for International Peace, 2018). Specifically, OPGEE_v1.1_draft_e is the data source for extraction processors, while data for refining processors are from PRELIM v.1.2 (https://www.ucalgary.ca/energy-technology-assessment/open-source-models/prelim). In addition, in order to characterize the current supply system at the global level, data on the relative contribution of different crudes from (ENI, 2018) have been used, referring to the year 2017.

In 2017, light, medium and heavy oils represented 31.7%, 54.8% and 13.5% respectively of the total crudes extracted (ENI, 2018). Tight oil (entirely light) from fracking accounts for 30% of the North American production (2018), that represents 12% of the world total extraction. We assumed that the amount from ultra-deep fields (>3000 m) worldwide equals that of tight oils, equally divided between light and medium crudes (this is relevant in order to associate the ultra-deep crudes with the appropriate refining). Therefore, overall unconventional oils (fracking and ultra-deep) are assumed to represent 7% of global production (Kapustin and Grushevenko, 2018).

In order to assign a proper relative share to the other 14 categories, we used production capacity from OPGEE v1.1_draft_e assessment (Carnegie Endowment for International Peace, 2018). The formula used for the calculation is a weighted average on the production capacity of each typology:

$$A = \frac{\sum_k^s \sum_{j=1}^r \sum_{i=1}^n PC_{i,j,k}}{\sum_{k=1}^s PC_k}$$

Where PC is the production capacity, n = number of oil fields of the same typology, r refers to sub-typologies of extraction considering water content and location (4), s are the sub-typologies of extraction considering API gravity (3). The contribution from depleted fields was rounded to 10% ("Light and medium depleted" fields 9% and "Heavy depleted" fields 1% on the total). The final result is reported in the column 'current situation' in Table 2, showing the relative contributions of all extraction typologies and taken as baseline reference for generating simulations.

Table 2. Relative contribution of extraction typologies to the total oil supply in the current situation (2018) and in the four simulations. Unconventional oils are reported in green.

Extraction typologies	**Current situation**	**Simulation 1**	**Simulation 2**	**Simulation 3**	**Simulation 4**
Light low water onshore	16%	8%	0%	0%	**1%**
Light low water offshore	3%	3%	3%	3%	3%
Medium low water onshore	28%	14%	0%	0%	**10%**
Medium low water offshore	13%	13%	13%	13%	13%
Light watery onshore	2%	9%	12%	12%	2%
Light watery offshore	1%	1%	1%	1%	1%
Medium watery onshore	4%	16%	22%	22%	4%
Medium watery offshore	4%	4%	4%	4%	4%
Heavy low water onshore	4%	4%	4%	0%	4%
Heavy low water offshore	2%	2%	2%	0%	2%
Heavy watery onshore	6%	6%	6%	0%	6%
Heavy watery offshore	0%	0%	0%	0%	0%
Ultra-Deep	4%	4%	4%	4%	**20%**
Fracking	4%	4%	4%	4%	**20%**
Light and medium depleted	9%	12%	24%	24%	9%
Heavy depleted	1%	1%	1%	14%	1%

Total	**100%**	**100%**	**100%**	**100%**	**100%**

2.4.2 Anticipation of possible scenarios

Starting from the current situation defined above (the actual composition of the global supply), four different simulations were explored (see Table 2). In all simulations and also in the 'current situation', the same overall oil supply is guaranteed and kept constant at 105 million barrels per day – from IEA's forecast "State Policies Scenario" (2030) - but the relative composition of the various structural and functional elements (extraction, refining) changes because of aging and the fossil transition toward unconventional sources. The assumptions for the simulations are:

- Simulation #1: 50% of the oil production from light and medium, low-water, onshore fields shifts to the respective watery types, and 50% of the light and medium, watery, onshore fields becomes depleted ("Light and medium depleted" fields).
- Simulation #2: the same as Simulation#1, but now 100% of the oil production from the selected types changes functional category;
- Simulation #3: same as Simulation #2, but in addition all heavy production types move to the heavy depleted type.
- Simulation #4: ultra-deep and fracking cover 40% of total production (20%+20%), at the expense of light and medium, low water and onshore pathways.

The first three simulations focus on the progressive decrease in the quality of existing oil fields (low-water fields becoming watery and depleted), which, based on the current evidence, is expected to take place during the next 40 years, as already stated in the introduction. The fourth simulation looks at the potential effects of a sensible increase in unconventional oil production, probably larger than what is considered plausible (Kapustin and Grushevenko, 2018), but still useful to highlight possible trends. The simulations are implemented by changing the relative contributions of the different functional types of extraction to the global production. As stated earlier the overall supply remains constant. The characteristics (unitary representation) of each type of extraction processor (its identity) is based on the current situation, and are assumed to remain constant. This assumption is discussed in section 4.2.

Information about the relative contributions of the specific sequential (extraction-refining) pathways inside the supply system is needed to scale up the information across the metabolic network both in the current situation and in the scenarios. These assessments are based on the data from (ENI, 2018). Ultra-light and light & sweet oils (73.5% of light types) are associated with hydroskimming technology, medium and heavy sweet crudes are converted in medium conversion facilities while the sour heavy crudes in deep refining plants. Tight oil from fracking goes 100% to hydroskimming; light, ultra-deep oils are supposed to be 50% light and 50% medium and follow the rules above, light and medium depleted are 100% medium converted and, finally, heavy depleted are 100% led to deep conversion. The refining shares have been kept constant throughout all scenarios. Table 3 shows a schematic representation of the refining assumptions.

Table 3. Refining shares associated with extraction typologies

Associated refining types	**Hydroskimming**	**Medium conversion**	**Deep conversion**
Light low water onshore	74%	26%	0%
Light low water offshore	74%	26%	0%
Medium low water onshore	0%	100%	0%
Medium low water offshore	0%	100%	0%
Light watery onshore	74%	26%	0%
Light watery offshore	74%	26%	0%
Medium watery onshore	0%	100%	0%
Medium watery offshore	0%	100%	0%
Heavy low water onshore	0%	19%	81%
Heavy low water offshore	0%	19%	81%
Heavy watery onshore	0%	19%	81%
Heavy watery offshore	0%	19%	81%
Ultra-Deep	37%	63%	0%
Fracking	100%	0%	0%
Light and medium depleted	0%	100%	0%
Heavy depleted	0%	0%	100%

Note that all deep refining is assumed to be done with coking facilities. For our purposes, distinction between coking and hydrocracking has not been considered, since we are not taking into account changing demand patterns. However, a ‘hydrocracking’ scenario would be more emission intensive. Coking optimizes gasoline production. Its energy carrier input requirements as well as emissions are lower than with hydrocracking technology, which is better for diesel production.

2.4.3 “Stated Policies Scenario”

By combining the unitary quantification per barrel, obtained from the scaling of metabolic processors into viable sequential pathways, with the relative extraction and refining shares, it becomes possible to appreciate the actual consumption of energy carriers in the system and CO_2 emissions, as well as products output per barrel in each scenario. The size of the system (barrels produced per day/year) can be scaled up to the magnitude required. In this work, we refer to the International Energy Agency’s (IEA) World Energy Outlook 2019 “Stated Policies Scenario” (International Energy Agency (IEA), 2019): the global oil production is projected to be 105 million barrels per day in 2030 and 106 million in 2040. We use the former quantity to scale up the analysis to the global perspective, both in the current scenario and simulations. This was done to specifically assess the qualitative effects of aging and “unconventionalization” against a fixed (quantitative) supply.

2.4.4 Data representation: normalized chromatic intensity

Maintaining data disaggregated is important for preserving a multi-dimensional information space (e.g., processors’ benchmarks for different typologies of energy carriers) and identifying useful patterns. However, data proliferation represents a significant challenge for the visualization of quantitative information. For this reason, in several tables (Tables 3-5), we have used Normalized Chromatic Intensity (NCI), that is gradients of color intensities, to facilitate the recognition of patterns (Velasco-Fernández et al., 2018). The creation of NCI representations follows three steps: first, identifying the maximum and minimum values for the selected variable over the set of data; second, calculating the range of values for the variable (difference between maximum and minimum value of the series); and third, assigning proportional intensities of color for the intermediate values in relation to its normalized distance to the extremes of the interval (maximum color intensity for highest values and minimum intensity for lowest ones). In this way, chromatic visualizations of patterns over the observed dimensions are obtained and outliers in the data set are easily identified.

3. Results

3.1 Typologies of production pathways and diagnostic of current situation

Table 4 summarizes the consumption of energy carriers and CO_2 emissions per barrel of oil products supplied across current, viable sequential pathways of the oil sector. Table 5 reports the arrays of oil products expected as outcome from each refining (functional) typology. Further details about mixes of oil products per sequential pathway are provided in the Appendix, Table A6, while in Tables A4 and A5 extraction and refining processes are separately reported.

Table 4. Viable sequential pathways of the oil sector (extraction - refining), requirement of energy carriers (energy-for-energy loop) and CO_2 equivalent emissions per barrel, unitary description

Sequential pathways		***MJ/bbl***				***KgCO2eq/bbl***
Types of extraction	**Associated types of refining**	**NG and RFG**	**Electricity**	**Diesel**	**Coke**	**GHG emissions**
Light low water onshore	Hydroskimming	387	13	7	0	42
	Medium conversion	545	19	7	25	56
Light low water offshore	Hydroskimming	473	17	13	0	50
	Medium conversion	630	23	13	25	63
Medium low water onshore	Hydroskimming	496	12	8	0	63
	Medium conversion	653	18	8	25	77
Medium low water offshore	Hydroskimming	330	12	5	0	37
	Medium conversion	487	17	5	25	50
Light watery onshore	Hydroskimming	722	47	6	0	95
	Medium conversion	879	53	6	25	109
Light watery offshore	Hydroskimming	820	18	5	0	92
	Medium conversion	977	23	5	25	105
Medium watery onshore	Hydroskimming	654	23	14	0	17
	Medium conversion	811	29	14	25	107
Medium watery offshore	Hydroskimming	471	21	4	0	48
	Medium conversion	628	27	4	25	62
Heavy low water onshore	Medium conversion	2025	27	1	25	174
	Deep conversion - coking	2544	32	1	49	214
	Deep conversion - hydrocracking	2848	39	1	41	236
Heavy low water offshore	Medium conversion	785	21	13	25	86
	Deep conversion - coking	1305	37	13	49	126
	Deep conversion - hydrocracking	1609	43	13	41	149
Heavy watery onshore	Medium conversion	672	37	20	25	83
	Deep conversion - coking	1192	53	20	49	123
	Deep conversion - hydrocracking	1496	60	20	41	145
Heavy watery offshore	Medium conversion	525	24	0	25	51
	Deep conversion - coking	1045	40	0	49	91
	Deep conversion - hydrocracking	1349	46	0	41	113
Ultra-Deep	Hydroskimming	496	15	40	0	68
	Medium conversion	654	21	40	25	82
Fracking	Hydroskimming	405	12	17	0	77
Light and medium depleted	Hydroskimming	728	44	7	0	72
	Medium conversion	886	50	7	25	86
Heavy depleted	Medium conversion	2391	26	1	25	158
	Deep conversion - coking	2911	42	1	49	199
	Deep conversion - hydrocracking	3215	48	1	41	221

Table 5. Relative composition of the oil products per barrel for different (functional) typologies of refining processors. Abbreviations: LHE: Liquid Heavy Ends.

	Hydroskimming	Medium Conversion	Coking	Hydrocracking
Gasoline	29%	36%	44%	38%
Jet Fuel	23%	19%	11%	11%
Diesel	10%	18%	31%	40%
Fuel Oil	10%	0%	0%	0%
Coke	0%	0%	10%	8%
LHE	28%	26%	3%	3%

From a unitary perspective, heavy and depleted pathways are, not surprisingly, the most energy and emission intensive (Table 4 and Fig. 15). But when enlarging the scale of assessment, considering the global production capacities of each typology, the picture changes. In fact, heavy oils, although most polluting in unitary terms (Table 4), are not a major reason for concern because of their limited capacity of production. When studying them using the "extensive processor" (aggregated quantities of flows), they do not play a substantial role, neither in delivering fuels nor in consuming energy carriers and emitting CO_2 (Table 6 and Fig. 16).

Comparing "Heavy low water onshore" with "Light low water onshore" pathways on a per barrel basis, the former shows a +311-562% emission range per barrel (depending on the typology of refining). However, the bulk of the global production (Table 2) is provided by light and medium, low-water and onshore fields, which together cover up to 45% of the worldwide crude supply. They account for the largest consumption of energy carriers and related emissions in the energy sector (Table 6 and Fig. 16). Currently, all the heavy and depleted pathways together account for only 28 $kgCO_{2eq}$ per barrel ('GHG emission' column, Table 6), equal to the sum of the light and medium low-water onshore pathways, at 29 $kgCO_{2eq}$/bbl. Nonetheless, heavy and depleted pathways are relevant considering their possible growth in the overall mix in the near future ("too big to ignore" (Hongjun et al., 2016)).

These results show the importance of maintaining non-equivalent representations of the oil sector to better inform decision makers by triangulating intensive (unitary benchmarks per types) and extensive descriptions (the extensive processors indicating the size of instances of types). Considering only emissions per barrel as if every sequential pathway had the same importance, misses the implications of the relative size and may lead to policy decisions with limited efficacy, as is the case with "smart taxes" on high-carbon oils (Gordon and Mathews, 2016).

Table 6. Requirement of energy carriers (energy-for-energy loop) and CO_2 equivalent emissions per barrel, weighted by the relative contribution of sequential pathways (Table 2) in the current situation. Unitary description.

Current Situation	***MJ/bbl***				***kgCO2eq/bbl***
	NG andRFG	**Electricity**	**Diesel**	**Coke**	**GHG emissions**
Light low water onshore	67	2,3	1,1	1,0	7,1
Light low water offshore	14	0,5	0,4	0,2	1,5
Medium low water onshore	184	5,1	2,2	7,1	21,7
Medium low water offshore	63	2,3	0,6	3,3	6,5
Light watery onshore	19	1,2	0,2	0,2	2,5
Light watery offshore	8	0,2	0,0	0,1	0,9
Medium watery onshore	29	1,0	0,5	0,9	3,8
Medium watery offshore	24	1,0	0,2	1,0	2,4
Heavy low water onshore	105	1,3	0,0	1,9	8,8
Heavy low water offshore	23	0,6	0,2	0,9	2,2
Heavy watery onshore	65	3,0	1,2	2,7	6,8
Heavy watery offshore	4	0,2	0,0	0,2	0,4
Ultra-Deep	21	0,7	1,5	0,6	2,8
Fracking	15	0,4	0,6	0,0	2,8
Light and medium depleted	80	4,5	0,7	2,3	7,8
Heavy depleted	29	0,4	0,0	0,5	2,0
Total	**750**	**25**	**9**	**23**	**80**

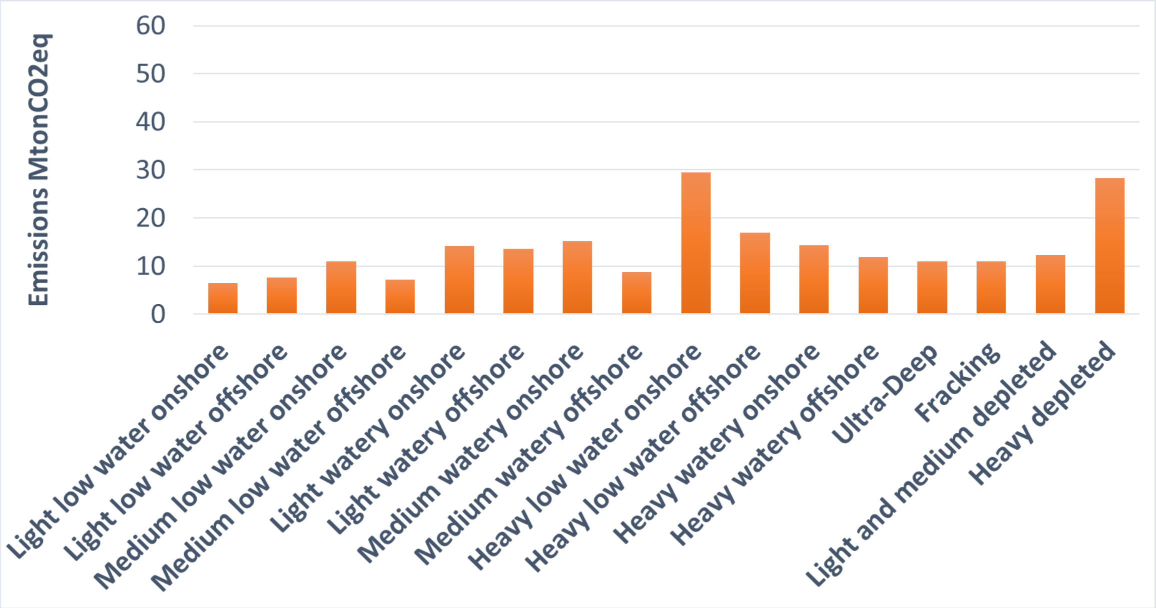

Fig. 15 Global annual absolute CO_2 emissions if oil supply would be equally distributed between sequential pathways - i.e., if every supply share in the columns of Table 2 were 6.25% - under the IEA's (World Energy Outlook 2019) "Stated Policies Scenario" 2030 production assumption (105 million barrels per day).

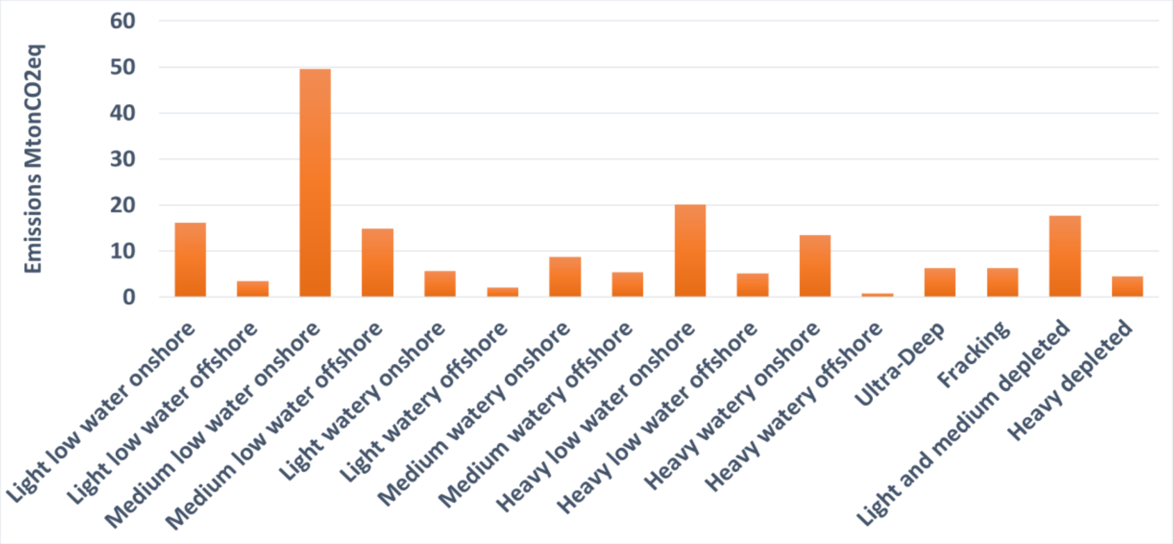

Fig. 16 Global annual absolute CO_2 emissions for the current relative composition of sequential pathways of oil supply under the IEA's (World Energy Outlook 2019) "Stated Policies Scenario" 2030 production assumption (105 million barrels per day).

3.2 Results of simulations

In this section, it is anticipated what will happen to the energy carrier requirements and CO_2 emissions of the energy sector when the relative contribution to the oil supply from depleted and watery oil fields progressively increases (simulations 1-3) or when the energy sector increasingly relies on unconventional sources (simulation 4).

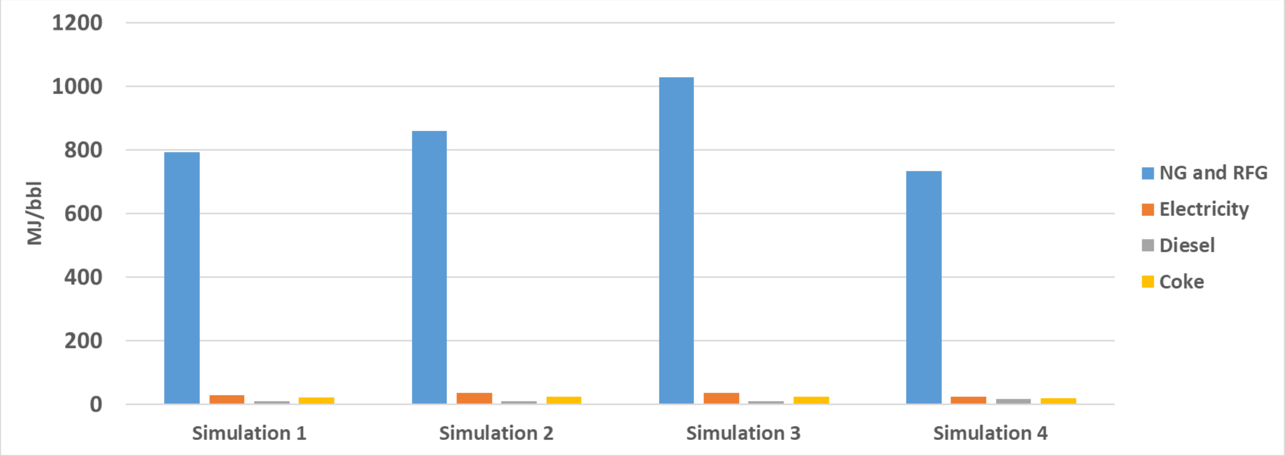

Fig. 18 Requirement of energy carriers per barrel of oil products for the four simulations provided.

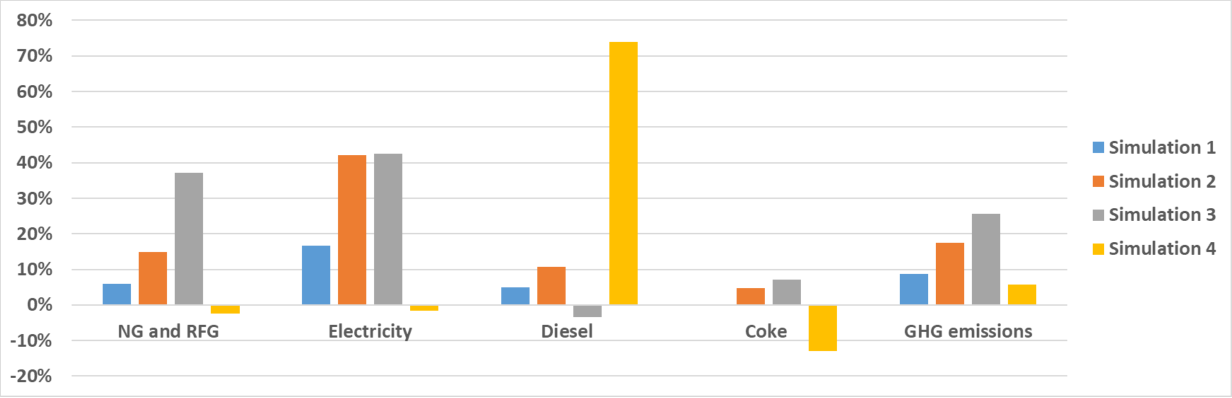

Fig.17 Comparative average increase per barrel of oil products in the requirement of energy carriers and CO_2 *emissions between the current situation (baseline) and the four simulations provided.*

Energy carrier requirements per barrel of oil for the four simulations is reported in Fig. 17. Energy carriers considered are natural gas (NG) and refinery fuel gas (RFG), electricity, diesel and coke. The relative increase in energy carrier requirements and CO_2 emissions of the 4 simulations compared to the current situation (baseline) is shown in Fig. 18.

In simulations 1-3, watery and depleted pathways progressively gain weight in the oil supply mix at the expense of light and medium low-water onshore ones. Since the former pathways are more intensive in terms of consumption of energy carriers and emissions, each barrel produced will cause higher emissions compared to the current situation. To maintain the current output of hydrocarbon fuels, a 6-26% increase in CO_2 emissions per barrel should be expected depending on the simulation considered (Fig. 18). The majority of those emissions are due to increased consumption of natural gas and electricity. Again, the difference between extensive and intensive characteristics is important here. Even if the use of natural gas and electricity as energy carriers is less emission intensive per unit of energy delivered (compared with diesel or coke, for example), it is the size of the supply of oil that matters. Incidentally, there are serious doubts about the possibility of maintaining oil production at the current level, since productivity per well drops substantially with reservoir depletion and the related increase in water content (waterflooding is a common secondary oil recovery technique to keep production high in spite of the deterioration of field quality) (Allison and Mandler, 2018; Craig Jr, 1971).

Compared to the effects of aging (simulations 1-3), a shift to unconventional pathways (simulation 4) appears less dramatic in terms of emission increases (Fig.

18). Although the use of diesel almost doubles in this simulation, in absolute terms this increase is much smaller than the increase in natural or refinery gas consumption observed in simulations 1-3, hence the relative emission increase per barrel is smaller. However, other relevant aspects, not explored in the present work, should be considered, such as technical difficulties in the extraction of ultra-deep fields (Haige et al., 2020) and their quick pace of decay requiring a continuous capital investment in power capacity for drilling new wells (Brandt et al., 2015).

The simulations indicate that the main drivers of increasing emissions are: (i) the increase in natural gas consumption because of aging; (ii) the increase in diesel consumption for the "unconventionalization" of oil sources. Natural gas is used heavily in extraction to generate the heat needed for EOR techniques: waterflooding and most of tertiary EOR technologies employ natural gas to pump fluids (water, steam or gases) and generate steam or direct heat to reduce the viscosity in the reservoir in order to extract crude. Deep refining is especially intensive in natural gas use due to the various hydrocracking, hydrotreating, desulfurization and reforming facilities needed to treat heavy oils and make the fuels compliant with environmental laws. Diesel is used mainly in ultra-deep extraction, due to the (almost exclusively) offshore location and geological nature of the reservoir (depth). In Tables A4 and A5 of the Appendix, more detailed quantitative results are provided.

A last observation is due on the quality of the oil products supplied. In our scenarios the relative composition of the mix of oil products supplied to society remains fairly constant (see Appendix, Table A7). This indicates that the quality of the final output is not significantly affected by aging or increased reliance on unconventional sources.

Given the large size of the global oil sector, these simulations are relevant for a responsible discussion about climate change. Depending on the simulation, the absolute increase in GHG emissions is between 251-747 $MtCO_{2eq}$/year for a total global production of 105 million barrels per day. These extra emissions are in the same order of magnitude as the emissions of the agricultural or manufacturing & construction sector of the EU27 and, in simulation 3, nearly comparable to the emissions of the EU transportation system (Climate Watch Data, 2016) (see Fig. 19).

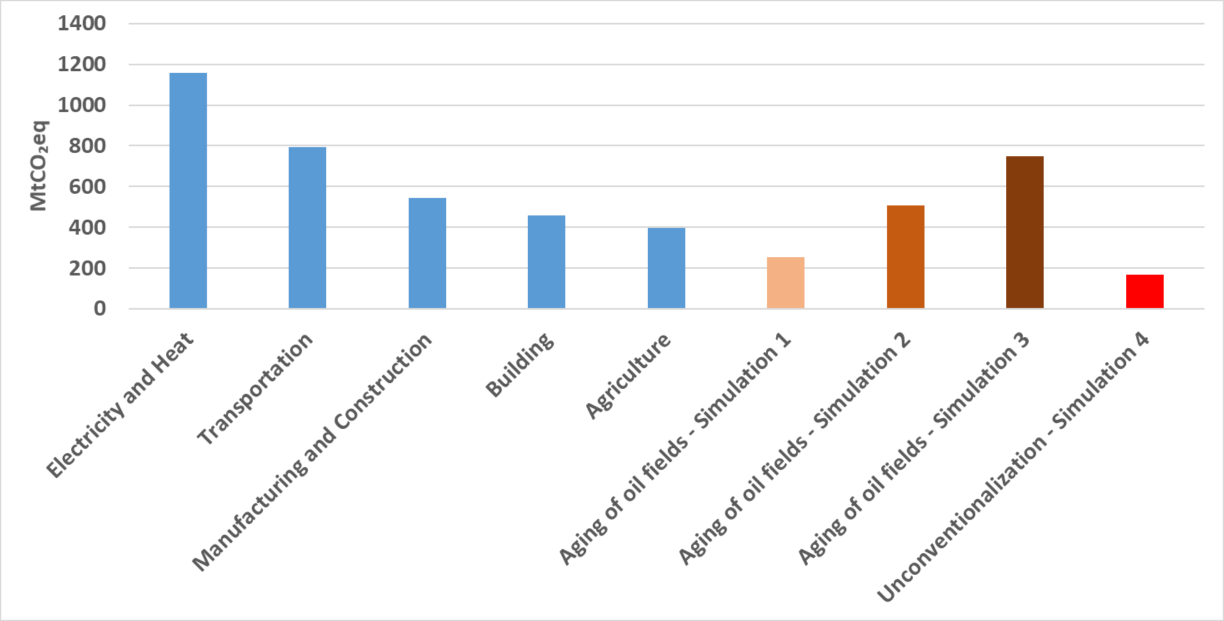

Fig.19 CO_2 equivalent emissions per end-use in EU27 compared with the marginal emission increase for the four simulations performed.

Thus, if we want to meet the energy demand of 105 million barrels per day by 2030 under the current energy policy frameworks and international pledges worldwide (i.e., the "Stated Policies Scenario"), we need to compensate for the declining performance of the oil sector by reducing emissions elsewhere. The "unconventional revolution" (Maugeri, 2012) will aggravate, not solve the problem: even if the unconventional barrel is slightly less emission intensive than crude from depleted pathways, emissions per barrel increase compared to the current situation, especially due to intensive diesel consumption in ultra-deep extraction. Renovated abundance of unconventional oil resources will exacerbate the absolute GHG emissions and the pressure on the climate system.

4. Discussion

This section highlights the strength and the novelty of the proposed relational analysis and addresses the limitations of the current study with regard to (i) synchronic versus diachronic analysis to study aging; (ii) input/output variables considered in the metabolic process; (iii) the scope of the study.

4.1 The strength and novelty of relational analysis

Relational analysis provides a robust and versatile tool for biophysical assessment in that it can define *typologies* of extraction and refining processes through the generation of *unitary* metabolic processors based on benchmarks.

Typologies and their unitary processors can be easily compared to each other and can be used to construct scenarios in which the relative contributions of typologies vary. More precisely, different types of oil production and refining can be analyzed in functional terms in relation to the role they play inside the energy sector even when considering energy sectors of different size (either observed or simulated). Indeed, the representation of relational networks based on metabolic processors offers the analyst flexibility. Using this tool, it is possible to integrate the unitary (notional) description with the extensive description (based on observation i.e., statistical data), building a bridge across dimensions and levels of analysis and allowing for the consideration of the effect of size and the spatial location of the energy transformations. Biophysical costs, environmental pressures and the supply of products delivered to society can be scaled across levels and quantified using simultaneously different metrics. Two main advantages of these features are:

1. It allows the analyst to generate a multi-criteria performance space characterizing the supply of oil products using ad-hoc indicators (e.g., specific input/output ratios) related to costs, efficiency and pollution;

2. The multi-scale, multi-dimensional description across different levels of analysis can be tailored to the specific problem the analyst wants to study. For instance, the representation of performance can be fit to relevant levels of analysis, e.g., a single stage of the process, a specific functional element, or the whole supply system.

Finally, as shown in the current study, relational analysis can be meaningfully used in two ways:

- Diagnostic mode, that is the description of the current metabolic pattern of the oil production sector across levels and dimensions of analysis;

- Anticipation mode, that is the creation and evaluation of future scenarios by changing the wiring inside and across the sequential pathways or by assuming different technical coefficients for the structural elements in the nodes.

Defining the constraints on both the biophysical (production process) and socio-economic side (fuel demand), the coherence and sustainability of fuel consumption patterns can be identified and, playing with the relationships found, anticipated.

4.2 Synchronic versus diachronic analysis to study aging

In this study, the changes in time of the functional types of the oil sector (diachronic data of the CO_2 emissions per barrel) are inferred by combining: (i) the benchmarks of structural types observed at a given point in time (synchronic data of the technical characteristics of structural elements); and (ii) anticipated changes in the relative mix of these structural types. This procedure overlooks the effects of possible technological improvements taking place at the level of specific processes (e.g., pumping volumes of flows). Nonetheless, when considering aging and “unconventionalization” as drivers of change, the relational analysis is robust given the comparative relevance of: (i) a possible increase in the technical efficiency within a given structural typology; and (ii) an important change in the mix of structural typologies within the given functional types. Indeed, technical improvements in the efficiency of the technological devices operating at the oil wells (structural elements) are much less relevant than changes in the mix of structural elements (e.g., the relative share of “Heavy watery onshore” or “Light low-water onshore” oil fields) determining the functional typology. The extraction of oil from depleted fields comes with huge amounts of (contaminated) produced water (including formation and injection water and added chemicals). Low-water fields typically show water-to-oil benchmarks of less than 1/4 (80% oil vs 20% water). With progressive depletion, these proportions may easily reach up to 4/1 (20% oil vs 80% water). In such a situation, any potential efficiency improvements per barrel in the individual structural types (at best in the order of 20-30%) are more than offset by the huge increase in the extracted volume to be processed in the new (anticipated) mix determining the functional type. The same holds true for unconventional extraction due to the advanced techniques needed to extract difficult-to-access (ultra-deep and tight oil) crudes. Regarding refining, while ultra-deep and fracking crudes are not problematic for refiners, more complex facilities are needed to process dirtier or stickier oil from aged fields.

For these reasons, we believe that a reliable estimate of the changes in time of the overall performance of the oil sector can be obtained by simulating only the changes in the profile of structural elements, assuming current technical benchmarks to be constant. A study by Parra et al. (Parra et al., 2020), analyzing the aging of

Ecuadorian oil reserves, validates these assumptions. Undoubtedly, for future analyses, it would be preferable to use time series of benchmarks from the same oil fields so as to include the combined effect of changes in technical characteristics of structural types and functional characteristics determined by the mix of structural types. However, historical series at the required level of data detail are generally not easily available.

4.3 Input/output variables included in the metabolic processors

The current study focused on energy carrier consumption and direct CO_2 emission in the oil sector to study the 'aging trap' of the energy transition. The economic – i.e., capital and operational expenditures – and technical investments – i.e., kW of power machinery and quality of technology employed – were not included in the metabolic representation. The economic dimension, albeit relevant, is out of the scope of the biophysical representation presented in this study. Regarding the power capacity dimension, the issue is the lack of available data. To the best of our knowledge, only oil companies have data at that level of detail, and those are not publicly shared. However, in future and for more refined analyses, it would be important to include economic and technical inputs too. In this way, one could study the effect of the continuous increase of investments in new technical capital, needed to overcome the challenges of aging (e.g., EOR) and the exploration and extraction of unconventional fields. In fact, rapidly decaying fracked wells (McNally and Brandt, 2015), and sophisticated ultra-deep extraction technologies (Beltrao et al., 2009; Haige et al., 2020) entail not only more direct emissions, but also important energy requirements and emissions embodied in the installed power capacity. A methodological discussion of how to integrate power capacity into the processor's representation has been provided by Diaz-Maurin (2016).

4.4 The scope of the study

The simulations presented in this paper are not meant to predict the future, but as a possible way to explore option spaces for energy transition by gaining insights into the consequences of the aging and complexification of the global oil sector. The main aim of the work is to provide a useful analytical framework for reflexive governance, capable of complementing the mainstream approach, which exclusively focuses on "optimization and control".

The selected taxonomy of extraction and refining processors is implicitly based on the historical and common accounting scheme adopted by oil companies, not on a

cluster analysis of the biophysical profiles (input and output of primary and secondary flows) of the oil fields (see Appendix, figures A7, A8, A9). This choice has been made because, in the world of oil, every field is a complex object, difficult to geologically characterize and exploit by engineers: uncertainty is the norm and every producer employs specific sets of technologies (Maugeri, 2006). Consequently, the biophysical profiles characterizing the extraction processors (but not the refining ones, that are less dispersed between instances of the same type) show high variability and every clustering constructed upon requirements of natural gas, diesel, electricity, coke and CO_2 emissions could easily be contested. Hence, in agreement with (Carnegie Endowment for International Peace, 2018), we selected API gravity, water content, location and depth as relevant attributes because of their implications for the capital investments in extraction and refining technologies.
However, the choice of the taxonomy of structural and functional elements and the choice of inputs and outputs in the processors can always be contested within the relational framework. This predicament is unavoidable in any analysis of complex systems across different levels and dimensions. Relational analysis makes this choice transparent. In fact, we are not claiming that our numbers are correct or indisputable, nor that we are providing an accurate assessment of the increase in the emissions/supply ratio of oil products due to the aging and complexification of the oil sector. What we showed is that the "oil aging trap" is a relevant aspect of the problem of climate change mitigation that should be (better) addressed in the narratives about decarbonization of the economy (and in the making of IAMs). Grounding the representation of the oil sector in a metabolic perspective allows the analyst to obtain a broader view of the reality observed.

5. Conclusions

The modern energy matrix still relies predominantly on fossil fuels and the transition to renewable energy sources is expected to take decades at least. In this paper we have shown that, while the clock ticks, the aging and complexification of the oil sector, in the form of increasingly watery and depleted fields and a progressive switch to unconventional sources, lead to increased energy carrier consumption and CO_2 emissions per barrel produced by the oil industry. This phenomenon is the result of efforts to merely *maintain* the current size of fuels output. This "oil aging trap" is often overlooked – e.g., in the IPCC decarbonization scenarios based on IAMs – but has important implications for the international efforts to contain climate change in the next decades to come.

There are several potential applications of the findings of this paper. First, the findings indicate that focusing exclusively on the emissions per barrel for specific oil typologies – e.g., energy policies based on LCAs – is potentially misleading and may lead to ineffective carbon taxes and emission trade policies, because these assessments overlook the relative importance of the various sequential pathways in the overall oil mix.

Second, addressing the main drivers of increased CO_2 emissions in the oil sector, namely natural gas for more complex drilling and deeper refining, should be among the priority concerns of energy policies. Reducing the use of natural gas (in the form of hydrogen) in complex refining – needed to supply high quality fuels from low quality primary oils - could be useful for climate change mitigation. Hence, energy policies that stimulate burning cleaner fuels and the upgrading rate of refineries should be carefully evaluated in the face of (i) possible trade-off between pollution and CO_2 emissions; and (ii) the creation of additional fossil fuels path dependency in the economy.

Third, rather than focusing all attention on the use of renewables to replace fossil fuel, more research is needed on the possibility of using renewables in fossil fuel extraction. Technologies such as Solar Enhanced Oil Recovery could prove useful for reducing emissions and, at the same time, by-pass the main problems of large-scale, societal implementation of renewable sources, namely intermittency and storage.

The operational framework presented in this paper has been developed specifically for governance purposes. It allows analysts and policy makers to identify relations and trade-offs between relevant and conflicting concerns associated with the production of energy carriers in societies still heavily dependent on fossil fuels, but willing to reduce CO_2 emissions. Our analysis illustrates the potentiality of the approach in providing a useful integrated characterization of the diversity of processes of energy conversions taking place in the oil sector, and in identifying priority areas for further research. Decisions of policy-makers should not be based on simplistic indicators aimed at indicating optimal solution (often used out of context). Missing the big picture because of a reductionist approach and a simplistic thinking that we can solve climate change simply through technological innovations and business models will force us to run the Red Queen’s Race: “It will take all the running we can do, just to keep in the same place” …but only for a limited time.

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Chapter 5. Securing fuel supply with unconventional oils: a metabolic perspective

This chapter is the transcript of the paper: "Manfroni, M., Bukkens, S.G.F., Giampietro, M., 2022. Securing Fuel Demand with Unconventional Oils: A Metabolic Perspective. Energy 261, 125256. https://doi.org/10.2139/ssrn.3965537", with only minimal modifications. The language and the structure used reflects the fact that this chapter was conceived as a stand-alone paper to be published in the scientific literature.

1. Introduction to the issue

The extraction of unconventional oil resources has seen an important increase in the past decade (Farrell and Brandt, 2006; Gordon, 2012; Maugeri, 2013, 2012). In 2017, ExxonMobil projected that the liquid fuel supply from unconventional sources, notably tight oil, deep-water crudes and oil sands, will increase from 20% in 2010 to 40% in 2040 (ExxonMobil, 2017; Gordon, 2012). These projections have been confirmed by Yergin (2020), the US Energy Information Administration (EIA, 2020) and the International Energy Agency (IEA) (2019). Note that in 2019, oil (conventional and unconventional) still represented 33% of the total primary energy consumed at the global level, which makes it pivotal to energy security (British Petroleum, 2020). It is also a critical supply chain component for 90% of all industrially manufactured products (Michaux, 2020).

Ironically, while there is an agreement on the projected fuel supply from unconventional oils, the definition of what exactly unconventional oils are, is less clear. According to Gordon, echoing the US Department of Energy (DOE), an oil taxonomy cannot be neatly defined as "new oils are emerging along a continuum from conventional crudes to transitional oils to unconventional oils, with their classification varying according to the ease of extraction and processing" (Gordon, 2012, p.1). Murray and Hansen draw the line between conventional and unconventional sources in vague terms: "*Conventional oil refers to production from reservoirs that have sufficient pressure, porosity, and permeability to flow freely. Unconventional oil is that which does not flow freely or requires special technologies to extract – as a result, it is more expensive to produce*" (Murray and Hansen, 2013). The IEA opts for an extensional definition instead, including tight, deep-water, extra-heavy oil, natural bitumen (oil/tar sands), kerogen, gas-to-liquids

(GTL), coal-to-liquids (CTL) and additives as unconventional resources (International Energy Agency (IEA), 2001). In this paper, we adopt the convention of the IEA.

Unconventional petroleum represents about 70% of known recoverable reserves worldwide, or possibly more (Gadonneix et al., 2010; Hongjun et al., 2016). Heavy oils and tar sands together represent about 32% of total recoverable resources, tight and ultra-deep oils account for about 10%. Kerogen is the most abundant unconventional resource at 35%, but has lower economic potential and energy content (Altun et al., 2006). Given the sheer magnitude of these unconventional resources (Wachtmeister, 2020), it is often assumed that we will not run out of oil for centuries and that the only obstacles are “above-ground”, i.e., maintaining prices sufficiently high to stimulate technological innovation for their exploitation (Adelman, 2004; Maugeri, 2006). Nonetheless, several scholars have raised concerns about the timing of this process to smoothly offset the decline of conventional flows (de Castro et al., 2009; Höök and Tang, 2013), as well as the upgrading rate of the global refining system, necessary to deal with the increased variability in crude qualities and to transform unconventional resources into useful high-standard products (Emerson Process Management, 2014; Graham and Merino Garcia, 2020; Olsen, 2015). Indeed, in this paper we will show that, despite their abundance, it is not assured that unconventional sources can substitute for conventional ones at the *societal scale*.

The energetic rentability and CO_2 emission of unconventional oils have been studied extensively with different methodologies. For example, Brandt et al. studied the investment of energy carriers and GHG emissions along the whole supply chain of both conventional and unconventional crudes, using Life Cycle Assessment (LCA) and adopting a “barrel forward” perspective (Carnegie Endowment for International Peace, 2018). They systematically found that heavy, viscous, and depleted fields are more energy and emission intensive per barrel produced than conventional extraction (Brandt, 2011; Masnadi and Brandt, 2017). ‘Low quality’ crudes (including synthetic substitutes) and the implementation of advanced Enhanced Oil Recovery (EOR), indispensable to extract oil from depleted/difficult reservoirs, invariably come with increased biophysical pressure (Brandt and Farrell, 2007; Brandt and Unnasch, 2010; Yuchen Liu et al., 2020). The Energy Return on Investment (EROI) of extra-heavy oils and tar sands has also shown to be relatively low compared to conventional oils (Brandt et al., 2013; Englander et al., 2015) and their CO_2 emissions higher (IHS Cera, 2010; Lattanzio, 2014). Net Energy Analysis

(NEA) studies confirm these findings: in the near future, the declining EROIs are expected to exacerbate the “energy cannibalism” (consumption of energy carriers to supply energy carriers) (Di Felice et al., 2018; Pearce, 2008), with repercussions on the feasibility of a rapid transition away from fossil fuels (Delannoy et al., 2021) and on the economy in general (Hall et al., 2014). Tight oil has emerged as the most promising source among unconventional oils (Brandt et al., 2015; Kapustin and Grushevenko, 2018; McNally and Brandt, 2015; Wachtmeister, 2020), with a net energy return and emissions intensity comparable to conventional fields (Brandt et al., 2016), even if the short-cycle technical (and financial) investments needed to maintain operations in time could substantially affect its viability (Wachtmeister and Höök, 2020). Potentialities of ultra-deep basins are still largely unknown, but preliminary results indicate low energy returns (Moerschbaecher and Day, 2011), and the highly complex technologies and infrastructures used in the extraction process present multiple challenges (Beltrao et al., 2009; Haige et al., 2020). Specific stages of the oil supply chains, such as extraction (El-Houjeiri et al., 2013), refining (Jing et al., 2020; Lei et al., 2021; Yeye Liu et al., 2020; Szklo and Schaeffer, 2007), and transportation (Greene et al., 2020), have been analyzed more in detail with the aim of identifying spaces for action to mitigate climate change. Other studies have focused on specific geographic regions (Cai et al., 2015; Masnadi et al., 2018b; Zhao et al., 2021).

The methodological focus in most of the above-cited studies is on the linear life cycle of individual crude feedstocks or oil products assessed in relation to a small number of performance criteria, such as CO_2 emission and/or energy carrier consumption per barrel of crude, or per unit of final product – mono or bi-variate assessments based only on intensive variables (Muthu, 2014). The main concern of these studies is to provide accurate numbers for characterizing the performance of the selected fuel supply chain (determined by a limited set of relevant attributes) within the chosen analytical boundaries (i.e., well-to-wheel or sub-systems like oil extraction, transport and refining). The ultimate purpose generally is to inform energy policies that favor the less energy and emission intense supply chains, crudes and/or final oil products (Brandt et al., 2018; Han et al., 2015; Masnadi et al., 2018a). The energy or emission intensity of consuming a unit of a specific oil product (e.g., gasoline) is considered the most relevant attribute of performance and is generally assumed to depend only on the consecutive processes involved in producing that specific product (from well to wheel) (Cai et al., 2015; Wallington et al., 2017; Wang et al., 2004). However, that is a too narrow focus and a shaky foundation to make appropriate policy claims at institutional level. Conundrums like the allocation problem, due to the unavoidable multi-functionality of efficient supply systems, make LCA analyses very dependent of contingent analysts' choices and affect the reproducibility of results (Cherubini et al., 2011; Kaufman et al., 2010; Moretti et al., 2017; Pelletier et al., 2015), while a consistent and unified framework is still struggling to emerge (Schrijvers et al., 2016; Wilfart et al., 2021). Furthermore, it is well known that changes in the demand of oil products may qualitatively affect the complex of extraction and refining (Motazedi et al., 2018). In fact, a product-centered and linearized representation of the energy supply misses the fact that the energy sector is an interactive functional component of society (Giampietro et al., 2012, 2013), the performance of which can only be assessed in relation to the requirements and expectations of the rest of society (Shove, 2017). From this perspective, supply and consumption can never be disentangled, but intrinsically co-evolve in time (Giampietro et al., 2013; Huettner, 1976; Maddox, 1978). When dealing with a complex set of energy transformations, in which internal loops generate impredicative causal relations, an excessive simplification of the representation carries the risk of missing relevant aspects (economic, social, ecological) of the problem (Giampietro et al., 2013; Murphy et al., 2011). Here lies the Achilles heel of LCA: societal consumption patterns are not embedded into the LCA linear representation. But the societal consumption practices bound the space of possible supply pathways and define their size; and hence, the quality of the *coupling* between supply and requirement affects *qualitatively* the integrated performance of the oil metabolism.

In this work, we attempt to fill this gap by adopting the perspective of societal metabolism (Giampietro et al., 2012; Sorman and Giampietro, 2013), and by conceptualizing the oil sector as an integral part of human society. We propose a novel methodology to assess the performance of the changing oil sector that is based on the semantically open accounting framework – Multi-scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) – and that provides an integrated representation of the societal metabolism of oil. More in particular, we explore the entanglement between patterns of crude oil exploitation, the resulting product slates made available by refiners (on the supply side), and the oil products required in the different end-uses in society (on the demand side). We identify potential constraints in the coupling of the supply and requirement of those oil products. We not only consider energy carrier consumption and CO_2 emission as relevant attributes, but various other criteria of performance related to the desirability, viability, and feasibility of the oil metabolism. The focus of our approach is not on the linear life cycle of individual oil product(s), but on the coupled production and consumption patterns of oil products at a higher level of abstraction. We illustrate our approach numerically by exploring the global oil metabolism with varying contributions of unconventional oils.

The paper is organized as follows: In section 2, we describe our methodological approach and define the descriptive domain of the analysis, as well as the production and consumption patterns of the oil products considered. In section 3, we illustrate the type of results yielded by the approach at the global level. In section 4, we discuss the relevance and novelty of our approach as well as its shortcomings. Section 5 concludes.

2. Methodology

2.1 A metabolic perspective on energy security

From a metabolic perspective, energy security refers to the sustainability of the societal energy metabolism, in line with the conceptualization of “low vulnerability of vital energy systems” proposed by Cherp and Jewell (Cherp and Jewell, 2014). Energy security thus is a property of the whole system, rather than a mere attribute of the energy supply chains or primary sources exploited (as is the working assumption in LCA). Giampietro et al. (Giampietro et al., 2021) has proposed four interdependent criteria for assessing the sustainability of the energy metabolism of complex social-ecological systems:

1. Feasibility: compatibility of the metabolic pattern with external biophysical (environmental) constraints beyond human control.
2. Viability: compatibility with internal biophysical, techno-economic constraints under human control.
3. Openness of the system (e.g., imports and exports required for sustaining the metabolic pattern).
4. Desirability: compatibility of the metabolic pattern with societal expectations.

Each of these four criteria spans a wide range of possible performance dimensions (see section 2.2.2). This is an important improvement compared to the mono-dimensionality of LCA analysis, focusing mostly on CO_2 emission.

Note that MuSIASEM has been purposefully developed to study the energy and food metabolism of complex social-ecological systems (Giampietro, 2004; Giampietro et al., 2013). In MuSIASEM, the energy sector is seen as a fundamental constituent component of the social-ecological system. It is the part of the system that exploits Primary Energy Sources (PES) from the environment to supply the energy carriers required (in quantity and quality) by the rest of society and by the energy sector itself (energy-for-energy internal loop). Therefore, the energy sector constitutes an important interface between the ecosphere (environment/ecological system) and the anthroposphere (socio-economic system). To explore energy security within the conceptual framework of MuSIASEM, we consider the impredicative relation between the energy supply – the transformation of PES into energy carriers in the energy sector – and the societal requirement of specific energy carriers to meet the desired end uses, including those of the energy sector itself. On the supply side, multiple combinations of pathways of PES exploitation can be used to produce a given profile of energy carriers (in quantity and quality). On the consumption side, different combinations of energy carriers (in quantity and quality) can be employed to express a specific set of end uses. The quantitative mapping between the energy carrier supply and requirement profiles generates possible metabolic states for the energy sector. The option space is composed by those states that are compatible with the viability and feasibility constraints and still allow a functional and desirable metabolic pattern for the society as a whole.

Note that in this paper we illustrate our approach at the global scale, and hence we do not consider the criteria “openness”. However, it is important to stress that at the national level, the extent of openness of the system will affect not only the feasibility and viability of the metabolic pattern – through the import of resources and export of environmental impacts – but also its desirability: is the dependence of societal energy security on imports and exports desirable?

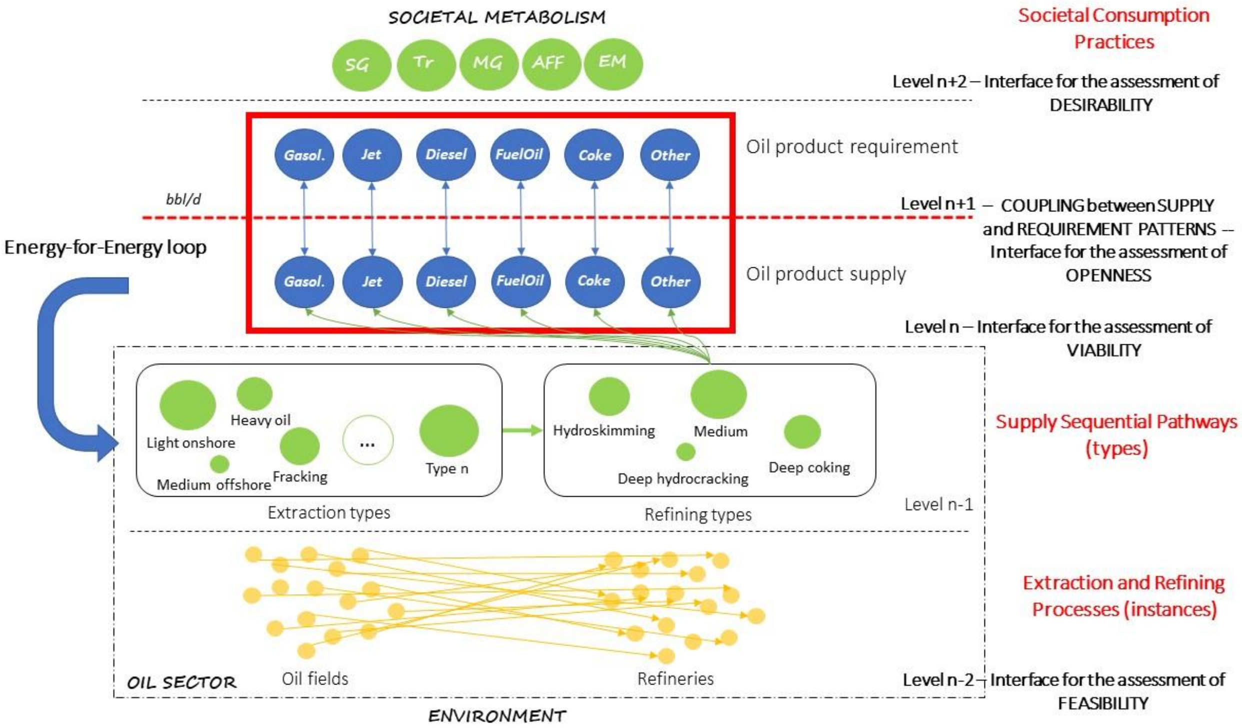

Fig.20 Multiscale representation of the oil sector. Acronyms: SG 'Service and Government', Tr 'Transport', MC 'Manufacturing and Construction', AFF 'Agriculture, Forestry and Fisheries', EM 'Energy and Mining' (excluding the oil sector).

In Fig. 20, we elaborate the above conceptualization specifically for the oil metabolism, the sub-system of the energy metabolism that is specifically concerned with oil exploitation. The society as a whole represents the high end of the system's hierarchical structure (*level n+2*) and the instances of oil fields and refineries represent the low end (*level n-2*). Note that with the term 'hierarchy' we do not imply unidirectional power relations, but mutually entangled relations in both directions (Salthe, 1985). End uses at the higher levels determine meaning and boundaries (the space of opportunities) for the activities taking place at lower levels, but at the same time the very existence of the upper levels is determined by what is biophysically possible (in terms of extraction and refining) at the lower scales (the space of realizations). The dynamic equilibrium in this specific set of hierarchical relations emerges at the interface between the oil products supplied and those required by the society, net of the internal energy-for-energy loop (*level n* ↔ *level n+1*). Any specific societal configuration entails specific requirements of oil products (*level n+1*), such as gasoline and kerosene for motorized transport or petrochemical feedstocks and heavy distillates for industry. On the other hand, the set of possible sequential pathways of extraction and refining, described by the structures and functions of the oil sector at *level n-1*, depends on geological-environmental constraints (e.g., oil field characteristics, water, and land availability) and techno-economic capacities (e.g., technology, capital, labor). We thus have a forced profile of required inputs (and resulting wastes) for operating the supply pathways and a forced oil product slate as output (a given profile of gasoline, diesel, and other types of fuels).

2.2 Oil sector taxonomy and multidimensional spaces across scales

To implement the metabolic perspective, we first provide a definition of the taxonomy of oil sequential pathways (extraction and refining) and pertinent categories of energy forms and dimensions of performance relevant for our purpose of assessing energy security in relation to viability and feasibility criteria. Following, extraction and refining types are characterized numerically, based on real instances, and possible sequential pathways are assessed.

2.2.1 Oil sector taxonomy

To date, the commercially most important unconventional oils are (i) tight oil, (ii) extra-heavy and tar sands (API gravity below 15, following the categorization given in (Carnegie Endowment for International Peace, 2018)), (iii) ultra-deep water oils (Beltrao et al., 2009; Rocha et al., 2003) and (iv) depleted fields, where advanced EOR techniques are used to extract the crude. We label here only the former three categories as ‘unconventional’. Depleted fields are treated as a separate category, even if often considered ‘unconventional’, given that the aging process is not the focus of the present work. We do not consider unconventional oil typologies that have not been proved commercially feasible or relevant (kerogen, methane hydrates, synthetic oils).
Both conventional and unconventional oil exploitation is typically composed of two basic steps:

i. Extraction and transport (upstream and midstream)
ii. Refining and distribution (downstream).

In this work, transport and distribution are not accounted for given that (i) their input requirement (and waste production) is negligible compared to that of extraction and refining, and (ii) we focus on the global level to illustrate our approach in general lines (accounting of transport and distribution would require a geographical contextualization of trade).

Extraction types are selected based on their technical and biophysical relevance for the supply process and categorized according to the following attributes (see Table 1):

1. API Gravity: Light, Medium or Heavy & Extra-heavy oils
2. Water content: Low Water or Watery
3. Location: Onshore or Offshore.

For this study, heavy and extra-heavy oil is defined by an API gravity between 10 and 15, and kept separate from tar sands, with API gravity <10.
In addition, a further five extraction types are considered (see Table 7):

- Fracking and ultra-deep typologies, being characterized by highly specialized extraction technologies with different biophysical requirements and environmental burdens.
- Depleted and heavily depleted typologies, being characterized by a long history of exploitation, where the effects of depletion are evident.
- Tar sands, having peculiar coal-like characteristic that affect every aspect of their exploitation and the final products.

Regarding refining, depending on the API gravity and sulfur content of the crude, four different types can be identified:

1. Hydroskimming conversion
2. Medium conversion
3. Deep conversion – coking
4. Deep conversion – hydrocracking

Complexity of refining increases with API gravity and sulfur content: more energy and technical intensive processes are required to transform heavier and dirtier oils (see Table 7).

2.2.2 Pre-analytical choice of relevant dimensions of performance

In line with MuSIASEM conventions, we consider a set of flow and fund variables that are relevant for characterizing the extraction and refining processes, where the concepts of ‘flow’ and ‘fund’ are defined as follows (Georgescu-Roegen, 1971):

- Flows: entities that do not maintain their identity during the analytic time frame; they are metabolized by funds to become something else. They describe what the system does.
- Funds: entities that maintain their identity during the analytical time frame; they metabolize flows and represent the structure of the system. They describe what the system is made of.

The following flows are considered in the analysis:

Input flows:

- Net consumption of natural gas and refinery fuel gas (MJ/bbl)
- Net and indirect (associated with imports) consumption of electricity (MJ/bbl)
- Net and indirect consumption of diesel (MJ/bbl)
- Net consumption of coke – only for refining (MJ/bbl)
- Net water consumption (bbl_{water}/bbl_{oil})
- Capital expenditures (€/bbl)

Output Flows:

- In-site and indirect CO_2 emissions ($kgCO_{2eq}/bbl$)
- Extracted quantity of oil (bbl/d)
- Refined quantity of oil (bbl/d)

Note that indirect consumption is related only to extraction, while net coke consumption is relevant only for refining and tar sands extraction.

As for input funds, we selected:

- Land use (ha/bbl) – (only for extraction)
- Labor (h/bbl)
- Fixed assets (€/bbl)

Lastly, the product slate (%) reflects the relative composition of the oil products. The product slate eventually supplied by viable production patterns is essential to assess the supply-requirement coupling. The set of oil products considered is the following:

- Gasoline
- Jet fuel
- Diesel
- Fuel oil
- Coke
- Other oils

Coke and other oils are grouped together under the label ‘other products’ for a coherent mapping between supply and requirement categories (see Appendix, section A4).

2.2.3 Multidimensional descriptive spaces and combined production functions

We define $\boldsymbol{d_p}$ as the array of performance benchmarks (the descriptive domain, see Fig. S1) at process-level, $\boldsymbol{d_{sp}}$ at the level of sequential pathway and $\boldsymbol{d_{cs}}$ at the level of the whole (combined) supply:

$$\boldsymbol{d_x} \coloneqq \{(d_1, d_2, \dots, d_n)\} \mid d_i \in \boldsymbol{R}$$

Note that $\boldsymbol{x}$ stands for the level at which the space $\boldsymbol{d_x}$ can be defined. $\boldsymbol{d_p}$ quantifies the pressures for single processes taking place inside the oil metabolism, such as extraction or refining. It is composed by the input/output flow and funds described in Section 2.2.2, except for the extracted and refined quantities of oil that are used as scaling factors to maintain the coherence of size across scales. $\boldsymbol{d_{sp}}$ is calculated by summing up the lower-level benchmarks, since it quantifies pressures resulting from oil operations carried out in series. To calculate $\boldsymbol{d_{cs}}$ we need to know the actual mix of sequential pathways employed inside the oil sector. This piece of information is strictly context dependent. We call $\boldsymbol{m}$ the vector that defines the relative composition of sequential pathways:

$$\boldsymbol{m} \coloneqq \{(m_1, m_2, \dots, m_v)\} \mid m_i \in \boldsymbol{R} \wedge \sum_{1}^{v} m_i = 1$$

With v identifying viable combinations of extraction and refining typologies (e.g., heavy and extra-heavy oils cannot be refined with hydroskimming refining facilities).

Thus, $\boldsymbol{d_{cs}}$ can be calculated as follows:

$$\boldsymbol{d_{cs}} = \boldsymbol{m} \times \boldsymbol{D_{sp}}$$

where $\boldsymbol{D_{sp}}$ represents the sequential pathway matrix $\boldsymbol{v} \times \boldsymbol{n}$. The rows of $\boldsymbol{D_{sp}}$ are composed by the arrays $\boldsymbol{d_{sp_i}}$ for every possible sequential pathway $i = 1,2, \dots, \boldsymbol{v}$ operating in the system; the columns are the dimensions of performance (the cardinality of $\boldsymbol{d_{sp_i}}$).

Finally, we define $\boldsymbol{s}$ as the set of oil products, the product slate:

$$\boldsymbol{s} \coloneqq \{(s_1, s_2, \dots, s_t)\} \mid s_i \in \boldsymbol{R} \wedge \sum_{1}^{t} s_i = 1$$

where $\boldsymbol{t}$ is the number of final oil products. As before, $\boldsymbol{s}$ can be defined at three different levels – process ($\boldsymbol{s_p}$), sequential pathway ($\boldsymbol{s_{sp}}$), combined supply ($\boldsymbol{s_{cs}}$). The overall product slate ($\boldsymbol{s_{cs}}$) is a function of the relative combination of supply pathways $\boldsymbol{m}$ in the total mix. The arrays introduced so far are *multidimensional spaces*, representing the domain ($\boldsymbol{d}$) and co-domain ($\boldsymbol{s}$) of our analysis.

The relational entailment between typologies of processes and/or sequential pathways, spaces of performance and product slates can be qualitatively coded by a set of production functions that associate every viable process/sequential pathway with its profile of pressures and outcome of oil products. The space of production functions (at the level of sequential pathways) can be defined by the following associative relation:

$$\boldsymbol{F}: \boldsymbol{D_{sp}} \rightarrow \boldsymbol{S_{sp}} \wedge \boldsymbol{F} \in \boldsymbol{R}^{v\,x\,(n+t)} \mid \boldsymbol{f}_k = \left(\boldsymbol{d_{sp_i}} \mid \boldsymbol{s_{sp_i}}\right), \forall\, \boldsymbol{s_{sp_i}} \in \boldsymbol{S_{sp}} \wedge \boldsymbol{d_{sp_i}} \in \boldsymbol{D_{sp}} \wedge \boldsymbol{f}_k \in \boldsymbol{F}$$

It informs us about how PES are converted into useful energy carriers (Table 7). There is some flexibility in the oil production process – refiners can decide to increase or decrease shares of high margin products depending on market conditions (changes of the array $\boldsymbol{m}$) – but not everything is possible. The library of sequential pathways in Table 7 accounts for this variability.

A variety of datasets has been employed to construct the library of sequential pathways. The energy carrier requirements and GHG emissions of the oil sector itself are from (Carnegie Endowment for International Peace, 2018). To the best of our knowledge, robust water consumption data are not available. Hence, water consumption data have been collected from different sources (Kondash and Vengosh, 2015; Rosenfeld et al., 2009; Sun et al., 2018; Veil, 2015; Wu et al., 2011) and processed as explained in the Appendix, section A4.2.2 (section S2.2). The metabolic benchmarks of capex, fixed assets and labor have been obtained from the oil companies ENI, Shell, Suncore and Chesapeake balance sheets and cash flows (Chesapeake Energy, 2019; Shell, 2020, 2019; Suncor Energy, 2019; WSJ, 2021). Land use intensities have been derived from typical values in the Uppsala Giant Oil Field Database (Höök et al., 2014; Sällh et al., 2015; Wachtmeister et al., 2017). Further details and more references are available in the Appendix, section A4.2.

*Table 7. Library of sequential supply pathways of oil products – matrix space **F***

LIBRARY OF PRODUCTION FUNCTIONS		MJ/bbl				kgCO2eq/bbl	bblwater/bbloil	ha/bbl	€/bbl		h/bbl	Product slate %					
Oil Fields Types	Associated Refining	Natural gas	Electricity	Diesel	Coke	GHG emissions	Net water use	Land use	CapEx	Fixed assets	Labor	Gasoline	Jet Fuel	Diesel	Fuel Oil	Coke	Other oils
Light Low Water Onshore	Hydroskimming	387	13	7	0	42	2,18	0,45	15	106	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	545	19	7	25	56	2,18	0,45	15	106	0,16	36%	19%	18%	0%	0%	26%
Light Low Water Offshore	Hydroskimming	473	17	13	0	50	8,79	0,04	15	106	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	630	23	13	25	63	8,79	0,04	15	106	0,16	36%	19%	18%	0%	0%	26%
Medium Low Water Onshore	Hydroskimming	496	12	8	0	63	4,32	0,45	15	106	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	653	18	8	25	77	4,32	0,45	15	106	0,16	36%	19%	18%	0%	0%	26%
Medium Low Water Offshore	Hydroskimming	330	12	5	0	37	3,20	0,04	15	106	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	487	17	5	25	50	3,20	0,04	15	106	0,16	36%	19%	18%	0%	0%	26%
Light Watery Onshore	Hydroskimming	722	47	6	0	95	8,83	0,90	15	106	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	879	53	6	25	109	8,83	0,90	15	106	0,16	36%	19%	18%	0%	0%	26%
Light Watery Offshore	Hydroskimming	820	18	5	0	92	7,88	0,08	15	106	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	977	23	5	25	105	7,88	0,08	15	106	0,16	36%	19%	18%	0%	0%	26%
Medium Watery Onshore	Hydroskimming	654	23	14	0	17	3,24	0,90	15	106	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	811	29	14	25	107	3,24	0,90	15	106	0,16	36%	19%	18%	0%	0%	26%
Medium Watery Offshore	Hydroskimming	471	21	4	0	48	4,24	0,08	15	106	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	628	27	4	25	62	4,24	0,08	15	106	0,16	36%	19%	18%	0%	0%	26%
ULTRA DEEP	Hydroskimming	496	15	40	0	68	3,91	0,04	16	105	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	654	21	40	25	82	3,91	0,04	16	105	0,16	36%	19%	18%	0%	0%	26%
DEPLETED FIELDS	Hydroskimming	728	44	7	0	72	4,47	1,80	15	106	0,16	29%	23%	10%	10%	0%	28%
	Medium Conversion	886	50	7	25	86	4,47	1,80	15	106	0,16	36%	19%	18%	0%	0%	26%
HEAVILY DEPLETED FIELDS	Medium Conversion	2391	26	1	25	158	8,86	3,61	15	106	0,16	36%	19%	18%	0%	0%	26%
	Deep Conversion - Coking	2911	42	1	49	199	8,97	3,61	18	126	0,11	44%	11%	31%	0%	10%	3%
	Deep Conversion - Hydrocracking	3215	48	1	41	221	8,99	3,61	18	126	0,11	38%	11%	40%	0%	8%	3%
FRACKING	Hydroskimming	405	12	17	0	77	0,63	0,98	16	105	0,16	29%	23%	10%	10%	0%	28%
HEAVY&EXTRA-HEAVY	Medium Conversion	1147	27	12	25	113	5,70	0,90	20	213	0,18	36%	19%	18%	0%	0%	26%
	Deep Conversion - Coking	1667	43	12	49	154	5,80	0,90	20	213	0,18	44%	11%	31%	0%	10%	3%
	Deep Conversion - Hydrocracking	1970	50	12	41	176	5,83	0,90	20	213	0,18	38%	11%	40%	0%	8%	3%
TAR SANDS	Hydroskimming	1687	57	738	136	146	1,87	1,01	20	213	0,18	29%	23%	10%	10%	0%	28%
	Medium Conversion	1845	63	738	161	160	1,87	1,01	20	213	0,18	36%	19%	18%	0%	0%	26%
	Deep Conversion - Coking	2365	79	738	186	200	1,97	1,01	20	213	0,18	44%	11%	31%	0%	10%	3%
	Deep Conversion - Hydrocracking	2668	86	738	177	222	2,00	1,01	20	213	0,18	38%	11%	40%	0%	8%	3%

2.3 Confronting supply and consumption patterns of oil products

Having defined the multiple levels of performance on the supply side, we can now embed the societal consumption patterns into the representation, and explore potential mismatches between production and requirement of oil products at societal level. To this purpose, we built four combined production functions with different contributions of unconventional pathways: (i) 'current supply' (baseline); (ii) 'unconventional light supply', assuming an increased contribution from fracking and ultra-deep pathways; (iii) 'unconventional heavy – coking supply', assuming an increased production from heavy, extra-heavy oils and tar sands using coking facilities in refining; and (iv) 'unconventional heavy – hydrocracking supply', similar to the previous one but using hydrocracking facilities for refining. We further consider three different societal consumption patterns of the main oil products. The first is the baseline situation, where the consumption pattern is assumed equal to the current global production pattern. The other two reflect the current oil product consumption profiles of the EU and the USA. Note that we do not seek to assess oil security for the EU or the USA, but simply use consumption profiles typical of those geographic regions to explore potential future bottlenecks in response to changing oil product production patterns.

2.3.1 Product slates associated with production functions

The four production functions have been generated by combining possible sequential pathways (Table 7), using the relative contributions (viable arrays $\boldsymbol{m}$) reported in Tables A16-A17 (Appendix, section A4). The associated multidimensional spaces are described in Table 10-11. Each production function provides as output a different profile of product slate (Table 9). Note that the selected combined production functions are not meant to represent any realistic scenario, but are 'what if' simulations to explore the multidimensional spaces $\boldsymbol{D_{cs}}$ and $\boldsymbol{S_{cs}}$. We perform our exercise at the global scale: the size of the global oil sector is assumed to be 105 million barrels of crude per day, following the IEA's forecast "State Policies Scenario 2030" (International Energy Agency (IEA), 2019). The baseline case is constituted by the current global supply pattern and has been adapted from (Manfroni et al., 2021) with the following modifications: (i) we introduced the ‘tar sands’ pathway that accounts for 2% of the global production (Englander et al., 2015); and (ii) heavy and extra-heavy pathways (grouped) are assumed to account for an 11% share rather than 14%. As for coupling extraction and refining, we took again (Manfroni et al., 2021) as reference, except for the refining of tar sands that is equally divided (50% each) between hydroskimming (syncrude oil) and deep conversion (dilbit) refining (Table A17). The relative refining shares for each crude have been kept constant for all four cases considered.

The other three simulations are based on the baseline, but with a progressive increase in the relative share of unconventional oils. The overall unconventional share on the global crude supply increases from 22% in the baseline supply to 60% in the unconventional supply simulations (see Table A16 and Figs. A14-A15):

1. ‘Unconventional light’ supply: the combined share of fracking and ultra-deep is increased from 8% to 60% of total global crude production.

2. ‘Unconventional heavy – coking’ supply: the contribution of heavy & extra-heavy oils and tar sands to the global crude production is assumed to be 40% and 20% respectively. The downstream refining is assumed to be done entirely with coking facilities.

3. ‘Unconventional heavy – hydrocracking’: the same as the previous one, but the refining is entirely performed with hydrocracking facilities.

The composition of final oil products in the four simulations (combined production functions) is shown in Table 8. Some considerations about performance are relevant here. First, note that in the unconventional light production function, the internal requirement of coke cannot be satisfied. Second, for the calculation of the internal energy loop (the differences between gross and net in Table 8), we focused only on crude oil products. We did not consider the internal use of the associated natural gas –

extracted together with oil from oil fields – as input for crude production. Natural gas is a by-product of oil production and is the most widely used energy carrier in the extraction and refining processes (Manfroni et al., 2021), hence relevant for the calculation of the EROI. As shown in Table A21, without considering associated natural gas, unconventional heavy pathways already use about 10% of their output of energy carriers for internal consumption (EROI = 10) and considering also natural gas would further reduce the overall benchmarks to well below 10 (6.5 according to (Delannoy et al., 2021)). Obviously, the numbers in Table A21 and Table 8 (describing the efficiency and size of the internal energy loop with different metrics) are not a realistic forecast (Kapustin and Grushevenko, 2018), but serve to flag potential problems of an extensive exploitation of unconventional oils.

Table 8. Typologies of product slate (matrix space $\boldsymbol{S_{cs}}$), i.e., the compositions of oil products produced in the four combined production functions. 'Net' and 'gross' refers to, respectively, the inclusion or exclusion of the internal oil-for-oil loop in the analysis.

	Gasoline	*Jet Fuel*	*Diesel*		*Fuel Oil*		*Coke*		*Other oils*
	Net	*Net*	*Gross*	*Net*	*Gross*	*Net*	*Gross*	*Net*	*Net*
Current	35%	19%	18%	17%	2%	2%	1.1%	0.4%	24%
Unconventional light	33%	21%	14%	14%	5%	5%	0.1%	**-0.2%**	27%
Unconventional heavy coking	38%	16%	22%	17%	2%	1%	5%	3%	17%
Unconventional heavy hydrocracking	36%	16%	26%	21%	2%	1%	4%	2%	16%

2.3.2 Typologies of societal consumption patterns of oil products

The requirement of energy carriers depends on societal end uses. However, for our illustration, we consider simplified patterns of oil product requirements without mapping them to specific societal subsectors and end-uses, nor do we consider trade. The set of societal requirements (consumption), quantifying the expectations of the rest of society from the oil sector, is defined as the multidimensional space $\boldsymbol{c}$:

$$\boldsymbol{c} \coloneqq \{(c_1, c_2, \dots, c_t)\} \mid c_i \in \boldsymbol{R}$$

We selected three arrays of societal oil product consumption (see Table 9):

1. World, where the consumption equals the current global supply of oil products – a proxy for the current consumption at the global level.

2. US, describing the current consumption pattern of oil products of the USA.

3. EU, describing the current consumption pattern of oil products of the EU.

The consumption of oil products in the baseline situation (‘world’) reflects the current supply scenario obtained from ENI (2018), assuming that consumption and production match at the global level (net of stocks). The US typology is based on data from the EIA (2021), and the EU one is calculated from Eurostat (2020). More details are available in the Appendix, section A4.

*Table 9. Societal requirement patterns of oil products – matrix space **C***

Oil product	***World***	***US***	***EU***
Gasoline	35%	45%	*16%*
Jet fuel	19%	8%	*3%*
Diesel	18%	20%	*54%*
Fuel Oil	2%	2%	*4%*
Other products	25%	25%	*24%*
Total	**100%**	**100%**	**100%**

Note that these profiles are special instances based on current ‘real’ consumption patterns inside delimited geographical regions. They serve to explore what would happen if the global oil product requirement would take the form of current US or EU consumption patterns.

Coupling these multiple consumption patterns to the four selected combined production functions allows us to anticipate the effects on the *integrated performance space*. The integrated performance space resulting from the coupling between the product slate j (production function j) and societal requirement r is defined as:

$$\boldsymbol{ip} \coloneqq \{(ip_1, ip_2, \dots, ip_n)\} \mid ip_i = e_{jr} \cdot d_i \ \wedge 1 \leq i \leq n, \ ip_i \in \boldsymbol{R}$$

Where e is the *coupling factor* that we define in the next section.

The integrated performance space can be interpreted as the multidimensional space of the societal pressures associated with the consumption of one barrel of oil products, given a determined production function. It describes the overall performance of the oil metabolism at the level of society. When *simultaneously* accounting for the supply and consumption patterns of multiple products that are *jointly produced*, intensive supply benchmarks (space $\boldsymbol{d_{cs}}$) account for costs from the perspective of producers, but consumption pressures (space $\boldsymbol{ip}$) may differ from the perspective of consumers. The mismatch between $\boldsymbol{d_{cs}}$ and $\boldsymbol{ip}$ consists in the additional pressures (i.e., the environmental, socio-economic, and technical) of the oil products supplied but not required.

2.3.3 Matching production and consumption: 'Crack Limiting Flow' and 'Coupling Factor'

Given the product slate $\boldsymbol{s_{cs}}$ associated with the production function $\boldsymbol{f}_k$, and the array $\boldsymbol{C_j}$ of societal requirement, the associated *Coupling Factor* (CF) can be defined as:

$$e_{kj} = max\ ({}^{c_i}/{}_{s_i})_{i=1}^{t}$$

The *Crack Limiting Flow* (CLF) is the oil product associated with the highest Coupling Factor.

Hence, CLFs are identified by the maximum distances between points of requirement and production for the same oil product (gasoline, jet fuel, diesel, fuel oil, coke & heavy ends), as is illustrated in Fig. 24. CFs can be seen as the quantitative supply adjustments needed to balance (limited) supply and requirement.

At the global level and in the long term, total consumption and production must match, net of stocks (not relevant in the long term since oil products decay over time). In practice, product slate and requirement (the formal attributes that account for, respectively, the quality of the PES exploited and the quality of the energy carriers required) will be different, thus potentially creating surplus of all the oil products other than the limiting one. Hence, in a closed system (as is the global system), coherence is given by adjustments up to coupling factors and net of the energy loop, generating the performance indicators of space $\boldsymbol{IP}$ and giving the correct size of the supply system (i.e., barrel of oil products produced per day). The internal consumption of energy carriers needs to be subtracted from the total output of the oil sector in order to calculate coupling factors, since the oil sector is part of society itself. Maintaining non-equivalent intensive (metabolic benchmarks, normalized per barrel) and extensive descriptions is crucial to check the coherence across scales.

We focus here on the supply side, but it is equally well possible to approach the analysis from the consumption side, to explore changes in social practices.

3. Results

In this section, we explore the metabolic network presented in Fig. 20 and the performance benchmarks of multidimensional spaces $\boldsymbol{D_{cs}}$ and $\boldsymbol{IP}$ resulting from the selection of the four combined production functions. Performance benchmarks at each scale are determined by (i) the library of sequential pathways, (ii) the dynamic coupling between production and consumption of oil products; and (iii) the size of the system – the barrels produced per day. Once these three factors are established, the absolute size of the system required to meet oil products requirement can be recursively ‘adjusted’ based on the crack limiting flow. The multiple dimensions relate to different domains (socio-economic, techno-biophysical and environmental), and hence the performance assessment will inform stakeholders about the feasibility and viability of the oil metabolism.

3.1 Supply side performance – Space $\boldsymbol{D_{cs}}$

Supply benchmarks (pressures) for the space $\boldsymbol{D_{cs}}$ are reported in Tables 10-11; a compact radar visualization is shown in Fig. 21. Note that the scale in Fig. 21 is logarithmic, hence differences are bigger than they appear on first sight. The dimensions associated with the viability criterion are: (i) hours of human labor (fund); (ii) fixed assets of oil companies (fund); (iii) profile of energy carriers requirement (quality and quantity, flows); (iv) capital expenditures (capex, flow). Dimensions in the feasibility domain comprise land use (fund), net water consumption (flow) and GHG emission (flow). The related gross and net (corrected for the internal energy-for-energy loop) output of oil products $\boldsymbol{S_{cs}}$ is shown in Table 8.

Table 10. Supply benchmarks – space $\boldsymbol{D_{cs}}$ – of the combined production functions: viability dimensions

	Natural gas MJ/bbl$_{oil}$	Electricity MJ/bbl$_{oil}$	Diesel MJ/bbl$_{oil}$	Coke MJ/bbl$_{oil}$	CapEx €/bbl$_{oil}$	Fixed assets €/bbl$_{oil}$	Labor h/bbl$_{oil}$
Current	759	25	24	25	14	113	0,13
Unconventional light	602	21	20	12	16	124	0,11
Unconventional heavy coking	1335	42	155	58	17	160	0,12
Unconventional heavy hydrocracking	1468	45	155	54	17	160	0,12

Table 11. Supply benchmarks – space $\boldsymbol{D_{cs}}$ – of the combined production functions: feasibility dimensions

	GHG emissions kgCO$_{2eq}$/bbl$_{oil}$	Net water use bblwater/bbl$_{oil}$	Land use ha/bbl$_{oil}$
Current	80	3,75	3,55
Unconventional light	78	3,23	5,34
Unconventional heavy coking	125	4,47	8,13
Unconventional heavy hydrocracking	135	4,48	8,13

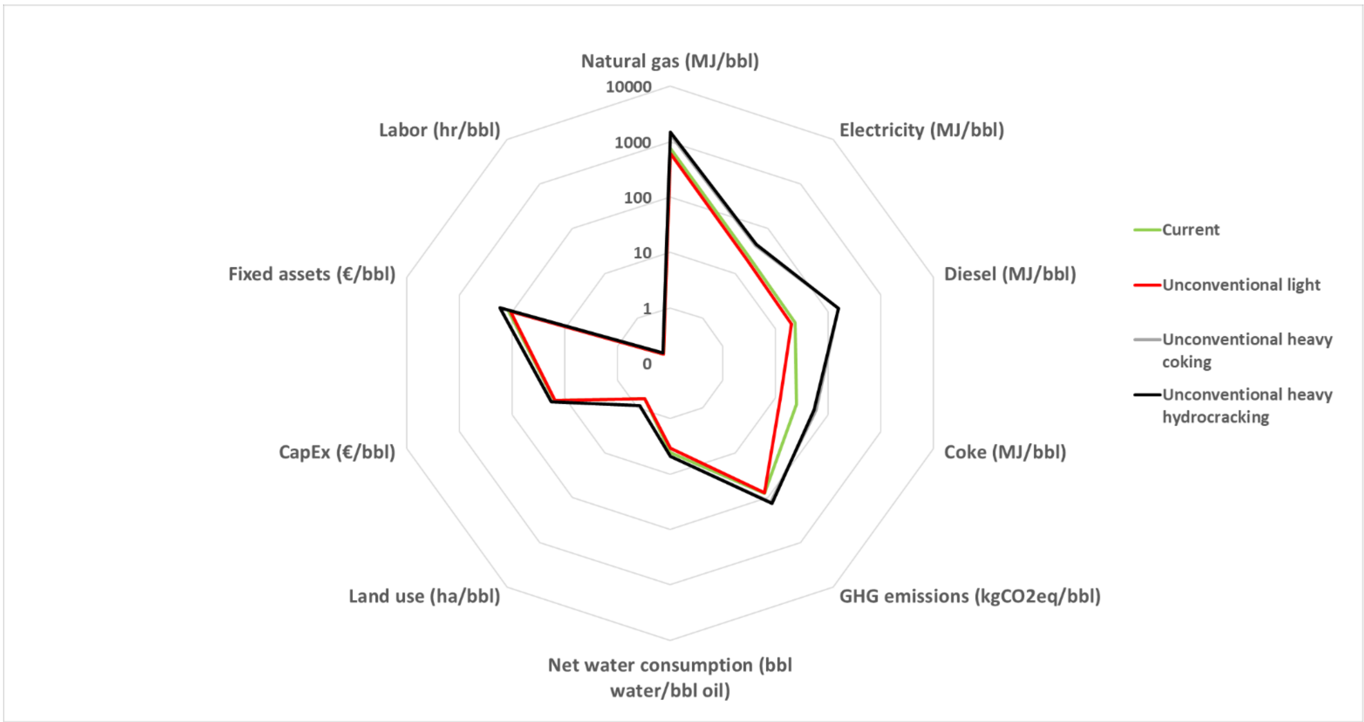

Fig.21 Environmental, socio-economic, and technical pressures associated with the four selected production functions (logarithmic scale, intensive description per barrel of oil produced)

The unconventional light supply pattern (in red) shows benchmarks similar (or better) to those of the baseline pattern (Fig. 21). The performance for fixed assets and land use is comparable (Fig. A18 and A24), but it is less intensive with regard to fuels and labor investment (Fig. 27 and A16). On the other hand, the unconventional heavy supply patterns show major increments across the entire set of benchmarks, both for coking (grey) and hydrocracking (black) (the grey and black pattern largely overlap in Fig. 21).

Fig. 22 shows the consumption of energy carriers per hour of labor (flow-fund benchmark, in MJ/h), a proxy of power capacity available per worker, net of the utilization factor, and per hectare of land (in MJ/ha), for the four combined production functions. A larger share of unconventional light sequential pathways in the supply mix improves both indicators, while a larger share of heavy ones deteriorates the situation, especially the performance of diesel utilization. In the same manner, Fig. 23 shows the CO_2 emissions and net water consumption per hectare, as well as the fixed assets and capex per hour of labor. The unconventional light production function performs better than the baseline on all indicators, except for capex (no changes), while the unconventional heavy supply typologies score worse, except for net water consumption.

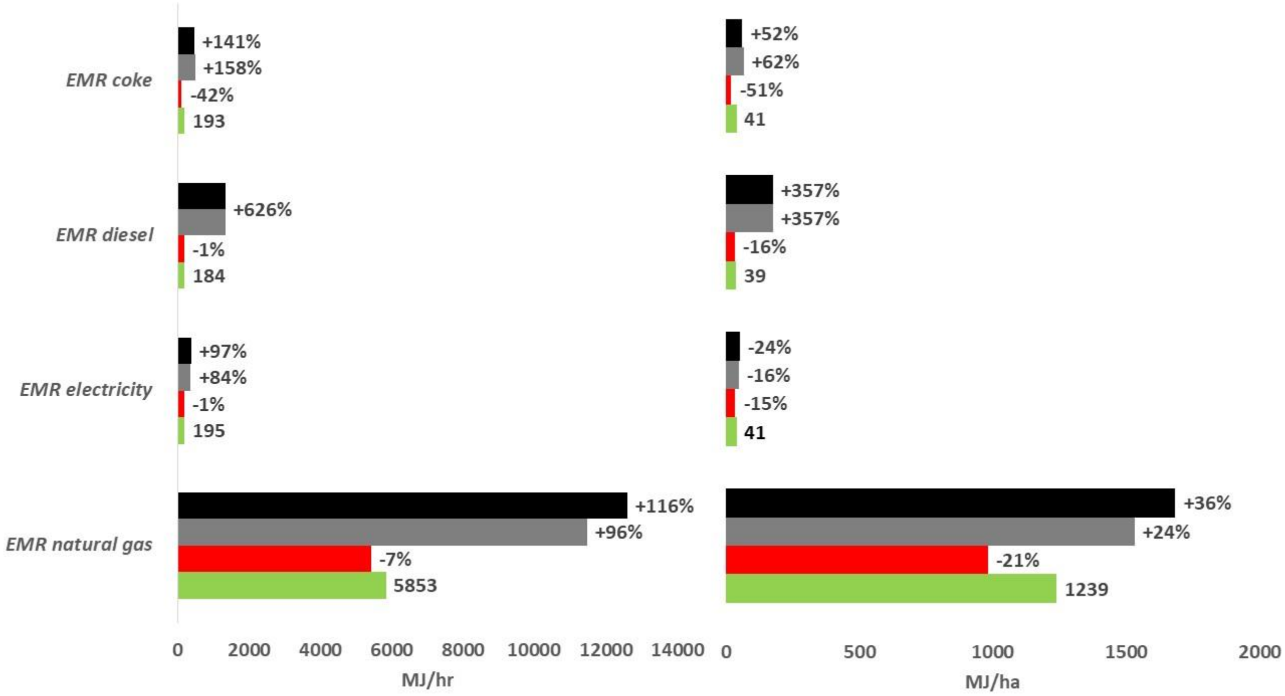

Fig.22: Consumption of energy carriers per hour of labor (MJ/h) and per hectare of land (MJ/ha) for the four combined production functions (supply typologies). For color legend, see Fig. 21.

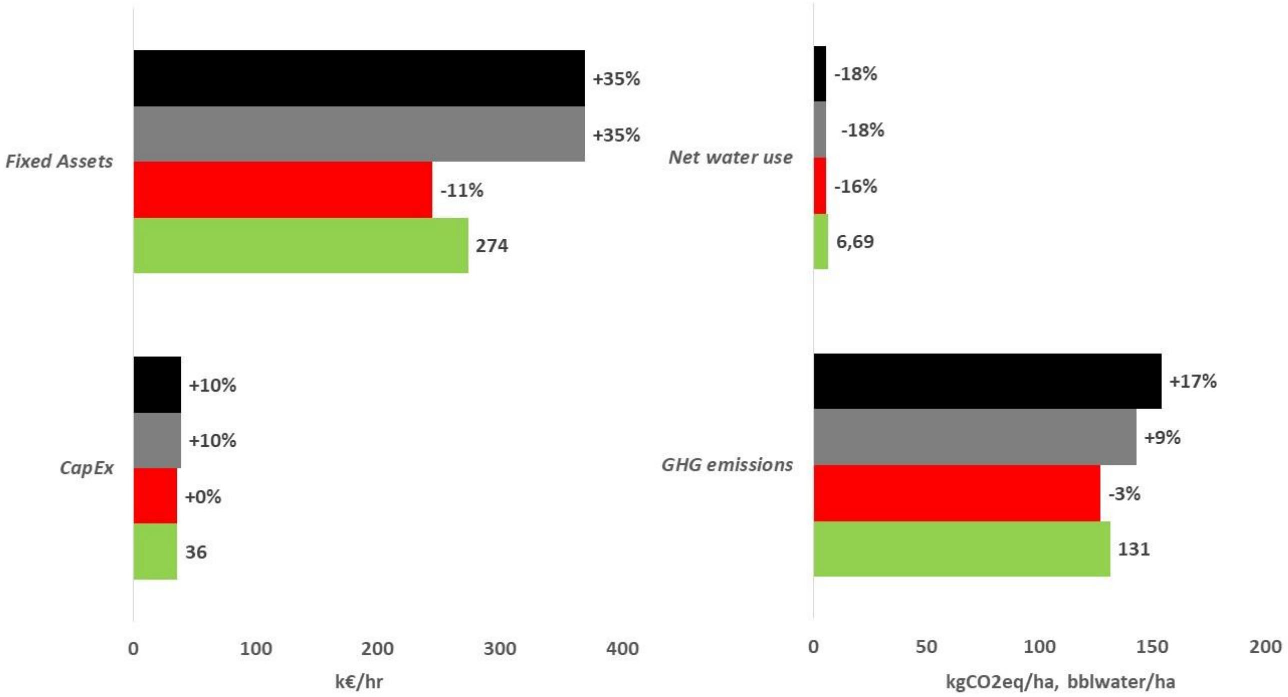

Fig.23. CO_2 emissions and net water consumption per hectare (right), and fixed assets and capex per hour of labor (left) for the four combined production functions representing the supply typologies

3.2 Integrated supply-consumption performance – Space IP

Using the library of sequential pathways and the overall size of the system ($105 \cdot 10^6$ bbl/d), we assessed the energy-for-energy internal loop – i.e., the oil products consumed by the oil sector to produce the oil products – of the combined production functions associated with the product slate typologies (Tables A24-A25). It is important to assess this internal loop as it affects the net societal requirement for oil products. We then compared the net oil product (EC) supply with oil product requirements for all the combinations between the four production and three consumption typologies, thus identifying the CFs (see Fig. 24, note that some product slates and societal requirements overlap). Corresponding CLFs are reported in Table 11. Note that CFs would be higher if not corrected for the internal requirements of the energy sector.

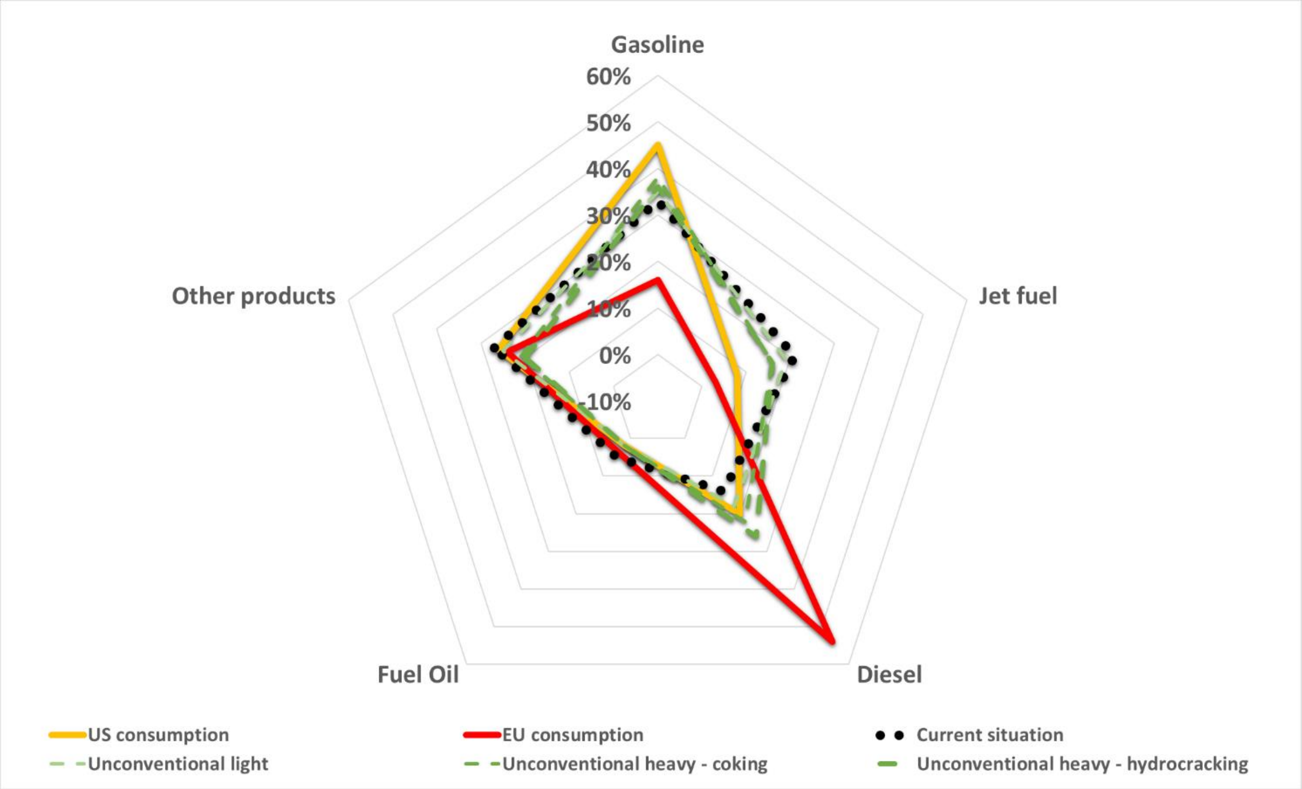

Fig. 24 Mismatches between net production and consumption of oil products across typologies of production and consumption patterns.

Table 11. Coupling Factors and corresponding Crack Limiting Flows across production and consumption typologies

	World		US		EU	
Current	1,00	-	1,27	Gasoline	3,08	Diesel
Unconventional light	1,26	Diesel	1,38	Gasoline/ Diesel	3,87	Diesel
Unconventional heavy coking	1,22	Other products	1,21	Other products	2,84	Diesel
Unconventional heavy hydrocracking	1,29	Other products	1,29	Other products	2,46	Fuel oil

The concept of CLF is useful to anticipate mismatches in net supply and requirement patterns. At the global scale (closed system), mismatches cannot be offset by trade, but only through increasing total supply. To better grasp the extent of the mismatch, we calculated the adjusted supply by scaling up production to meet the limiting flow, as shown in Fig. 6, and the associated integrated performance space ***IP*** (Fig. 7).

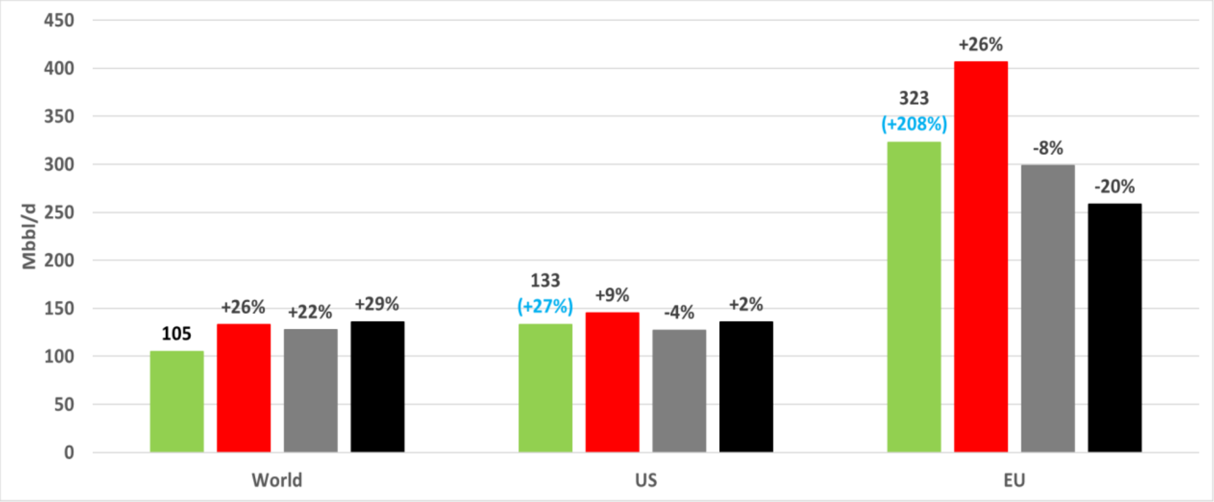

Fig.25 Adjusted scale of the oil sector (daily production of barrels of crude) to meet CLF for the combinations of production and consumption typologies. Marginal increases in total supply (%) caused by different requirement profiles against the supply baseline are reported in light blue. Marginal increases (%) caused by changing the production function against the same requirement are reported in black.

In Fig. 25, the baseline for comparison is represented by the current product slate coupled with the current oil product requirement (‘world’, green bar). The equilibrium is established at 105 million barrels of crude per day. Changing product slate typology (combined production function – red, green, black bars) generates a marginal increase in oil sector size (daily production of barrels of crude) as indicated in black on top of the bars. The percentual increase due to changes in societal requirement pattern (World → US → EU) is indicated in light blue. Note that the societal requirement is far more influential than the combined production function for matching oil product supply and requirement. For instance, if the whole world would adopt the EU consumption pattern, we would run into serious problems, as shown in Fig. 26 for the environmental pressures (the full integrated performance space is illustrated in the Appendix, section A4). The more a society ‘specializes’ its consumption on a restricted set of refinery products (e.g., low-sulfur diesel in the EU or gasoline in the USA), the more difficult it becomes to match production and consumption patterns, thus facing potential consequences of an increased biophysical and economic pressure of an ‘unbalanced’ oil sector.

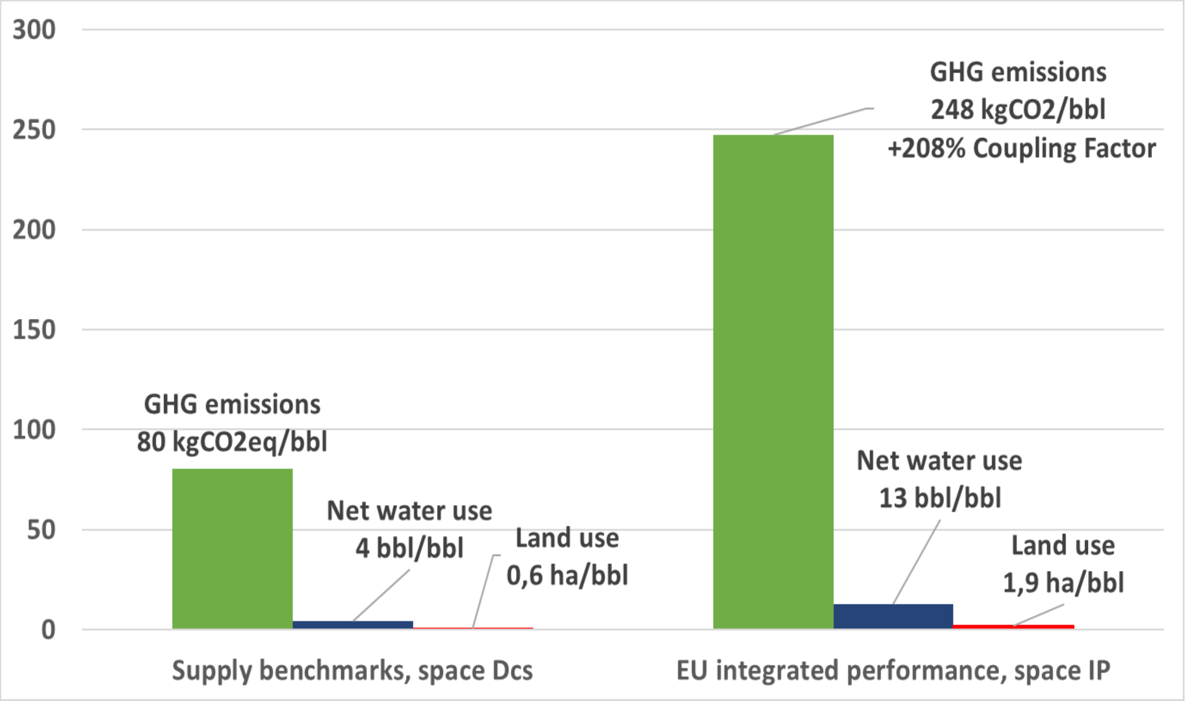

Fig.26 Environmental performance of an EU demand-driven enlargement of the global oil sector (current production pattern), to match the requirement of diesel, compared to baseline performance (current consumption). See the Appendix, section A4 for the biophysical-technological (Fig. A29), environmental (Fig. A33) and socio-economic (Fig. A37) performance.

4. Discussion

4.1 Novelty and strength of the proposed approach

Our metabolic perspective and conceptualization of energy security as the sustainability of the societal energy metabolism offer important advantages over traditional LCA analysis. As observed in the introduction, LCA is marked by a linear product-centered approach, where every oil product is considered individually, independent from the context – hence forcing analysts to use heavy contingent assumptions to deal with joint production and consumption issues and multi-functionality of energy systems – and by a limited performance space (e.g., considering only CO_2 emissions). It typically establishes a linear direction of causality over the quantitative relations and therefore cannot handle the existence of mutual dependence between different variables (impredicativity). We overcome these issues by enlarging the analytical boundaries of the system (our focus is on supply and requirements patterns, rather than individual products) and by considering a multidimensional performance space to assess the feasibility, viability, and desirability of the societal oil metabolism. Indeed, our combined supply space ($\boldsymbol{D_{cs}}$) and integrated performance space ($\boldsymbol{IP}$) constitute a fundamental difference with the LCA approach.

The use of flows and funds, non-equivalent representations (intensive and extensive), and multiple analytical dimensions is another important novelty of our approach. It allows us to:

1. assess the comparative performance of different energy supply systems (intensive)
2. check the actual impacts of the biophysical pressures in relation to feasibility and viability criteria (extensive)
3. identify trade-offs among multiple dimensions (e.g., water, land, energy, labor, capital) in relation to policy claims (intensive and extensive)

For instance, Fig. 27 shows intensive and extensive benchmarks of labor requirements for different combined production functions (supply typologies). The intensive description in the upper part of the figure is typical of LCA and NEA. While useful to compare different supply chains, it gives only partial information about the actual performance of the system. The extensive description in the lower part of Fig. 27, on the other hand, simultaneously considers: (i) the combined production functions; (ii) the different societal requirements of oil products; (ii) the required size of the oil sector (i.e., application of the CF). This representation thus informs us about the actual pressure, in this case, on the anthroposphere. As shown for this specific example, even if the labor intensities per barrel of the unconventional heavy pathways are higher than that of the baseline, this is not necessarily also the case for the overall workload requirement. In fact, for the EU requirement pattern (but not the World and US patterns) the overall labor requirement of unconventional heavy pathways is the lowest. The same analysis has been done for several other dimensions (land, water, capital, etc., see Appendix, section A4) and their combined use allows an assessment of trade-offs of policy choices, both on the production and consumption side. In this regard, it is relevant to recall that MuSIASEM is a semantically open accounting framework and therefore allows for the selection of relevant dimensions (attributes) by the users, thus encouraging an informed discussion among different agents.

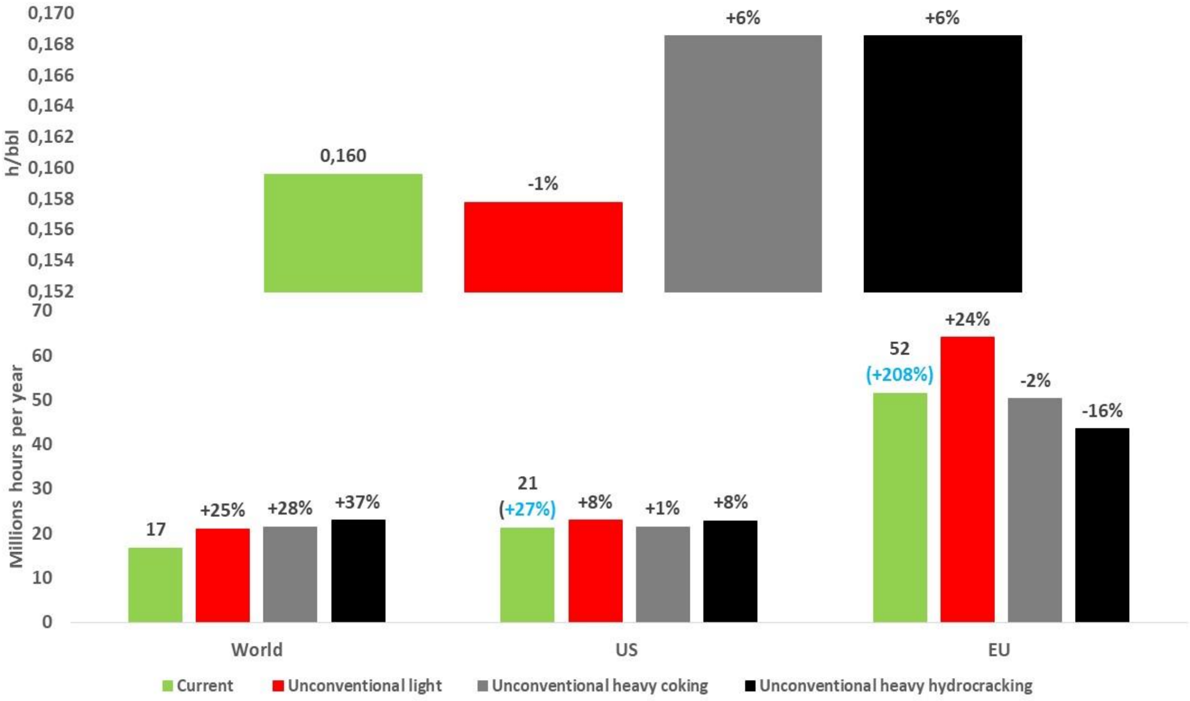

Fig.27 Labor requirement per barrel (h/bbl) of the different combined production functions/supply typologies (fund, intensive description) (upper graph) and total hours of human labor (Mh/year) employed in the global oil sector (fund, extensive description) (lower graph)

The use of the Crack Limiting Flow (based on Liebig's law of limiting products), rather than the mere availability of primary energy sources, as an indicator of functional bottlenecks in the oil metabolism also represents an important step forward. The quality of the product slate refinable from different oil assays from around the globe in relation to the evolution of the oil product requirement (Favennec, 2022) is a well-known issue from an economic (Ruble, 2019) and a technical standpoint (Marafi et al., 2019) (e.g., to increase petrochemicals and reduce gasoline and diesel). Traders and refiners optimize their crack spreads[28] in relation to: (i) the demand of oil products from international markets; and (ii) the availability of different crude assays (WTI, Brent, medium or heavy Russian and Arabic oils). There is a general (but vague) understanding about the role of refiners in relation to decarbonization issues from a socio-technical perspective (Griffiths et al., 2022) and that of (shortages of) diesel in the current energy crisis (Turiel, 2022). However, there is a lack of scientific tools that bridge the quality of product slates (and related feedstocks) with societal consumption practices and assess the implications for the resulting biophysical performance. This work has attempted to fill this gap by providing a tool to operationalize the analysis of this issue and put it at the service of sustainability researchers.

4.2 Shortcomings of the proposed approach

In the current work, the methodology has been illustrated at the global scale for the sake of simplicity. We did not geo-localize oil exploitation nor consider trade of oil products among geographic regions. Several other studies on energy security have specifically and exclusively focused on import/export patterns and models aimed at representing those networks of trade flows (Ji et al., 2014; L. Liu et al., 2020). However, in agreement with Baldwin (1997) and Cherp and Jewell (2014), we believe that a definition of energy security as securitization of imports *per se*, without relating these trade flows to the energy metabolic pattern at the national and global level, has limited value.

The metabolic benchmarks of the production functions (Table 7) represent internal and external pressures. This analysis should be complemented with geographical contextualization to assess the impacts on local ecosystems and societies. For instance, water and land requirements of unconventional oil exploitation may not be much of an issue in certain regions of the USA but can be in arid or densely populated areas. Trade among geographic regions may offset local shortages of oil products, as

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[28] From Wikipedia: *"**Crack spread** is a term used in the oil industry and futures trading for the differential between the price of crude oil and that of the petroleum products extracted from it. The spread approximates the profit margin that an oil refinery can expect to make by "cracking" the long-chain hydrocarbons of crude oil into useful shorter-chain petroleum products."*

is evident from the better performance of the ‘world’ consumption pattern compared to either the US or EU consumption pattern.

In our analysis, we did not consider potential limits of extraction and refining capacity. This would require the integration of power capacity in the set of relevant attributes (dimensions) included in the analysis. Such limits may soon become relevant, notably for refining capacity, as companies are discouraged to invest in either exploration or refining capacity in the current political climate of low-carbon energy transitions and ‘peak oil demand’ (Dale and Fattouh, 2018; Deloitte Research Center for Energy & Industrials, 2020). Refineries are expensive, requiring investments with long pay-back periods, and if we expect a continuous change in both the crude slate (input) and required product slate (output) we should consider the need of continuously upgrading the global refinery system. For instance, tight oil may soon face bottlenecks in refining conversion capacity: “*US refining system approximately hits the ‘refinery wall’ at 40% light tight oil on the total capacity*” (Graham and Merino Garcia, 2020). This capacity limit will be lower at the global level given that the global refining system on average is designed to operate at full capacity with a high supply of medium to heavy oils. Hence, refiners worldwide might not be able to absorb the +26% additional supply linked to a transition to unconventional light pathways (Table 11, Fig. 25). In addition, high shares of light (tight) oil in the supply mix narrow down refiners’ margins (Janssens and Fitzgibbon, 2015). Note that at present, global fossil fuel subsidies are still high – estimated by the International Monetary Fund (IMF) at about US$6 trillion in 2021 (Reuters, 2021), of which the larger share comes from “"under-charging" for the environmental costs associated with the fuels. This may change in the near future.

A last, but important drawback of our approach is that it requires extensive and complex sets of raw data. These data are not always readily (publicly) available and require the use of multiple data sources that, more often than not, use different protocols. This implies that the analyst will have to handle different taxonomies and accounting methodologies. For instance, in the current study, consumption data are from both the Eurostat and EIA databases, which implement different oil product taxonomies (see Appendix, section A4.3.1 and A4.3.2, for the mapping relations). On the production side, data were derived from (Carnegie Endowment for International Peace, 2018), which reports only aggregate categories, hence more detailed assessments of specific oil cuts (e.g., petrochemicals, that comprise a relevant and increasing share of refinery products) are difficult to execute. A uniform protocol for taxonomies and accounting rules is urgently needed if we are to coherently assess societal energy metabolism from PES to energy services (Giampietro and Sorman, 2012).

4.3 Policy relevance

In spite of the drawbacks of our approach, we believe that the metabolic perspective offers several entry points for policy making in the domain of energy security. Indeed, solutions for decarbonization should not only be sought by advocating more technological innovation, new business models or selectively discouraging the consumption of individual emission-intensive oil products (Brandt et al., 2018; Gordon and Mathews, 2016; Griffiths et al., 2022; Gudde et al., 2019). Instead, we should analyze this issue by considering fuel production and consumption as an integral part of the functioning of society (Giampietro and Bukkens, 2022).

At the global scale, any stable metabolic state entails that supply and requirement patterns of oil products must match in the long term. The currently unbalanced requirements of diesel and gasoline in, respectively, the EU and USA in relation to the global product slate can only be maintained because non-limiting, low-quality products (e.g., heavy fuel oils and coke) are exported to and used in countries with looser environmental regulations. For instance, China has seen an increase in the import and use of petcoke in response to the increase in unconventional heavy oil refining in the USA and Canada (Tao, 2015). Simply meeting either the US or EU oil product consumption pattern at a global scale would be impossible without significantly increasing the daily global production. In the case of the EU, this would require triplicating the current production (+208% marginal increase, up to 323 million bbl/day, see Fig. 26), which is clearly an implausible option. Hence, the EU would have to push for developing unconventional heavy oils and/or significantly reduce diesel consumption. On the other hand, for the USA it would be advisable to reduce gasoline requirements and maintain a high refining capacity for light products (i.e., gasoline and naphtha).

Diesel is undoubtedly the most critical fuel in matching oil product supply with requirements. It has a crucial role in industry and heavy transport and represents a staple in the industrialization of developing countries. In addition, current international climate policies, requiring relatively clean fuels and compliance with energy efficiency standards, are likely to further push diesel demand in countries like China and India. While diesel is easily distilled from medium and heavy (cheaper) oils without deep refining, tight oil, the most promising unconventional light resource, with metabolic benchmarks comparable to conventional resources, cannot provide a large share of middle distillates. Indeed, diesel is consistently the crack limiting flow in the unconventional light supply pattern (Table 11). It follows that if we go down the path of unconventional light oils, solely meeting current diesel demand would already imply an increase in overall supply (+26% with the current global consumption pattern, +36% and +234% respectively with US and EU requirement patterns, see Fig. 25) and associated biophysical pressures (Fig. A30). Extensive exploitation of unconventional heavy pathways, with a relative higher diesel supply, would reduce the total supply required to meet current demand patterns, but not necessarily the associated biophysical pressures because diesel production in these pathways is inefficient (Tables A20-A21). For instance, total GHG emissions would increase for all the requirement patterns considered (Fig. A23). In this regard, it is important to observe that the current policy line of applying carbon taxes (“smart tax”) on carbon intensive oils (Gordon and Mathews, 2016; International Energy Agency (IEA), 2021; Masnadi et al., 2018a) considers only one dimension of performance (GHG emission). Consequently, exploitation of heavy oils is discouraged due to their carbon intensity (Welsby et al., 2021) and the oil sector is increasingly being pushed toward reliance on (aging) conventional oil – which is gradually becoming more emission intensive (Manfroni et al., 2021) and more impacting on the environment in general (Parra et al., 2020) – and unconventional light crudes (tight oil), while the transition to a low carbon energy matrix based on renewable sources is expected to take shape (International Energy Agency (IEA), 2021).

Broadening the discussion beyond the oil sector, substitution of biofuels, green hydrogen and ammonia for diesel – for instance as pursued by IMO (Englert et al., 2021) – and fossil fuels in general, is unlikely to materialize in the near future. Thus far, the experience with biofuels has been negative (Cadillo-Benalcazar et al., 2021) and the production of alternative synthetic fuels is still in a stage of low technological readiness. Electric vehicles – expectedly powered by solar and wind in the future (International Energy Agency (IEA), 2020) – are expected to reduce gasoline consumption in the USA and diesel in the EU. However, their large-scale implementation is still questionable due to lack of storage needed for scaling up the supply of intermittent sources of electricity to the grid (Renner and Giampietro, 2020) and lack of materials for the batteries of a new fleet of electric vehicles (Tokimatsu et al., 2018). Moreover, modern societies will still need heavy oil products for industrial and agricultural inputs as well as light distillates and plastic for the functioning of the economy: the use of petrochemicals is ubiquitous and growing (International Energy Agency (IEA), 2018). As we have shown, unconventional light pathways cannot even meet their own internal coke requirement (Table 8), while increased exploitation of unconventional heavy oils (to sustain diesel production), could face bottlenecks of light petrochemicals.

5. Conclusions

We have shown that the energy security of a complex society cannot be captured at a single scale of analysis (primary energy source exploitation) or by a single dimension of performance (GHG emission). Reducing a complex issue, as is the sustainability of the societal energy metabolism, into a simplistic representation of a technical issue by adopting a linear product-centered approach is a crucial flaw (Sovacool and Mukherjee, 2011). The metabolic perspective on energy security, illustrated in this paper, overcomes this limitation by considering the compatibility of the contingent metabolic pattern of demand and supply of oil products – the admissible set of relations over primary energy sources, energy carriers and end uses of a given society – with external (feasibility) and internal (viability) constraints. In our approach, admissible metabolic states are defined by two main drivers: (i) the desired societal energy end uses and the corresponding requirement of specific oil products (desirability) and (ii) the realizable production functions, their corresponding product slates and multi-dimensional integrated performance space (their pressures on the economy and the environment). The reverse of the medal is the amount and detail of the data required for carrying out the analysis.

We demonstrated that, at the global level, the flexibility in the output of oil products, given by the feasible and viable sequential supply pathways, is low. This constraint may become more pronounced in the near future because of potential bottlenecks in the oil extraction and refining capacity. Adjusting consumption patterns (desirability) will therefore be increasingly important for the sustainability of oil metabolism rather than optimizing the supply side (viability, feasibility). However, changing consumption patterns means changing social practices (Shove, 2018, 2017), and this implies a difficult ‘lock in’ to overcome (Unruh, 2002, 2000). How the societal consumption pattern of oil products relates to end uses is therefore an important field for future work in relation to decarbonization pathways and energy security.

The illustration of our approach at the global level did not consider trade of primary energy sources and energy carriers and hence did not assess the sustainability criteria of openness. The oil metabolism at the national level is characterized by extreme openness, and hence the performance space related to the viability and feasibility criteria would better be geo-localized to account for the externalization of economic and environmental pressures. This is a priority in the further development of our approach.

Responsible energy policies should consider the oil sector as an integral part of society, and oil products not as independent elements, but as product slates jointly produced to meet societal requirement for energy carriers. Labeling specific oil products as relatively clean or dirty per se (in an attempt to find “optimal limits” of CO_2 emissions and other solutions adopting a narrow option space (Andress et al., 2010; European Parliament, 2018; Schnepf and Yacobucci, 2014) distracts from the main concern of how to reduce overall oil consumption. There is no such thing as a good or bad primary energy source or energy carrier, only sustainable or unsustainable societal metabolic patterns. At the end of the day, the deliberation over which metabolic pattern we want to pursue is a social, political, and cultural process, and not a purely technical one.

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Chapter 6. Lessons learned and possible implications

6.1 Reflections on possible socio-economic and biophysical implications

What has been presented in this thesis clearly flags the existence of a trade-off between preserving the integrity of the natural processes that stabilize the climate on this planet and the fragility of the energy sector, heavily dependent on oil, in providing an adequate power level to modern Western societies. Unfortunately, given the urgency of climate change mitigation, considerations on preserving a functioning oil metabolism have been completely ignored. But in relation to the sustainability of modern social-ecological systems, these considerations are just as important as climate ones: the possible solutions to the need to preserve both climate stability and a functioning global energy system are in conflict and must be mediated assessing resulting trade-offs. In Chapter 4, we saw that, in the near future, the biophysical pressures of oil production, specifically CO_2 emission intensity per barrel, will progressively increase due to the depletion of high-quality, light and medium gravity oil fields, which represent the backbone of current global oil extraction. Supply chains from depleted reservoirs will become the main emitters of CO_2 in the oil industry: in order to exploit mature fields, more energy carriers (especially natural gas and diesel, depending on future extractive choices) have to be invested by the global economy just to maintain current production – this fact can be imagined as a hypertrophic left-side in the metabolic processor of Fig. 3, and it is captured by the thicker self-referent arrow of the energy & mining sector in the bottom side of Fig. 5b. Therefore, in spite of an already critical current situation, the feasibility with the admissible environment, particularly climate stability, will be put under further pressure. In Chapter 5, we saw that supply and consumption of oil products at the world scale must be coupled to secure the viability of global oil metabolism. Any limiting product may halt economic growth, representing a constraint for the internal viability of modern societies (their social-economic organization). Given the fact that:

(i) conventional oil fields have been on a plateau or declining for decades now and the rate of new discoveries cannot keep the pace with natural depletion (Höök et al., 2009) – hence average reservoir is aging worldwide;

(ii) unconventional oils are the only type of resources that has seen their production grow in recent decades (especially American tight oil); and

(iii) global demand is driven up by Asian economies, which have a preference for middle distillates;

the world is likely to face widespread shortages of diesel. What the oil sector offers to society is not anymore what the society expects it to be – this fact can be imagined as a hypotrophic right-side in the metabolic processor of Fig. 3 and as the hypotrophic black arrow between dissipative and productive sectors of Fig. 5b, representing viable supply, compared with the hypertrophic red arrow with black dotted outline, representing actual requirement from dissipative sectors, that cannot be matched. Finally, in Chapter 3 we showed that high-quality energy supplies in productive sectors (the Strength of Exosomatic Hypercycle, SEH) are essential to nurture the power level of metabolic dissipation of modern economies (the Biophysical Economic Pressure, BEP), making it possible to biophysically support a high material standard of living. This aspect is related to the biophysical viability and the societal desirability of modern social practices.

The big picture that emerges by putting together this set of case studies is that, sooner or later, the performance of the oil sector will be insufficient to assure the needed energy metabolic rates of productive sectors to maintain the societal consumption practices we are currently enjoying in modern Western societies. We can generalize our statement to the whole energy sector, even if we looked only into the oil metabolism in the present work, for a simple reason. As we saw in Chapter 5, the endogenous viability of the oil metabolism depends, among other factors, on the absence of crack limiting flows (analogous to the limiting factors of the Leibig’s law in agriculture). Crack limiting flow prevents the stabilization of the metabolic pattern, leading to halting growth and collapse to an inferior, but viable, power level of metabolic dissipation. The limiting functional system for the whole societal metabolism can be seen as equivalent to the limiting flow for the oil metabolism. Thus, the oil sector can be seen as the limiting functional system inside the energy sector. In a super-connected, globalized economy, unless substitution of the limiting system is possible (we will briefly discuss this point in section 6.2), the stage for senescence is prepared.

Therefore, if our assessments are somewhat indicative of the real situation worldwide, Western economies, and especially the EU (for its high diesel consumption and heavy dependence on external resources), are rapidly heading towards societal senescence. In section 1.3, I defined societal senescence as the "'unpreparedness for change', a failed adaptation to possible, different, future environments, and as a "progressive freezing" of the metabolic activity in the current state to maximally preserve what can be sustained by a declining flow of available energy". The senescence of the oil metabolism originates in the extraction sector, the direct interface between the social-economic system and its admissible environment, and propagates upward, to the refining sector, the whole energy sector and, eventually, the whole society. If primary energy resources are not efficiently collected from the environment by the upstream sector, more biophysical inputs will be needed to provide secondary flows to the social-economic system (Chapter 4). The societal metabolism will have to invest comparatively more biophysical resources (flows and/or funds) into productive sectors, at the expenses of dissipative ones, to exploit depleted natural resources (with diminishing returns on the investment), and the admissible environment will have to dispose of more and more wastes per barrel extracted. Nevertheless, unless new primary energy sources of high quality are found soon, a continued reliance on oil will imply that the productive sectors will not able to match the requirements of oil products of the rest of the economy, due to one or more limiting flows (Chapter 5). These increasing biophysical instabilities will be temporarily adjusted by international trade, through increasing debt. However, when the social-ecological system expands to a global scale, and/or cannot find balance anymore by externalizing pressures on, and importing useful secondary flows from, other social-ecological systems, it may slip into a destructive spiral of supply and demand (Turiel, 2014), with stagflation, debt bubbles and inequalities as typical diagnostic signs. That is, an adaption process of the global societal metabolism to the real biophysical possibilities offered by the admissible environment.

In contrast to what most economists would expect as a signal of scarcity, it is volatile crude oil prices, instead of chronically high prices, the distinctive mark of the senescent stage. Actually, high prices are a systemic healthy signal: they put the economy into recession, in an adaptive attempt to regain balance with the biophysical capacity of the environment. Periods of low prices are the critical tipping points, where the power capacity in supply systems is destroyed (e.g., during COVID pandemic). The global economy may find itself in a situation of "drillers without fields and fields without drillers". National oil companies of countries that base their economies entirely on oil extraction may stop drilling, due to the high production costs, economic and biophysical, which make the activity unprofitable. This could happen despite the large political and social stakes involved and the willingness to accept lower margins than Western competitors. On the other hand, Western oil majors do not see any upstream investments sufficiently rentable on a medium-long term by their historical standards. Thus, they may prefer a careful long-term management of their concessions instead of maximizing extraction from the best wells (and therefore profits) in the short term, while moving their core business to supposedly more advantageous sectors (e.g., renewables, rebranding from Oil & Gas companies into "energy companies")[29]. This is an option for companies working in diversified economies (as oil majors usually do), but not always for national oil companies that usually operate in economic contexts very dependent on natural resource extraction.

In section 2.4, we defined the beginning of the societal senescence when the ascendency of productive sectors starts declining. Given the current global supply chain disruption we are currently in (not only related to the

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[29] My two cents: the comparable economic performance of electric renewable technologies with fossil fuels is due to the increased production costs of the former and global monetary manipulations to favor the latter (debt, credit leverage and targeted subsidies), not to real technological breakthroughs. The perception of the renewable market as a rentable one could be just a short-term mirage.

COVID pandemic but multi-dimensional), and the reluctancy of Western oil companies to expand their supplies despite record high prices – as well as OPEC countries, pumping below the allocated quotas –, we can find several reasons to argue that we already hit a global stage of senescence. We may conventionally establish the year 2021 as the mark of transition into this terminal phase of the globalized economy, likely prompted by diesel shortages (even if arguably the real date is earlier). Post-COVID energy demand grew rapidly to pre-pandemic levels, but without adequate supplies of cheap diesel, global mining, manufacturing and transport were severely structurally impaired and unable to keep the consumption pace.

6.2 Reflections on possible policy implications

The process of decision making involving complex systems can and should be informed by multiple, even contrasting, narratives to generate a viable option space for social and political action. Thus, instead of narrowly focusing only on the reassuring message of 'prediction and control' through technological innovation, relational analysis aims at identifying critical vulnerabilities of the oil metabolism and quantitatively assessing the biophysical constraints on the feasibility, viability and desirability of modern societal metabolism. This "quality check" is useful to avoid wrong political choices and to rediscuss the underlying socio-technical imaginary. What if the green transition will not keep up with the promise to decarbonize the global economy while assuring energy security and a good material standard of living for all? That we have to continue to use fossil fuels. And what would be the consequence of a senescent oil metabolism for the globalized social-ecological system? We should carefully consider these questions in the sustainability debate and assess critical scenarios.

The very first step to face our current global sustainability predicament is to get full awareness of the limits to growth: a globalized, growing economy must eventually mature and die. Only then, Western societies may disclose their full adaptive capacity to learn how to deal with the problematic, developmental nature of their existence. They need a re-birth into a new identity to persist. Our governments, institutions and citizens should stop trying to "solve" the current sustainability predicament within the same framing that created the problem in the first place, reproducing the same problems again and again over time and at higher scale – a "*more of the same"* strategy. The whole package of measures envisioned by the EU with its European Green Deal seems to me fostering different material arrangements – basically, changing from fossil to renewable energy sources, transformers and infrastructures (an electrified economy) – while maintaining the fundamental scope of generating economic growth and high material standard of living (through financial markets and established institutions) – the "teleo-affective structure, domain of symbols, meanings and beliefs" of current social practices (Schatzki, 2010). In other words, even if we are trying to change the structures used for our purposes, we want to maintain the expression of the same original functions. Consider the Net Zero to 2050 report (International Energy Agency (IEA), 2021a) for the sake of discussion. There are multiple, acknowledged biophysical-rooted concerns on the large-scale viability of the green project. Here the more relevant ones: (i) shortages of minerals and metals critical for the transition to electric renewable technologies – identified by the same International Energy Agency (IEA, 2021b); (ii) dependence of renewable supply chains (mining, manufacturing and transport) on fossil fuels, especially diesel for mining and logistic; (iii) intermittency and storage issues (Renner and Giampietro, 2020) – policymakers are basically trying to "fossilize" electric renewable technologies[30], that is to make them fit into those useful characteristics that are typical of fossil fuels, like transportability and high energy density. Until these issues are not solved, and let's see if they are solvable in a reasonable timeframe, policies that push renewable energy (entailing the development of technologies not in a mature state) may do more harm than good: they subtract precious secondary energy carriers from the societal metabolism, preventing investments in the fossil structures that maintain our energy sector functioning, thus representing an overhead on the current fossil energy matrix instead of a net energy source. Moreover, due to the global push toward cleaner fuels[31] and smart taxes – an issue

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[30] An expression that I borrow from Antonio Turiel.

[31] *"Regulatory stringency on fossil fuel quality may lower GHG impacts at the end-use combustion point, it leads to more challenging crude processing within the oil refining plant, with associated higher energy*

commented more extensively in Chapter 4 and 5, and also in the Appendix, section A1 –, we are generating policy incoherence across multiple scales, putting additional pressure on international diesel supply and trade. On the other hand, policies such as large-scale implementation of electric vehicles and the attempt to ouster Russia from international markets put direct pressure on European refiners, further eroding their assets and the possibility to maintain an adequate operative capitalization. Elaborating on European oil independence from Russia, this seems to me extremely unlikely in any timeframe. European refineries are designed for medium oils, that is, for Russian blends. Russian crude is of the perfect quality for European refiners, and that is because European and Russian oil sectors share a long history of cooperation and co-evolution. Furthermore, the European refinery sector has already been in constant decline for at least a decade, with a consequent increased reliance on the international market (more imports of oil products) (Concawe, 2022). European refiners will hardly have the resources to invest in such a radical change in their operational capacity to adjust for lighter American or African blends. Meanwhile, it seems that in the Middle East, the only other strong producing region of medium oils, OPEC producers do not have enough capacity to cover their production quotas, much less to compensate for the Russian one (Berman, 2022; Goehring and Rozencwajg, 2022). For the reasons seen in Chapter 5, the United States cannot support Europe as far as oil is concerned. American crude is too light for European tastes, and its possible abundance on the market would reduce the differential between light and heavy crude assays, further decreasing the economic margins for European refiners. Actually, the competition with American refiners remains strong, given their technological superiority, and could intensify if tight oil increases its weight on the market (Fitzgibbon and Rogers, 2014). US are indeed a strong competitor.

Since we still live in a civilization where almost 85% of our final consumption of energy is from fossil sources, if we actively try to

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intensity. This trade-off in where in the oil refining value chain emissions and energy intensity occur is a form of “carbon leakage” that needs to be addressed.” (Griffiths et al., 2022, p.29) destabilize the global refining system, promoting a large-scale renewable substitution of the fossil energy matrix or putting additional pressures on diesel supply and trade, we may end up with the final result of an accelerated societal senescence. Either because the overhead investment to build new green structures, while maintaining the old fossil ones functioning until the transition takes place (Di Felice et al., 2018), requires additional biophysical flows in the face of a declining performance of the oil sector (as explained in Chapter 4); or because of the increasing, direct pressure on critical points within the energy metabolism, like destabilizing the gasoline and middle distillate market with large-scale adoption of EVs, in the face of a constrained diesel supply (as explained in Chapter 5). Therefore, we not only need a multi-criteria, prioritized assessment of energy policies to check if their intended effects are coherent among each other (Appendix, section A1) and with the overall social goals, but also evaluate the overall multi-scale effect on the developmental trajectory of the whole social-ecological system, to preserve its maturity as long as possible. For that, we need to establish a new vision of the future, a new socio-technical imaginary. Current mainstream energy and climate policies may be worse than doing nothing: they would like to further increase the ascendency of global economy, but by preventing the social-ecological system to naturally adapt to its developmental trajectory, they accelerate its decline.

The quality of the relational analysis proposed in this thesis cannot be proven in scientific terms. However, the descriptive power of the relational framework lies in the ability to grasp the evolution in time of functional organizations. Quantitatively to some extent, as we proposed in Chapter 3,4 and 5 (given the complex nature of social-ecological systems[32]), but for sure intuitively. Methodologies for techno-economic or climate assessments that focus exclusively either on structural or functional realizations are inadequate to even perceive the entanglement of social relations that made up social-ecological systems, the very relevant focus of sustainability science. The adoption of a relational

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[32] Recall the note of section 2.1: "*a complex phenomenon is a phenomenon that requires a simultaneous perception and representation of its various relevant aspects using several non-equivalent narratives and dimensions and scales of analysis*" (Giampietro, 2021).

framework in sustainability science sheds light on “uncomfortable knowledge” (Rayner, 2012) and gives us insights about the viable option space for social-ecological systems. This is the ultimate proof of its utility: people exposed to this kind of analysis are holistically informed and empowered to generate their meanings and take responsibilities in their lives accordingly.

6.3 A humble proposal for an alternative narrative

“However, I strongly agree that the term "sustainable development" is oxymoronic (C. Hall and R. Beal, unpublished manuscript). Infodynamically, growth occurs in the immature stages of a system's development, whereas sustainability is possible only from maturity onwards, although the likelihood of achieving it diminishes as a system continues to senesce. [...] My own recommendation for sustainability, rooted in infodynamics, would be for a system to try to preserve infodynamic maturity for as long as possible.” (Salthe, 2003)

To embrace a real transformative pathway, we need first to integrate both functional organizations and Nature into a unified theoretical and methodological framework, i.e., the relational framework, to guide sustainability assessment and social-political action. Then, we need to integrate irreversibility (i.e., Time) into the framework: evolution and change are constantly unfolding independently from human will, bounded by a developmental trajectory. We need to foster types of transformation consisting of endogenous, relational and reflexive changes in current social practices. In order to do that, we need to consider the complexity of the whole societal metabolism and assume the responsibility of political choices. Radical change should not be based on optimal, win-win solutions grounded in technological innovation and new business models, but on informed deliberations over problematic social, economic, ecological and cultural trade-offs. Pursuing excessive epistemological simplification due to the exclusive adoption of simplified economic narratives as guiding tools for political and social action is a deadly choice in the long term. The green transition discourse is obscuring alternative imaginaries, such as one of a sustainable human-Nature co-evolution based on an ecological and relational *weltanschauung*. Unsurprisingly, since the cultural homologation and the *reductio ad unum* of the entire world (under market forces) are well-known features of capitalism. The colonization of the ecological imaginary by the techno-optimist discourse is part of a bigger picture of negation of Limit that is taking place in our modern culture.

At a more practical level, a real transformative path should therefore aim at realizing a "gentle aging": slowing down the rate of substitution of structural realizations that constitute the societal metabolism, in order to maximally preserve biophysical funds in time (e.g., people and vital energy systems); while slowly changing the functional organization of social practices. The current societal metabolism should be partially, or totally, deconstructed to leave space for something else, hopefully maximizing the stability of the system in front of an increasingly less hospital environment. Modern societies need to face the "tragedy of change" (Funtowicz and Ravetz, 1994), deciding what to lose, functionally, in order to move forward the developmental path. Remaining immature and fast-growing is not a viable long-term option. The first step in this direction is therefore to assess and reframe the current collective perceptions and representations of the causal network of relations that generates our habitable order, in order to build different anticipative models. We should aim for a different collective socio-technical imaginary, defined within a new cultural paradigm, hence re-think the mainstream entanglement of purposes, meaning and beliefs to act differently in society. This would lead to re-discuss the relations between socio-economic agents across different societal scales – citizens, families, companies, institutions, etc. –, that determine current material and formal arrangements (e.g., technical know-how and competences, juridical procedures) oriented toward economic growth within free-market democracies. A transformative path does not necessarily entail the substitution and/or upgrade of the material arrangements: our societies do not necessarily have to become "green", trying to substitute the current energy matrix with another one with the same functions, yet inferior performance; investing (and maybe wasting) immense resources and entropy in the process, that could be used otherwise. Material structures and arrangements must be decoupled from their current functions and reframed for new end uses, preserving them structurally (maximizing their lifespan) without contributing to the reproduction of social practices aimed at increasing the ascendency of the social-ecological system.

Turning again our attention to the oil metabolism, a possible transformative strategy could be the following. Responsible policies should aim at using the entire spectrum of refining products and take into account the country's fuel consumption pattern, instead of focusing on carbon intensity of isolated final products, as we argued in the discussion sections of Chapter 4 and 5. In the EU, shifting from diesel to gasoline and fuel oil would put the fuel supply-demand equilibrium in balance and reduce the uncoupled CO_2 emissions. However, this is not true for US, that instead should reduce its huge consumption of gasoline in the transport sector. Context-specific policies are thus necessary. Instead of carbon taxes on high-carbon oils or large-scale adoption of electric vehicles, that narrow down refiners' profit margins and hinder the sector's economic viability, the focus in the EU (and in the world) should be to preserve it as long as possible, while an effective and gradual descent in final oil uses is taking place. On the long run, foster investments in deep refining capacity could be a more profitable option for refiners, for strategic reasons and for ensuring high cash flows due to worse market conditions or the necessity to handle crudes difficult to process (e.g., heavy oils). *"[…] for a producer of a very large volume of even conventional heavy or medium sour crude, investment in conversion capacity to expand the high-value demand curve can, for periods of time, provide higher overall pricing across all barrels. If the volume is high enough, this can justify investment in even very high capital conversion projects*" (Janssens and Fitzgibbon, 2015, p.6). Actually, it seems that investments in complex refining have been rising over the last decades, despite the adverse market conditions, especially in Asia, Middle East and Latin America – not in Europe, where the sector has been declining for about two decade. Complex refiners prefer a high supply of medium-to-heavy oils *("weighted average API gravity of EU crude imports in 2016 was 35.2°, nearly unchanged for the last 30 years"*(Petroleum Economist, 2018)): in this way, the residual fuel oil price is maintained low (at the substitution price), the light-heavy differential wide and simple refiners are cut off from the market, given a high demand of light products (Fitzgibbon and Shankar, 2016). It appears quite clear that refiners around the world are betting for an uncertain and difficult future market where unconventional heavy crude are a fundamental part, despite their higher environmental and climate pressures (Chapters 4 and 5). Moreover, heavy oil exploitation needs naphtha, from American tight oil (US Energy Information Administration, 2020), to dilute the sticky, high-viscosity crudes and make them suitable for long distance transport through pipelines; thus, the production of the two main types of unconventional oils is strictly entangled (Argillier et al., 2005). We still need a multi-criteria analysis to avoid inconsistencies between energy and climate policies at different scales, but after establishing a new final purpose – preserving current funds inside the oil metabolism as long as possible – the effects of each policy can be weighted differently. Emitting more CO_2 to keep alive the refining sector while cutting in a consistent way final consumption can be socially acceptable, and more effective as well in climate terms. It is likely that the world's thirst for fuels will not be satisfied only with "low-carbon" oils, but by a combination of conventional, tight and heavy crude, for a long time to come; and refiners need to keep the pace.

It is time to open up the option space by adding new degrees of freedom for sustainability policies. We have to imagine a radically different set of social practices constructed around a new hierarchy of values[33] and with a different horizon of finality. A radical shift in the collective consciousness can be done relatively quickly if we embrace a transformation of current cultural and scientific paradigm, hopefully leading to different framing of the sustainability predicament, away from a growth paradigm and toward a new social-economic model. However, this could result in a dangerous process of failing to bring forth a new

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[33] This is even more true in Europe, likely the most exposed region worldwide, due to the lack of relevant indigenous natural resource, the deindustrialization process that took place over the last 30 years, its huge population density, demographic structure and dependency ratio.

habitable order out of the chaos of change. If you perturb a complex system, you have irreducible uncertainty on the effects of that perturbation. Therefore, we as sustainability scientists should assume a posture of ‘reluctant radicals’:

“You want to be very careful about doing large-scale experimentation with large-scale systems, because the probability that a scheme you want to implement in a large-scale social system will have the results you intended is negligible. […] A proper strategy to implementing social change requires humility. You’re probably not as smart as you think. Start small, and start with things that you actually could adjust. That you actually do understand. That you actually could fix. […] Modern men don’t see God because they don’t look low enough (quoting Carl Jung).”
Jordan Peterson, Canadian psychologist and professor, during a speech.

Before being anxious to propose optimal solutions to ill-defined problems (“save the planet”), we should collectively stop, think very deeply about our modern condition and start communicating again with each other. The “emergency approach” (panic decision-making under uncertainty) to sustainability issues is deleterious, with the potential to lead straight to ineffective policy action at best, and totalitarian and centralized solutions at worst. One should not hide under the carpet the uncomfortable knowledge about the current inadequacy of renewables to sustain current modern societies, or the impossibility of a circular economy, not to admit that we need to face a radical discontinuity. Sustainability challenges require reflexivity, solidarity and the acceptance that failure will be an inherent part of the complex adaptation. Renewed perceptions and clear thinking are also prerequisite for effective social and political action, to redefine our collective hierarchy of values and affective relations necessary to move forward together in an uncertain future. Current scientific and social-economic paradigms are falling apart and we need new eyes, a new thinking, a new language and a new ontology to perceive and think about the world. Then, maybe, if we are able to tolerate the responsibility of changing a very well-established system that indeed generated wealth for large shares of human population, act very, very carefully and cautiously with humility toward the envisioned transformation. Start small, change your individual perceptions and behaviors, build together common ideas to develop alternative social practices. We should be worried about one-size-fits-all, top-down global solutions, coming from an unreflexive, uncontested, self-proclaimed moral superiority, usually justified by "evidence-based" (Western) science, that is implemented through a violent rhetoric of social catastrophism. In my opinion, the very first step in this direction is to look deeply inside the biophysical limits experienced by current social-ecological systems. This thesis wants to be a humble attempt to support a move in this direction.

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Chapter 7. Conclusions

7.1 Contributions

“Only when we realize that our human nature is problematic, we can begin to explore our best potentials” (Raymond Peat).

In the present thesis, I have put forward a relational framework with the aim of exploring the biophysical limits of the global oil metabolism, and how the energy-time nexus affects the development of modern social-ecological systems. Building on the legacy of the *Multi-Scale Integrated Assessment of Societal and Ecosystem Metabolism* approach and practice theory, in this thesis I proposed a unified methodological framework, based on metabolic processors for the quantitative representation of social-ecological systems, as a conceptual tool to dissolve the modern epistemological separation between Nature, Society and Technology. The relational *weltanschauung* is depicted theoretically in Chapter 2, and then tested in methodological applications. The methodological applications proposed throughout the thesis suggest that the global oil sector has likely already entered into a phase of senescence, the final developmental stage for complex adaptive systems, that kicks in when size and connectivity of productive sectors start declining. In Chapter 4, I discussed how conventional crude supply is progressively aging worldwide and its exploitation is increasingly threatening the planet's climatic stability. In Chapter 5, I explored in detail, from a relational perspective, how the future predominant reliance on unconventional oil sources, rather than representing an "unconventional revolution", resembles more likely the last, desperate stage of fossil fuels exploitation. The last breath of a decadent society: we are scraping the bottom of the barrel, trying to make profitable the use of non-optimal resources that cannot functionally replace the old conventional ones.
In relation to the research questions:

1. How does energy metabolism stabilize social practices in modern societies? Or in other words, how the profile of allocation of human time

- an emergent property of society's metabolic pattern - is affected by the performance of the energy sector?

This question has been answered in Chapter 3. The chapter illustrates how the performance of the energy sector is intertwined with the stability of Western societal metabolism, i.e., the relational network of social practices that enable our Western high material standard of living and lifestyle. Acknowledging this entanglement is essential to understand the risk of the current reliance on imports and immigration to solve shortage of labor in the primary sectors of the economy.

2. How can we characterize the structural and functional factors that compose the energy metabolism from a relational and biophysical perspective and assess their performance in relation to the overall metabolic pattern of modern societies?

Chapters 4 and 5 explored this question and provided examples of how to characterize the performance of the energy sector in relation to the biophysical demand of modern societies – i.e., the profile of required products from the energy sector and the profile of inputs that the society is willing to give to it in exchange.

3. How much is the metabolism of developed societies dependent on oil and to what extent, and can unconventional oils substitute for the cheap and easy conventional one?

Chapter 5 has presented a methodological framework that can be used to answer this question. The achieved insights are the result of a preliminary analysis and represent a tentative answer to this question.
We can see the overall connection over the chapters by considering that Chapter 3 constitutes a conceptual interface between the technical, biophysical and the societal discourse, where energy and social practices are unified using the relational approach. Within this holistic framework, Chapter 4 and 5 focus on specific bottlenecks that could destabilize this large-scale picture. Insights and possible implications of the work done in this thesis are explored and discussed in Chapter 6. I argue that the performance of the oil sector is potentially a bottleneck for the

performance of the whole energy sector. If that is true, and thus the performance of productive sectors is not adequate to match societal requirements coming from dissipative sectors, a deep rearrangement of our way of life onto the real biophysical possibilities, indicated by a reallocation of human time and biophysical funds in general (power capacity and land use being prominent ones), should take place. When dealing with the inevitable developmental nature of social-ecological systems on a global scale, current energy policies seem to neglect the implications of biophysical constraints when trying to put the global economy back on the growth path (although "green"), in spite of the deterioration of the resource base. This desperate effort may actually accelerate the biophysical decadence of the global economy. However, this hypothesis needs to be explored more extensively in future works.

7.2 Limitations and future research

The main methodological limitations encountered during the present endeavor have been discussed in the respective chapters, to which reference should be made. Here I care to emphasize again the importance of having access to high-quality datasets. Metabolic assessments require big sets of different data properly categorized and organized, and geo-localized enough to be meaningful for specific contexts. Dataset organized in this way are generally missing. That implies a long handcraft work to generate those databases for a valid metabolic assessment, higher probability of errors, and more time and resources to be spent on each individual analysis. A shared, regularly updated dataset, in the form of a world map, would be of invaluable value.

The present Ph.D. thesis has been written within the idea of Post-Normal Science. As I stated repeatedly throughout the text, the arguments and the results presented do not represent definitive statements of truth. Rather, they should be considered as clues about the nature of the energy predicament we are currently facing in the West. The information collected is limited and the uncertainty associated with my analysis is high. Therefore, various research lines are suggested to further expand our knowledge of the energy metabolism and make more robust the analysis.

1. *Metabolic characterization of the whole energy sector:*

It is essential to expand the type of methodological assessment done for the oil metabolism to the whole energy sector. In my view, currently the most important functional systems that require a careful characterization from a biophysical and relational perspective are the coal and natural gas metabolisms. Coal, because it is the first Asian fuel, it is currently sustaining economic growth for the most part of human population living in the East, and it may return to a central importance in the West too, due to the declining performance of the oil sector. Coal is quite versatile, being potentially used in power generation, industry – especially the "four pillars of modern civilization": steel, cement, ammonia, plastics, all hard-to-abate sectors given the scale at which those products are required – and residential sectors. It can substitute for oil and gas for most of common end uses and it is easy to move around, although not as easily as oil. Natural gas, because of its vital importance in global economy as a feedstock for production of fertilizers and plastics. It is also a flexible power back-up generation and a potential substitute for several societal end uses currently fueled by oil. However, both coal and gas will eventually (or are they already?) face diminishing returns on extraction due to natural depletion, and declining performance of their functional supply systems, just as it is happening with oil. Therefore, mapping out the whole fossil energy metabolism will be of paramount importance for deliberating over future transformative scenarios.

2. *Mapping different energy metabolisms worldwide:*

Mapping energy metabolisms worldwide is a second important research line. Describing the different development stages at which different economies find themselves is crucial to get transformative policies right. For instance, Latin American countries show different societal metabolisms compared to Europe or China. Meaningful energy and climate policies need to be contextualized properly, in relation to local biophysical feasibility, techno-economic viability, social desirability and the degree of openness acceptable for possible security and development issues. Crucial is the distribution of funds. Human activity and power capacity allocations are strong indicators of the development of modern societies, that show evolutionary convergence around typical patterns (as shown in Chapter 3). While in relation to the characterization of the profile of human activity the methodological foundations have been laid out, in relation to the characterization of the profile of power capacity this aspect has yet to be fully developed. In the present thesis, a thorough characterization of the distribution of power capacity across functional supply sectors and societal consumption practices is missing. Yet, power capacity is a crucial factor to has to be addressed in relation to the sustainability of social-ecological systems, and in particular energy systems, to effectively generate a complete framework of causation (in the Aristotelian sense). Power capacity represents a relevant 'efficient cause': the agent that promotes change. Again, mapping the distribution of power capacity is strictly related to the development stage of the societal metabolism under analysis. This assessment is essential to generate effective, context-related, transformative policies. A methodological expansion of the current framework is therefore needed.

3. *Energy-food nexus security and loss of European biophysical independence:*

Exploring the nexus between food and energy security is vital for assessing future adaptation scenarios. Natural gas is the main feedstock for production of ammonia. As calculated by Vaclav Smil, without fertilizers most of current global population could not be fed (Smil, 2001). Diesel and oil fuels are necessary for agricultural equipment, irrigation and tractors. Assessing the metabolic entanglement between fertilizers supply, farmland, agricultural power capacity and human time allocation can shed light on the biophysical constraints concerning adaptation policies to climate change or resource scarcity. This kind of analysis is even more relevant if applied to homogenous economic and geographic regions, e.g., the EU. Europe is likely the most exposed region to biophysical limits, due to its heavy dependence on international energy markets, and a very bulky socio-political player on the global landscape, due to its aging population, high biophysical consumption, highly complex, transnational political and institutional networks. Assessing biophysical security (food and energy) in Europe is of paramount importance within the current geo-political landscape. Preliminary studies done with MuSIASEM have shown a worrisome dependence of EU on imports that represent a serious threat to its food security (Renner et al., 2020).

4. *Energy transitions and practice for alternative futures:*

The natural continuation of the work presented in this thesis is the development of an innovative methodological toolkit to assess the feasibility and desirability of energy transitions from the perspective of societal metabolism. This toolkit can be used to (1) *identify possible decarbonization pathways,* by generating a multiscale and multidimensional characterization of transformative scenarios, for modern societies. A quantitative analysis carried out using this methodology should be able to characterize how changes in the quality of the biophysical factors characterizing the performance of the energy sector may negatively affect its ability to support modern societal consumption practices. These factors include the quality of primary energy sources, conversion coefficients, the role of international trade and pressures on the environment. This analysis should explore and visualize how these factors could be affected by natural depletion, technological innovation or green substitution, energy efficiency, implementation of new energy policies or geopolitical tensions; and (2) *explore the viability of biophysical scenarios for future adaptation*. Here the focus is on the internal coherence of existing networks of biophysical flows (energy, food, materials) and funds (machinery, infrastructures, human time) required to stabilize the metabolic pattern of modern societies. This research line is important in order to identify effective allocations of biophysical funds (e.g., power capacity, human activity, farmland) across the whole socio-economic system in the context of a desired low carbon future.

When thinking about a radical energy transition we cannot expect to just substitute fossil energy with wind and solar at *ceteris paribus* conditions. Rather, we have to look forward to how current consumption patterns will be affected by a different biophysical quality of supply. It is my hope that, by showing its effectiveness in informing societal deliberations over sustainability issues when dealing with real world applications, we, metabolic scientists, will be able to push forward the adoption of a relational paradigm in sustainability science and provide practitioners with useful tools to better understand the uncertain world we live in.

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Appendix

A1. Surfing the oil hierarchy: a multiscale assessment of decarbonization pathways for the EU oil sector

This section is the transcript of the conference paper: “Manfroni, M., Velasco-Fernández, R., and Giampietro, M., 2022 Surfing the oil hierarchy: a multiscale assessment of decarbonization pathways for the EU oil sector”, published in the proceedings of the “5th International Conference on Energy and Environment: bringing together Engineering and Economics”, held in Porto, Portugal 2-3 June, 2022. The language and the structure used reflects the fact that this chapter was conceived as a stand-alone paper.

A1.1 Abstract.

In this article, we present a relational approach to analyze the EU oil metabolism. The oil supply system and consumption practices are described as a complex network of transformations across multiple scales carried out by metabolic processors, showing different profiles of production factors. We explore the entanglement between typologies of EU refineries, the quality of crude oil intake (local or imported), human time allocation and trade patterns, with the goal of identifying lock-in mechanisms and checking the coherence of the European decarbonization agenda. Results flag the inconsistency and contradictory effects of the EU decarbonization agenda. A large-scale implementation of electric vehicles for private transport, reducing the relative contribution of gasoline and diesel in the oil product mix, is not economically viable for European refiners and emphasize the EU dependence on international trade. Carbon taxes on high carbon oil products entail a shift in the opposite direction, favoring the production of light distillates (e.g., gasoline) but with the need of changing the quality of oil imports, hence current geopolitical energy relations. It is concluded that integrating a metabolic approach into the EU energy governance toolkit is crucial for achieving systemic transformations toward a low carbon society

A1.2 Introduction

A radical decarbonization of the global economy is unanimously advocated by the major international actors to tackle the worst effects of climate change. The mainstream envisioned mechanism for global decarbonization is a mix of substitution policies and a reduction of global demand coming from changes in citizens’ behaviors (International Energy Agency (IEA), 2021). However, energy systems are complex (Di Felice et al., 2022): any serious transformative policy of either energy consumption or production practices will have systemic effects, potentially disrupting energy security and meeting resistances to change across hierarchical scales and dimensions (economic, social, environmental).

In this work, we propose an innovative methodology for energy governance, aimed at exploring the impredicative coupling between the oil supply system and the set of consumption practices of oil products for the EU28. Our metabolic tool is grounded in the semantically open Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) framework and applied with relational analysis. Applications have already been developed for the supply side (Di Felice et al., 2019; Parra et al., 2020), while societal consumption practices have been thoroughly described in (Velasco-Fernández et al., 2020). Fully integrated analyses have been developed to explore the EU food metabolism in relation to food security concerns (Cadillo-Benalcazar et al., 2020). Here we explore the EU oil production and consumption patterns across multiple scales (i.e., the oil hierarchy) with the goal of identifying lock-in mechanisms and checking the viability and coherence of the envisioned decarbonization agenda, focusing our simulations on the systemic effects of Electric Vehicles (EVs) and carbon taxes policies. We show how the proposed methodological toolkit has the potentiality to inform policy deliberation in support of energy transition.

A1.3 Materials & Methods

A1.3.1 Characterizing impredicative relations across the multiscale structure of energy systems

Energy systems are dissipative, hierarchical and adaptive (Bale et al., 2015; Prigogine, 1980). They degrade favorable gradients of external energy flows to build up new structures and functions, their organization and operational dynamics unfold over multiple components interacting across different spatial and temporal scales, and they are able to evolve in response to external or internal perturbations through feedback loops. A minimum of three scales is necessary to fully describe energy transformation processes inside energy systems, what is defined the basic triadic structure (Salthe, 1985): a focal level, i.e., the observation scale, where the phenomenon of analytical interest takes place; an upper level, that establishes finality (functional entailment) – the purpose of the process, why does that transformation occur? – and a lower level, that provides material and formal possibilities (structural entailment) – technology involved, geological resources and constraints, material requirements of the transformation process. Our focal level is on the coupling between supply and requirement of oil derivates; final energy uses determined by the EU socioeconomic structure at the upper level provide meaning to the EU oil sector (e.g., how much gasoline is demanded for European transport, or light products as industry feedstocks); extraction and refining processes define the biophysical and technological possibilities at the lower level (e.g., how much hydrocracking capacity is installed in the EU to cover internal diesel requirements). These three scales are connected by feedback loops within the hierarchical structure, affecting simultaneously one another in impredicative ways: the environment supplies a specific “crude diet” and requires specific technologies for extraction and refining; available energy carriers are used efficiently only in specific final uses, establishing in time a specific set of societal consumption practices and technologies (e.g., engine vs electric vehicles); the socioeconomic structure and political expectations, determined by established and expected final energy uses, in turn put pressure on the environment and on the oil sector. If a specific entanglement of relations provides closure – i.e., when it is feasible in relation to external/environmental constraints, viable in relation to internal institutional-technical-economic constraints and socially desirable – it becomes over time the established metabolic state of society (among the possible ones). Causality flows in different directions at different scales. For example, changes in the final uses due to EV policies propagate top-down through the oil hierarchy, while changes in oil quality due to aging oil fields (Manfroni et al., 2021a) or in the oil products available (e.g., limitation on trade or transformations in the EU refining capacity) affect the metabolic state in bottom-up direction.

The relations between scales are the focus of the social-metabolic approach. MuSIASEM builds on the flow-fund model introduced by Georgescu-Roegen (Georgescu-Roegen, 1971) to represent the components of social-ecological systems. Using the flow-fund distinction, energy transition can be understood as a process of changing the structure of the economy (funds), in order to metabolize different energy carriers (flows) coming from low carbon sources. Funds are typically responsible for the generation of lock-in mechanisms. For instance, power capacity, both in supply (oil rigs, extraction platforms, pipelines and refineries) and in consumption (cars, trucks, industrial equipment), and availability of skilled labor hours are structural properties of a society that are not easily modifiable over a short period of time. On the other hand, European international trade patterns (flows of oil commodities or labor embodied in imported commodities) can be altered more rapidly to compensate for potential mismatches between internal supply and requirement, albeit within the limits imposed by other societies and international trade agreements, and with potential geopolitical energy security issues. Hence, any energy policy that fosters changes in consumption practices (e.g., EVs) or in the quality of oil supply (smart tax on high carbon oils (Gordon and Mathews, 2016)) needs to deal with the entanglement between typologies of EU refineries and their “design crude oil”, human time allocation and trade (sociotechnical lock-ins) and contemplate a systemic rearrangement of the overall metabolic pattern, not only contingent substitution of typologies of energy carriers (electricity vs fossil fuels).

The quantitative representation of the relations between structural and functional elements across the multiscale structure has been done using metabolic processors. Metabolic processors can be interpreted as extended production functions that represent an expected (functional) or observed (structural) profile of inputs and outputs (flows and funds) associated with a specific process, such as oil extraction or refining. Looking at the EU oil hierarchy represented in Figure 1, processors are associated with the green ovals and describe the biophysical performance of those specific nodes inside the metabolic network. Then, by bridging the relations between processors across scales and looking at sequential pathways determined by either material or hierarchical entailments (different elements expressing the same function at the higher level), we can quantify the performance of the overall energy production and consumption patterns inside the oil hierarchy. More comprehensive theoretical explanations and methodological applications of metabolic processors can be found in (Di Felice et al., 2019).

A1.4 Data & Simulations

First, we made a diagnosis of the current EU oil hierarchy. We mined data from (Eurostat, 2020) to characterize the consumption profiles of oil products in the EU28 in 2018, the refining output, imports and exports of crude oil and oil derivatives. The characterization of the EU refining sectors, in terms of distillation, catalytic cracking, coking and hydrocracking capacity has been gathered from (Concawe, 2022; OGJ, 2021). Human time allocation has been calculated using data from Eurostat “Population & Demography” (Eurostat, 2018a, 2018b) and (Manfroni et al., 2021b). After having described the current EU oil hierarchy, we simulated possible effects of decarbonization policies by introducing perturbations in the current metabolic pattern. A first simulation involves a complete shift to EVs: 100% of the gasoline and diesel burned for private mobility are assumed to be saved by a large-scale implementation of EVs in the near future. Then, we simulate the possible effects of applying smart taxes on high carbon oils and oil products, forcing a shift in the current quality of EU crude oil imports toward lighter ones. We identify and discuss major lock-ins to be addressed by European policymakers.

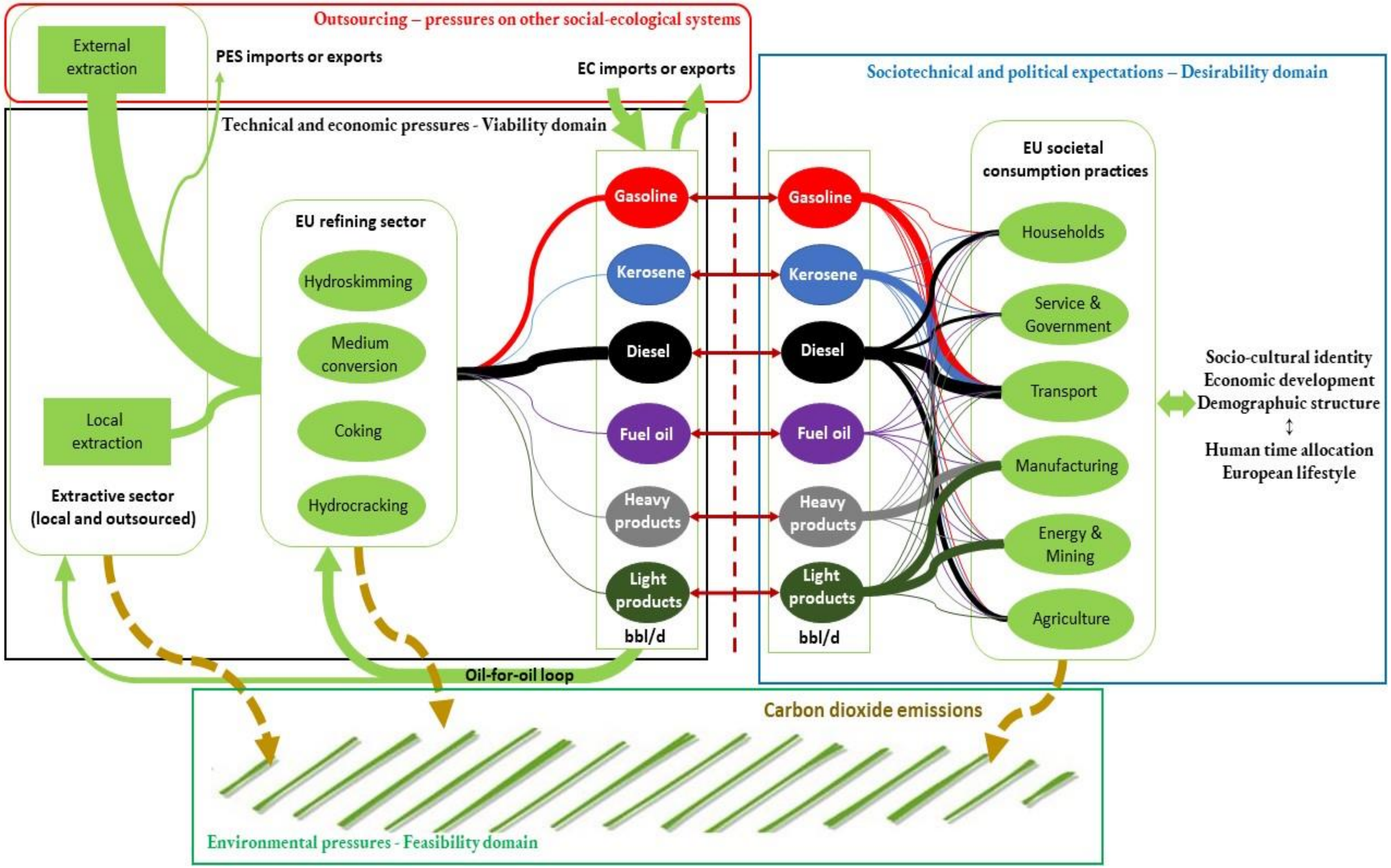

Fig. A1: Multiscale representation of the EU oil hierarchy

A1.5 Results & Discussion

A1.5.1 Diagnostic of the EU supply and consumption practices

EU consumption practices of oil products are heavily unbalanced towards diesel (Figure 2). Furthermore, 78% of diesel is burned for transport activities. Calculating the energy metabolic rates (Velasco-Fernández et al., 2018) for each sector gives us an indication of the level of technical capitalization in relation to oil commodities-burning devices (Figure 3). The larger the technical capitalization and the human time invested in one sector, the harder it is for energy policies to induce changes, i.e., to break the lock-in. Transport is the most problematic sector in this regard (besides it emitting 70% of the total CO2 emissions at the consumption point). Note that most of the available time in Europe is allocated to the household sector, followed by the service & government and transport sectors.

The EU consumption practices of oil products are sustained by a refining specialized in processing medium to heavy oil to provide large shares of middle distillates, i.e., diesel (Figure 4). Indeed, 57% of European crude oil is medium gravity from Russia and Middle East, that represent together 58% of total crude imports (figure 5). Despite the maximized diesel production, imports of diesel are still necessary to satisfy the huge EU requirement. The same is true for kerosene and light products (employed as petrochemical feedstock in chemical industry). Excessive gasoline production is exported mostly to the USA, fuel oil and heavy ends to Asia.

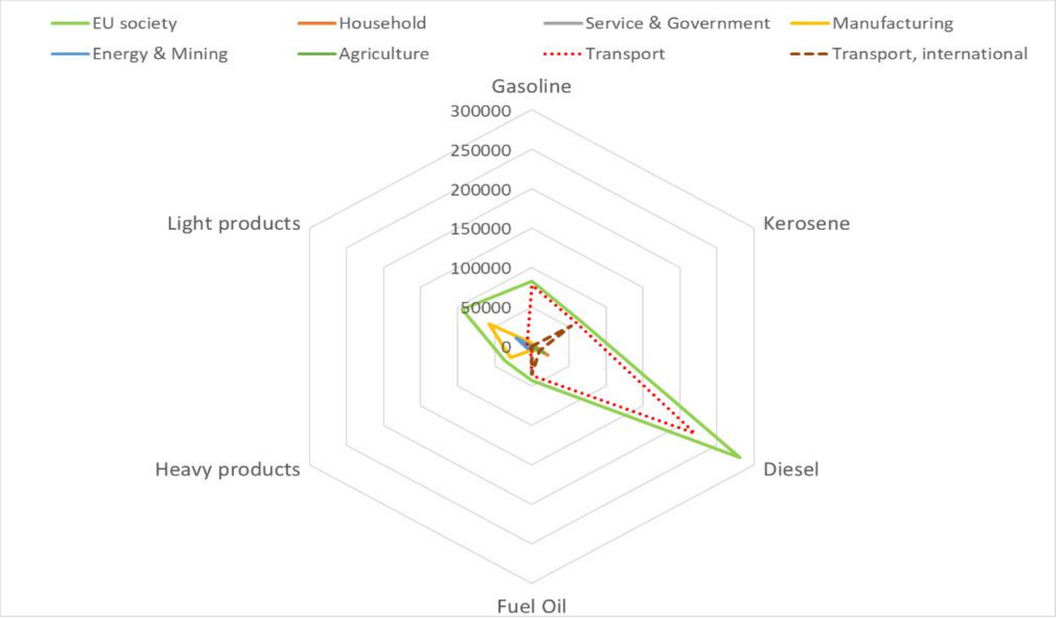

Fig. A2. Consumption pattern of oil derivatives across EU socioeconomic sectors (ktoe, 2018)

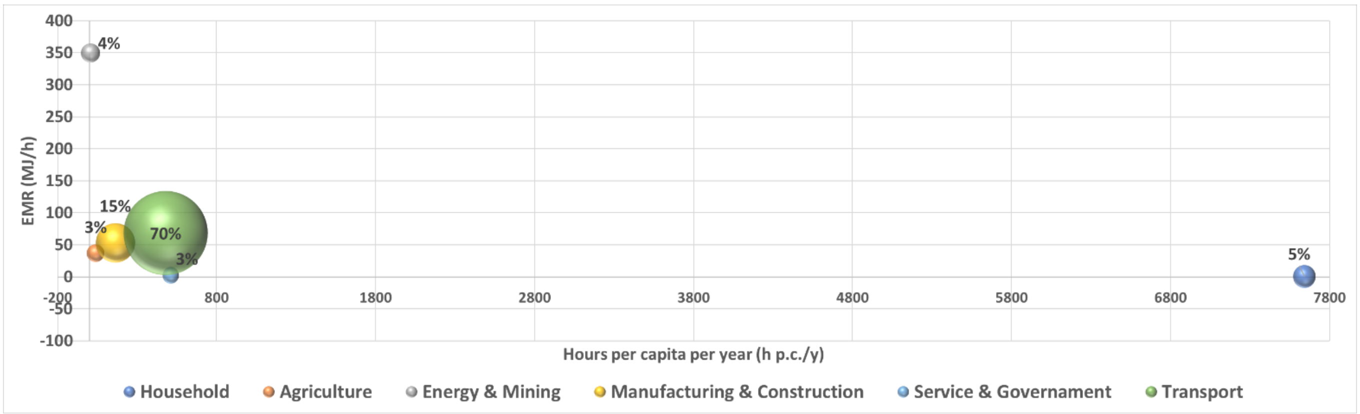

Fig. A3. Energy Metabolic Rates (EMRs) of oil derivatives and shares of CO_2 emissions across EU socioeconomic sectors, 2018

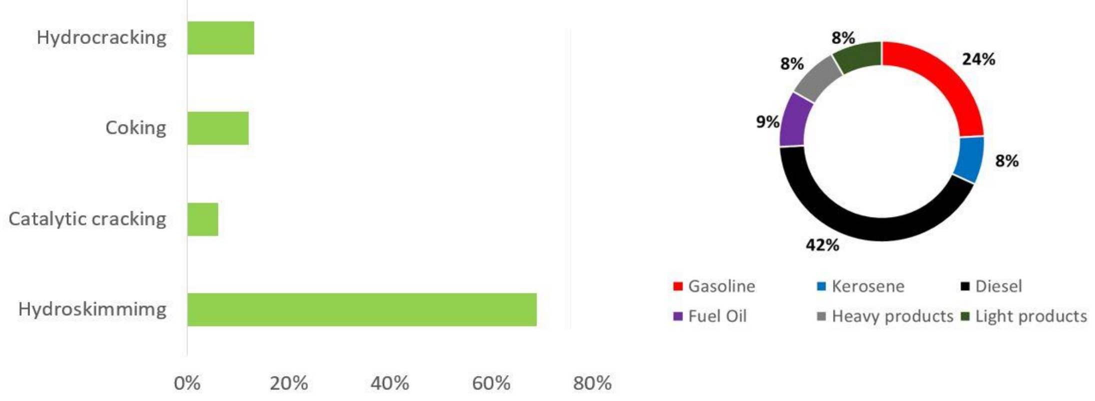

Fig. A4. EU mix of refining capacity and set of oil products supplied (numbers do not sum to 100% due to rounding)

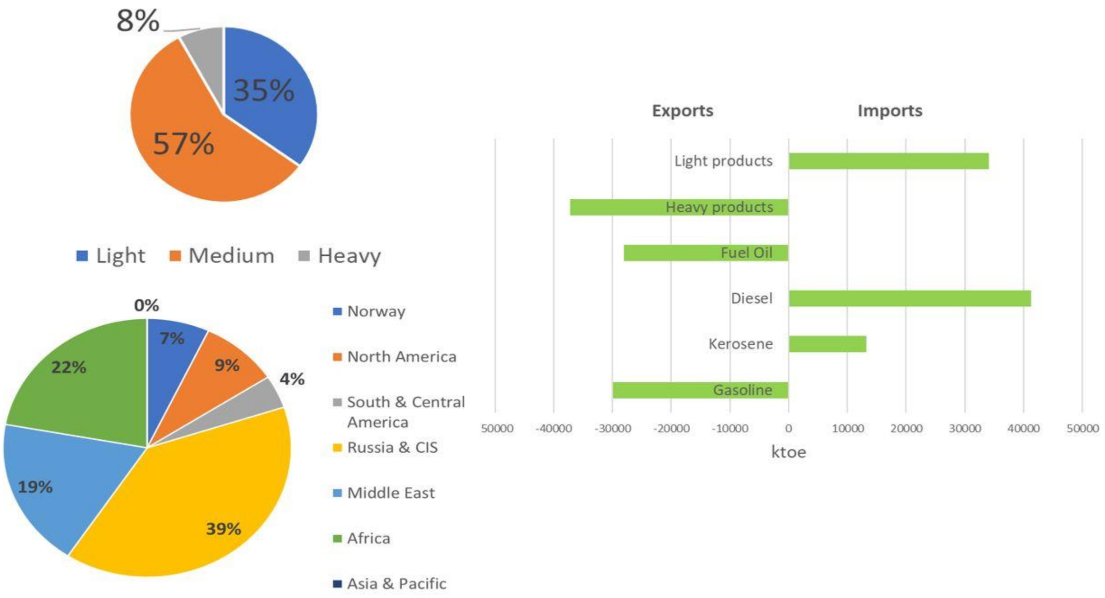

Fig. A5. EU crude diet and trade pattern, 2018

A1.5.2 Anticipation of EU decarbonization policies

Starting from the specific context of the EU28 depicted above, decarbonization policies aimed at changing its established metabolic pattern need to bring a systemic rearrangement across all the scales and flow-funds profiles (changes in the identity of metabolic processors). A large-scale implementation of EVs for private transport entails a shift in the oil product consumption pattern (reported in Table 1). However, even assuming that EVs are a low-carbon option (although this is not necessarily the case (Di Felice et al., 2021)), and that substantial reductions of emissions can be realistically achieved (taking into account the whole transition process (Di Felice et al., 2018)), it is not assured that the resulting consumption pattern will be viable at the scale of the entire system. Overall refining capacity will shrink by about 26% and gasoline demand to zero, with heavy negative effects on the crack spread, the economic viability of European refiners and energy security issues. Hence, to survive on the market, it is likely that EU refiners will increase the flows of imports and exports (increasing their exposure to international markets) instead of reducing their capacity or adapting to the new local demand, thus mostly offsetting the efforts of reducing emissions.

On the other hand, smart taxes on high carbon oils (Brandt et al., 2018; Gordon and Mathews, 2016) and oil products will push the European “crude diet” toward lighter oils (less emission intensive): this means profound changes in the selection of importing countries, away from Russia and Middle East and relying more on US light tight oil; and a lighter barrel of refined products (more light distillates). But it is doubtful that the EU can heavily rely on the USA for energy supplies, given the constraints in the transport capacity and that the refining fleet is designed to operate with middle to heavy oils (actually increasing the investment in that direction), to comply with a strong final demand for diesel – light oils show low yield of middle distillates production. Furthermore, in the light of the effects of the EVs, the two policies are contradictory: EVs will reduce the demand for light products, while smart taxes will push for the supply of a lighter barrel of final products.

Table A1. Comparative of current and simulated supply, consumption and trade patterns of the EU28

	EU supply pattern	**EU trade pattern**	**EU consumption pattern**	**EU consumption pattern with EVs**

Gasoline	24%	-10%	14%	1%
Kerosene	8%	3%	11%	16%
Diesel	41%	5%	47%	41%
Fuel Oil	9%	-2%	7%	10%
Heavy products	8%	-2%	6%	9%
Light products	8%	8%	16%	23%
Total	98%	2%	100%	-26%

A1.6 Conclusion & Further Research

In this work, we have shown the potentialities of a multiscale approach to energy governance. We explored the European oil hierarchy, “surfing” upward (supply → consumption) and downward (consumption → supply) the oil hierarchy, to highlight the criticalities of the EU energy agenda and showed that decarbonization is a complex process that takes place simultaneously across multiple scales. Energy policies that focus on a narrow domain, simply fostering substitution of oil products for “green” electricity (i.e., flow-for-flow substitution instead of a reallocation of funds such as power capacity and human time) usually overlook impredicative relations and lock-in mechanisms across the whole hierarchy, and may not result effective in enhancing a systemic change. Instead, the purpose should be establishing a new, low-carbon societal metabolic pattern, integrating in a coherent way changes in the quality of supply with societal adjustment in consumption practices. In future research, two crucial points need to be addressed. First, an assessment of installed power capacity, (i.e., kW of technical capital used) in the production and, even more importantly, in the consumption of energy carriers. Changing “transport practices” (or any other social practice) means manipulating its sectoral EMR and the profiles of: (i) time allocation to private or public transport; and (ii) machinery/vehicles allocated to private or public transport (trade logistic and international shipping/aviation). Indeed, it is fundamental to account for these funds to achieve robust low-carbon scenario assessments. Second, we need to enlarge the analytical domain and represent the whole energy sector to generate a broad information space for energy governance. A large-scale transition to renewable sources and associated infrastructures may result unsustainable within the current European lifestyles pattern.

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A2. Supplementary Material to Chapter 3

A2.1 An accounting methodology for human time allocation outside paid work

An important practical problem in the analysis of societal metabolism is to establish meaningful relations between the demographic structure of the population and the time allocation to the functional categories of a taxonomy of social practices not only inside but also outside paid work. In fact, in the official statistics these two features are dealt with separately. On the one hand, time use surveys provide profiles of social practices (functional categories) in relation to different typologies of individuals (structural categories), i.e., data on how employed/unemployed, active/inactive, students, housekeepers or retired people spend their time throughout the day. On the other hand, demographic statistics provide the population structure per age, sex, nationality, residence, etc. There is no obvious relation between the definition of these structural types of individuals – often defined *ad hoc* in relation to the purpose of the survey – and demographic statistics. This makes it difficult to obtain semantic and quantitative closure in the time accounting at societal level. Therefore, the following steps were performed to obtain the data for Fig. 1: (1) the definition of meaningful accounting categories of human activity (taxonomy); (2) the construction of the expected patterns of time use per structural type based on this taxonomy; and (3) the assessment of the distribution of the population over the various categories of structural types (scaling to societal level).

(1) A taxonomy of social practices outside the paid work sector is provided by the "Harmonized European Time Use Survey" (HETUS) 2008 Guidelines (which, in turn, is based on earlier experiences with the Multinational Comparative Time-Budget Research Project (Szalai, 1966)). HETUS is the European methodological reference for time use surveys. It proposes the following time allocation categories (see left column in Table A2): Personal Care; Employment; Study; Household & Family Care; Voluntary Work & Meetings; Social Life & Entertainment; Sports & Outdoor Activities; Hobbies & Computing; Mass Media; and Travel & Unspecified Time Use. Note that in the time allocation literature, the categories Voluntary Work & Meetings; Social Life & Entertainment; Sports & Outdoor Activities; Hobbies & Computing; and Mass Media are often grouped as "expressive activities" (Pentland et al., 2002), as they are activities that people choose to do during their free time and unrelated to productive or maintenance chores.

Some of the HETUS categories were too fine-grained for the purpose of our study, and some were irrelevant for certain typologies of individuals (i.e., the population requiring nurture and care). Therefore, we merged and renamed some of the HETUS categories. The semantic bridge between our conceptual framework (used in Fig. 1) and the HETUS taxonomy is shown in Table A2. The categories 'Physiological overhead' (PO) and 'Requiring Nurture and Care' (RNC) represent non-disposable time (not subject to choice). The categories 'leisure, culture & study' (LCS) and 'residential & mobility' (R&M) represent disposable time (subject to choice: potentially available for paid and unpaid work).

Table A2. Correspondence between HETUS categories and the categories used in the present study for time allocation outside paid work

HETUS categories	**Present study**	
	Adult population able to work	**Dependent population**
Paid work	Paid work	-
Personal care	Physiological overhead (PO) (non-disposable time)	Physiological overhead (PO) (non-disposable time)
Study Voluntary work & Meetings Social life & Entertainment Sports & Outdoor activities Hobbies & computing Mass media	Leisure, Culture & Study (LCS) (disposable time)	Requiring Nurture & Care (RNC) (non-disposable time)
Household chores & Family care Travel and unspecified time use	Residential & Mobility (R&M) (disposable time)	

(2) Time allocation patterns for different types of individuals were obtained from the Spanish Time Use Survey 2009-2010 (Instituto Nacional de Estadistica (INE), 2011a). This data is consistent with the HETUS methodology and amenable to our categories of accounting shown in Table A1 (Instituto Nacional de Estadistica (INE), 2011b). Implementing the correspondence between the HETUS classification and our taxonomy, the time allocation patterns shown in Figure A1 were obtained. Note that 'students' are defined as individuals > 15y old who are actively engaged in higher (post-secondary or tertiary) education; 'early retired' are

people who receive ‘anticipated old age pensions’ or ‘benefit from early retirement for labor market reasons’; ‘others’ match with INE’s ‘inactive people’. The following assumptions were made: for the category children <15y, PO was assumed equal to that of ‘students’, while the remainder of their time was classified as RNC. In line with the criticism found in the literature (e.g., Marois et al., 2020) on the conventional age dependency ratio, in which the dependent population is simply defined as (0-14 plus >65), we adapted the concept of ‘dependency’ by accounting for the fact that a non-negligible part of the population >65 is still ‘active’ (i.e., performing unpaid work, such as household chores and child care, and potentially available for paid work). Based on data of (Spijker and Zueras, 2020), we estimated this ‘active’ share at 20%. For the active elderly (>65), we assumed a time allocation profile equal to that of the ‘early retired’, while for the other elderly, we assigned the same time to PO, but allocated the remainder of their time to RNC (see Fig. A1). The ‘unfit for work’ aged 15-64 were included with the dependent population; their time was assumed to be divided equally between PO and RNC (50-50).

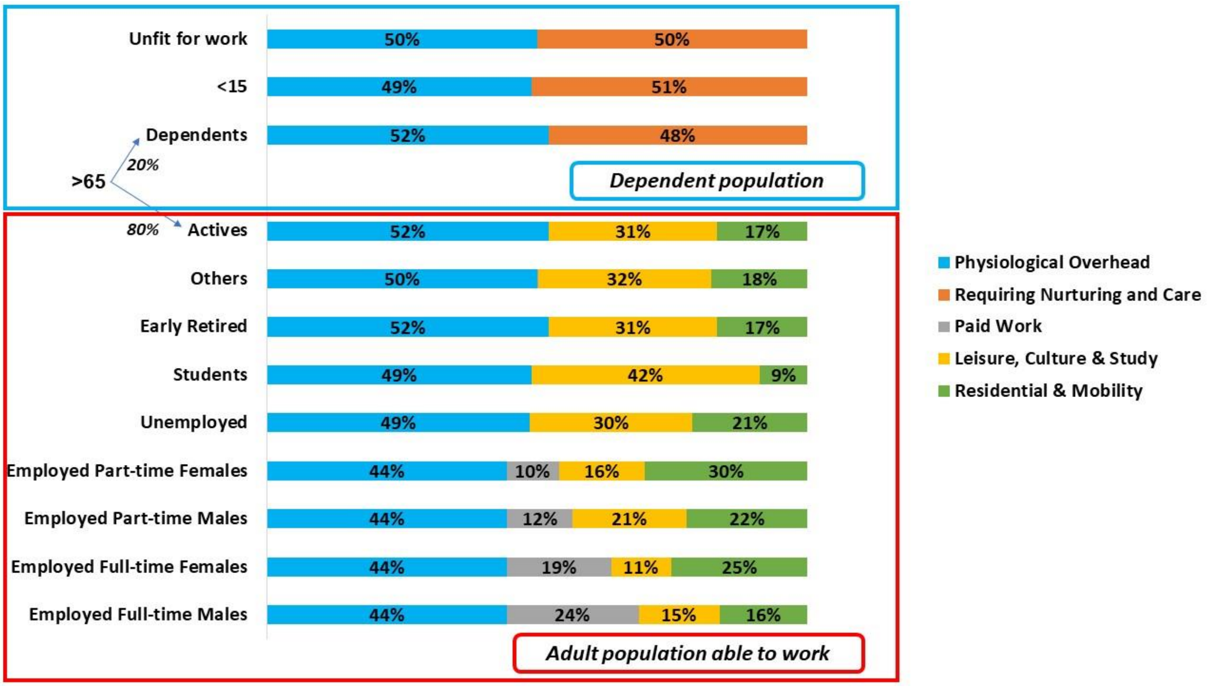

Fig. A6 Profile of time allocation for different typologies of individuals. Data elaborated from the 2009-2010 Time Use Survey for Spain (Instituto Nacional de Estadistica (INE), 2011a).

(3) In the next step, the time allocation patterns of these types of individuals were linked to the demographic structure of Spain, to scale data to the national (societal)

level. The number of individuals per structural type was obtained from Eurostat. The scaling process is detailed in Table A2.

Table A3. Profile of time allocation by different types of individuals (in hours per capita)

	Profile of social roles											
Spain 2012	*Employed Full Time Males* **19%**	*Employed Part Time Males* **1%**	*Employed Full Time Females* **13%**	*Employed Part Time Females* **4%**	*Unemployed* **12%**	*Students* **8%**	*Early Retired* **1%**	*Others* **2%**	*Unfit for work* **6%**	*<15* **15%**	*>65* **17%**	**100%**
Set of human activities	***Hours per capita per year***											***Total Hours per Activity***
Physiological overhead	745	53	506	157	529	330	44	280	108	648	793	**4194**
Requiring Nurture and Care	-	-	-	-	-	-	-	-	108	677	144	**929**
Paid Work	409	14	221	34	0	0	0	1	0	0	0	**680**
Leisure, Culture & Study	252	25	126	56	325	284	26	180	0	0	378	**1653**
Residential & Mobility	273	27	288	106	232	60	14	100	0	0	205	**1304**
Total HA per social role	**1679**	**119**	**1141**	**353**	**1086**	**674**	**85**	**560**	**217**	**1324**	**1521**	**8760**

Time profiles are calculated per capita according to the following equation:

$$H_{i,j} = I_i * 8760 * A_{j,i}/tot\_pop$$

where I is the array of percentual fractions of individuals belonging to m categories of structural types, 8760 is the annual quantity of hours per capita, $A_{j,i}$ is the matrix representing the percentual fractions of time allocated to activity j (summed over the set of n categories) of the structural type I (out of m structural categories), tot_pop is the country population (Spain 2012).

Closure of the accounting is verified if:

$$\sum_{i=1}^{m}\sum_{j=1}^{n} H_{i,j} = 8760$$

Note that the solution proposed here for the time accounting is of an exploratory nature. The ultimate purpose is to establish (and quantify) entanglements across demographic data referring to structural types and data referring to time allocation of typologies of individuals, in order to enable triangulations (sudoku effect) in studying the effect of possible changes in either demographic structure or social practices in the future. The reader should be aware that the information provided in Table A2 does not reflect the individual choices of time use (i.e., preferences associated with individual behaviors), but the expression of social practices at a higher level of analysis. Indeed, only a multi-level, metabolic analysis of the entanglement between exosomatic energy use and human activity – as proposed in this study and exemplified in Fig. 1 and Fig. 2 – allows an integrated study of the formation (historical lock-in or forced emergence) and the functional nature of social practices.

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A3. Supplementary Material to Chapter 4

A3.1 Additional data on the functional processors and sequential pathways referred to in the main text

Table A4. Metabolic profiles (i.e., identities) of extraction processors: consumption of energy carriers and CO$_2$ emissions

Extraction processors	**MJ/bbl**				**kgCO2eq/bbl**
	NG and RFG	**Electricity**	**Diesel**	**Coke**	**GHG emissions**
Light low water onshore	90	4	7	0	25
Light low water offshore	176	7	13	0	32
Medium low water onshore	199	3	8	0	46
Medium low water offshore	33	2	5	0	20
Light watery onshore	425	38	6	0	78
Light watery offshore	523	8	5	0	74
Medium watery onshore	357	13	14	0	76
Medium watery offshore	174	11	4	0	31
Heavy low water onshore	1570	1	1	0	143
Heavy low water offshore	331	5	13	0	55
Heavy watery onshore	218	21	20	0	52
Heavy watery offshore	71	8	0	0	20
Ultra-Deep	199	6	40	0	51
Fracking	108	2	17	0	59
Light and medium depleted	431	35	7	0	55
Heavy depleted	1937	10	1	0	127

Table A5. Metabolic profiles of refining processors: consumption of energy carriers and CO$_2$ emissions

Refining processors	**MJ/bbl**				**kgCO2eq/bbl**
	NG and RFG	**Electricity**	**Diesel**	**Coke**	**GHG emissions**
Hydroskimming	297	10	0	0	17
Medium conversion	454	16	0	25	31
Deep conversion - coking	974	32	0	49	71
Deep conversion - hydrocracking	1278	38	0	41	94

Table A6. Viable sequential pathways of the oil sector: supply of oil products per barrel, unitary description

Sequential pathways							
Types of extraction	**Associated types of refining**	**Gasoline**	**Jet Fuel**	**Diesel**	**Fuel Oil**	**Coke**	**LHE**
Light low water onshore	Hydroskimming	29%	23%	10%	10%	0%	28%
	Medium conversion	36%	19%	18%	0%	0%	26%
Light low water offshore	Hydroskimming	29%	23%	10%	10%	0%	28%
	Medium conversion	36%	19%	18%	0%	0%	26%
Medium low water onshore	Hydroskimming	29%	23%	10%	10%	0%	28%
	Medium conversion	36%	19%	18%	0%	0%	26%
Medium low water offshore	Hydroskimming	29%	23%	10%	10%	0%	28%
	Medium conversion	36%	19%	18%	0%	0%	26%
Light watery onshore	Hydroskimming	29%	23%	10%	10%	0%	28%
	Medium conversion	36%	19%	18%	0%	0%	26%
Light watery offshore	Hydroskimming	29%	23%	10%	10%	0%	28%
	Medium conversion	36%	19%	18%	0%	0%	26%
Medium watery onshore	Hydroskimming	29%	23%	10%	10%	0%	28%
	Medium conversion	36%	19%	18%	0%	0%	26%
Medium watery offshore	Hydroskimming	29%	23%	10%	10%	0%	28%
	Medium conversion	36%	19%	18%	0%	0%	26%
Heavy low water onshore	Medium conversion	36%	19%	18%	0%	0%	26%
	Deep conversion - coking	44%	11%	31%	0%	10%	3%
	Deep conversion - hydrocracking	38%	11%	40%	0%	8%	3%
Heavy low water offshore	Medium conversion	36%	19%	18%	0%	0%	26%
	Deep conversion - coking	44%	11%	31%	0%	10%	3%
	Deep conversion - hydrocracking	38%	11%	40%	0%	8%	3%
Heavy watery onshore	Medium conversion	36%	19%	18%	0%	0%	26%
	Deep conversion - coking	44%	11%	31%	0%	10%	3%
	Deep conversion - hydrocracking	38%	11%	40%	0%	8%	3%
Heavy watery offshore	Medium conversion	36%	19%	18%	0%	0%	26%
	Deep conversion - coking	44%	11%	31%	0%	10%	3%
	Deep conversion - hydrocracking	38%	11%	40%	0%	8%	3%
Ultra-Deep	Hydroskimming	29%	23%	10%	10%	0%	28%
	Medium conversion	36%	19%	18%	0%	0%	26%
Fracking	Hydroskimming	29%	23%	10%	10%	0%	28%
Light and medium depleted	Hydroskimming	29%	23%	10%	10%	0%	28%
	Medium conversion	36%	19%	18%	0%	0%	26%
Heavy depleted	Medium conversion	36%	19%	18%	0%	0%	26%
	Deep conversion - coking	44%	11%	31%	0%	10%	3%
	Deep conversion - hydrocracking	38%	11%	40%	0%	8%	3%

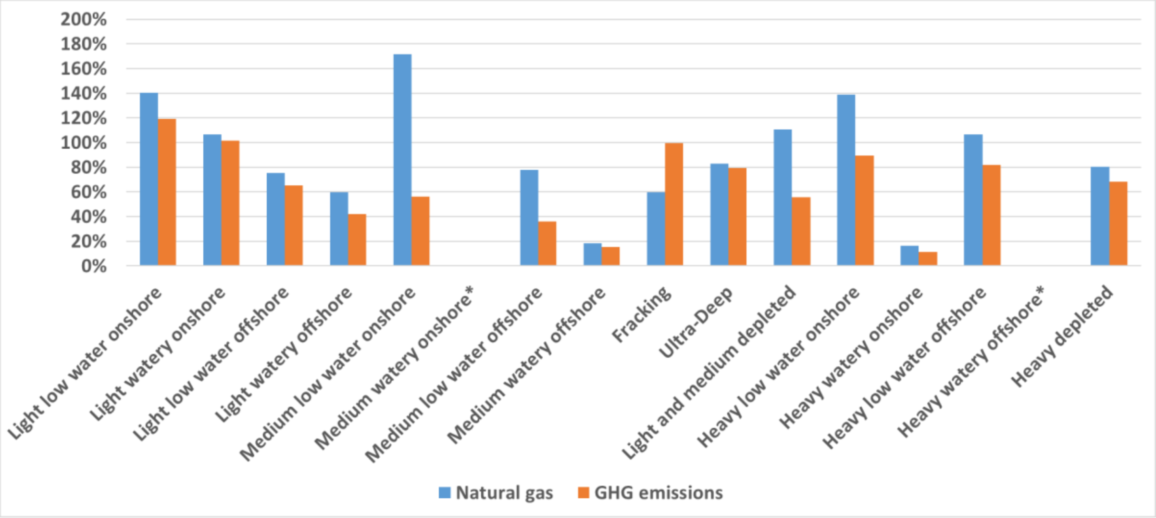


*Fig. A7. Visualization of the ratio "Standard Deviation/Average" of the natural gas consumption (in blue) and GHG emissions (in orange), calculated over the specific oil fields (instances of extraction, structural elements) belonging to the same extraction (functional) typology. Standard deviation is consistently high for both flows for most extraction (functional) typologies, entailing high data variability for the characterization of oil fields. *benchmarks refer to a single field.*

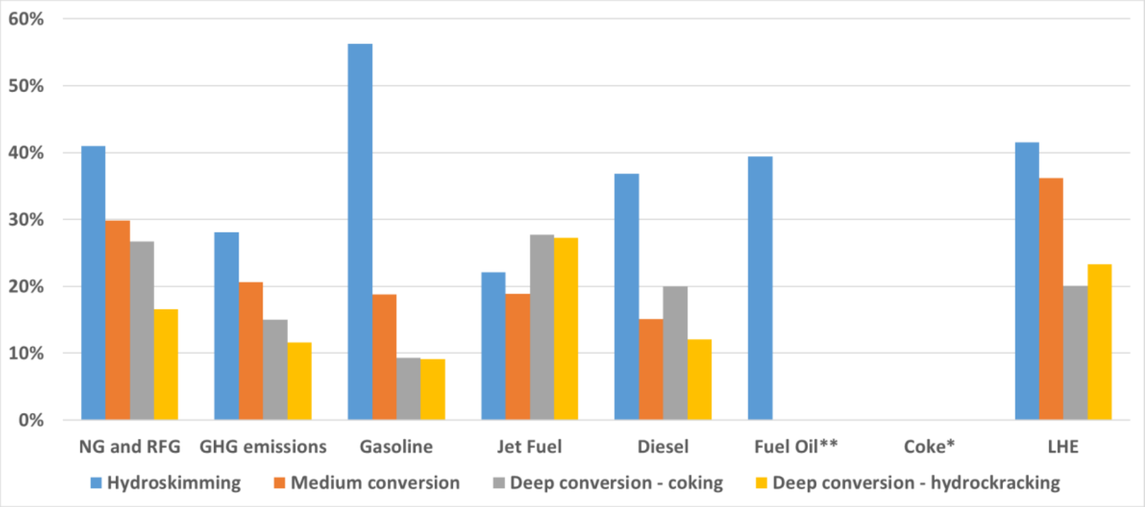


*Fig. A8 Visualization of the ratio "Standard Deviation/Average" of the natural gas consumption, GHG emissions and oil products (gasoline, jet fuel, diesel, coke, Liquid Heavy Ends), calculated over the refineries (instances of refining, structural elements) belonging to the same refining (functional) typology. *PRELIM assumption: coke is not used in refining; **PRELIM assumption: fuel oil is completely converted to high-value products (gasoline or diesel) in refinery types other than hydroskimming.*

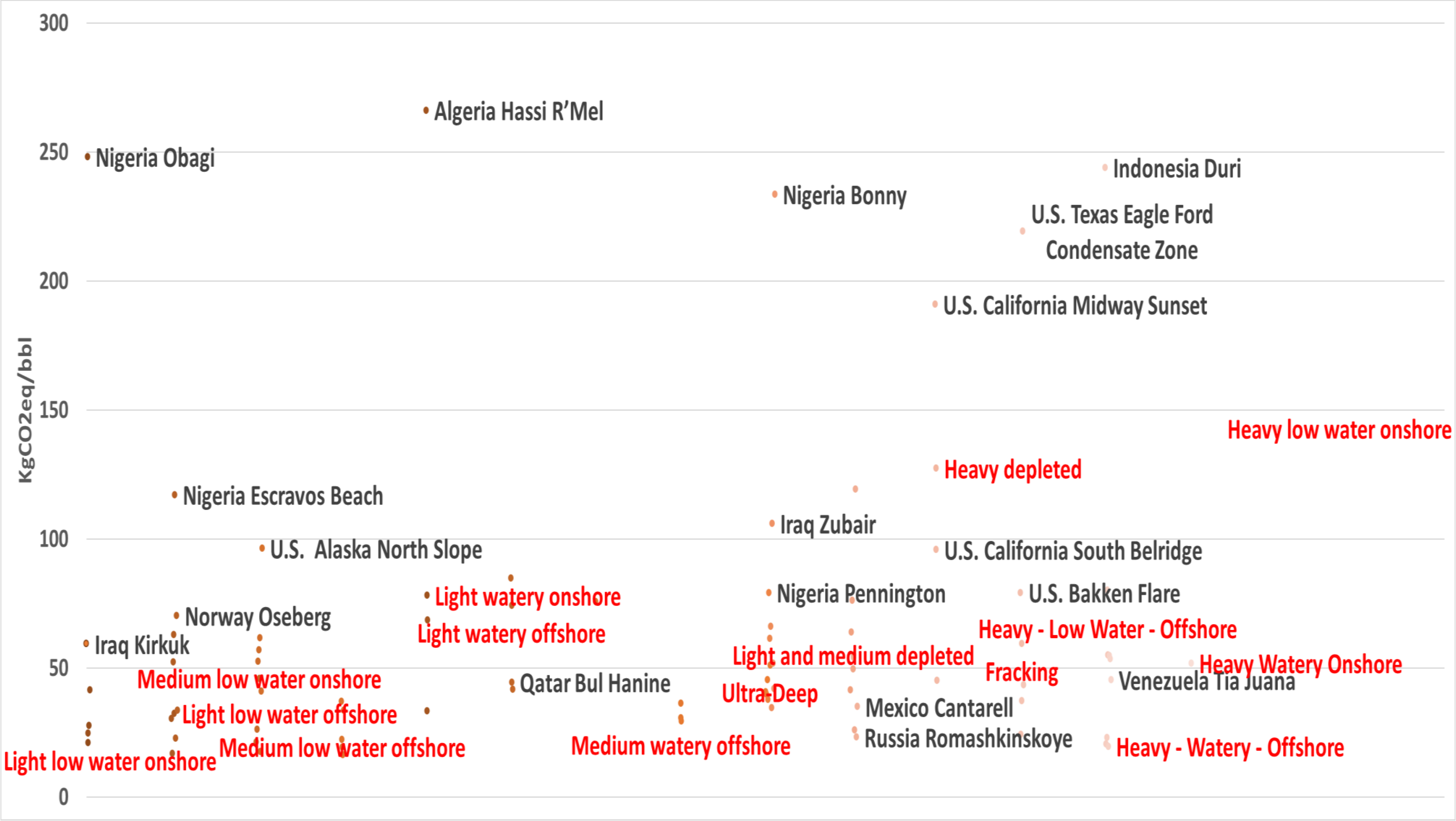


Fig. A9. CO_2 emissions per barrel supplied, per oil field (e.g., "Nigeria Obagi", structural element in black) and per extraction typology (e.g., "Fracking", functional element in red). Note that large standard deviations are cause by the outliers in the upper part of the figure, however most of the fields are consistent with the benchmark of their reference type.

Table A7. Mix of oil products, in quantity and quality, in the current situation and in the four simulations

Simulations	**Gasoline**	**Jet Fuel**	**ULSD**	**Fuel Oil**	**Coke**	**LHE**
Current situation	36%	19%	18%	1%	1%	24%
Simulation 1	36%	19%	18%	1%	1%	24%
Simulation 2	36%	19%	18%	1%	1%	24%
Simulation 3	36%	18%	19%	1%	1%	24%
Simulation 4	34%	19%	16%	3%	1%	24%

A3.2 Extraction data processing from the OPGEE dataset

Each oil field in the OPGEE_v.1.1_draft_e dataset presents different energy consumption and GHG emissions, that are reported in the "Energy consumption" and "GHG emission" sheets. Data from tables 3, 4, 5, 6 ("Energy consumption") and total direct (table 1, "GHG emission") and indirect emissions (table 2, "GHG emission") have been used to construct the sixteen typologies of extraction processors. OPGEE data are reported in MMBtu/day and gCO_{2eq}/day, so for our scopes they all have been converted to MJ/bbl and $kgCO_{2eq}$/bbl of oil, using daily capacity production of respective fields.

For each oil field, the following set of data has been collected, out of the whole information:

- ✓ Natural gas (NG): on-site (net) consumption;
- ✓ Diesel: imports (equal to the net consumption by OPGEE assumption) and indirect consumption associated with imports;
- ✓ Electricity, on-site (net) consumption (entirely imported due to OPGEE assumption) and indirect consumption associated with imports;
- ✓ GHG emissions: direct emissions due to the consumption of energy carriers on-site and indirect consumption associated to diesel and electricity imports;
- ✓ Production capacity per field, in order to make the conversions and to assess the magnitude of each typology in the production mix.

These are the five main categories of energy carriers. Direct GHG emissions are summed up and not reported for specific associated energy carrier. The dataset contains also information about:

- Water-to-Oil ratio;
- Field depth and location (onshore – offshore);
- Sulfur content.

This information was used to construct the extraction (functional) typologies, as reported in Table A5.

Table A8. Assumptions for identifying the taxonomy of extraction (functional) processors. Adapted from OCI – Oil Climate Index (Carnegie Endowment for International Peace, 2018)

Classification	**API crude category (API degrees)**
Heavy	0 - 21,99
Medium	21,99 - 31,99
Light	>31,99
	Sulfur content (S %wt)
Sweet	<0,5
Sour	0,5
	Depth (m)
Shallow	0 - 2133,6
Ultra-Deep	>3352,8
	Water-to-Oil ratio (bbl water/bbl oil)
Low water	0 - 4
Watery	>4

In order to generate the unitary description and calculate the benchmarks for consumption of energy carriers per extraction type, values from specific oil fields have been weighted averaged on the production capacity. Using a bottom-up approach, we generated unitary benchmarks of extraction types observing special instances (structural elements) of oil fields.

$$EC_k = \frac{\sum_{i=1}^{n} EC_{i,k} Pr_i}{\sum_{i=1}^{n} Pr_i}$$

$$GHG_k = \frac{\sum_{i=1}^{n} GHG_{i,k} Pr_i}{\sum_{i=1}^{n} Pr_i}$$

Where k = category of carriers (for instance, NG exports), n = number of oil fields of the same type, EC = energy carrier in MJ/bbl (natural and refinery gas, diesel, electricity), GHG = GHG emissions in $kgCO_{2eq}$/bbl, Pr = production capacity per day (bbl/day). In this way, it is possible to define a general taxonomy based on intensive (unitary) processors that can be tailored to specific cases by simply introducing the size of the system under analysis. Note that the average is weighted on the extraction capacity (volume of barrels extracted per day). Therefore, bigger fields assume more importance than smaller ones inside the network representation.

A3.3 Refining data processing from the PRELIM dataset

Data for each refinery have been collected from the "Main input & output" sheet of PRELIM model v1.2. In the column "Energy use", types of carriers reported are heat, steam, hydrogen (SMR, Steam Methane Reformer and CNR, Catalytic Naphtha Reformer), electricity, FCC (Fluid Catalytic Cracking) catalyst Regeneration and excess of RFG (Refinery Fuel Gas). For our scope, we defined the following categories and performed a mapping with PRELIM categories:

- Natural gas and refinery fuel gas (NG+RFG);
- Electricity;
- Diesel;
- Coke;
- GHG emissions.

Electricity matches straightly between the two sets of accounting. Heat, steam and hydrogen SMR sub-categories are summed up and the total goes to "NG+RFG". Hydrogen via CNR is supposed to be entirely obtained from natural gas. FCC Cat. Regeneration is supposed to be done through coke burning. Diesel use in refineries is zero. The "Diesel" category is conserved for matching with extraction categories, but there is no direct diesel use in refining (Table A2). Excess of RFG is always zero due to PRELIM assumptions. Regarding GHG emissions, total emissions are directly reported under the “GHG emissions” category in our model. Refineries have been grouped according to their configuration into the four typologies of the selected taxonomy and benchmarks obtained using simple average calculation. No weighted average has been performed this time, since refinery capacity production is elastic and very dependent on external factors (market).

The categories of oil products selected for our model are reported in the list below, and another mapping with PRELIM’s one has been done:

- Gasoline;
- Jet Fuel;
- Diesel;
- Fuel Oil;
- Coke;

Gasoline maps directly with PRELIM’s “Blended Gasoline”, Jet Fuel with Jet-A/AVTUR, Diesel with ULSD (Ultra-Light Sulphur Diesel), Fuel Oil, Coke and Liquid Heavy Ends (LHE) are the same of PRELIM’s. Surplus of Refiney Fuel gas is always zero for PRELIM’s assumption.

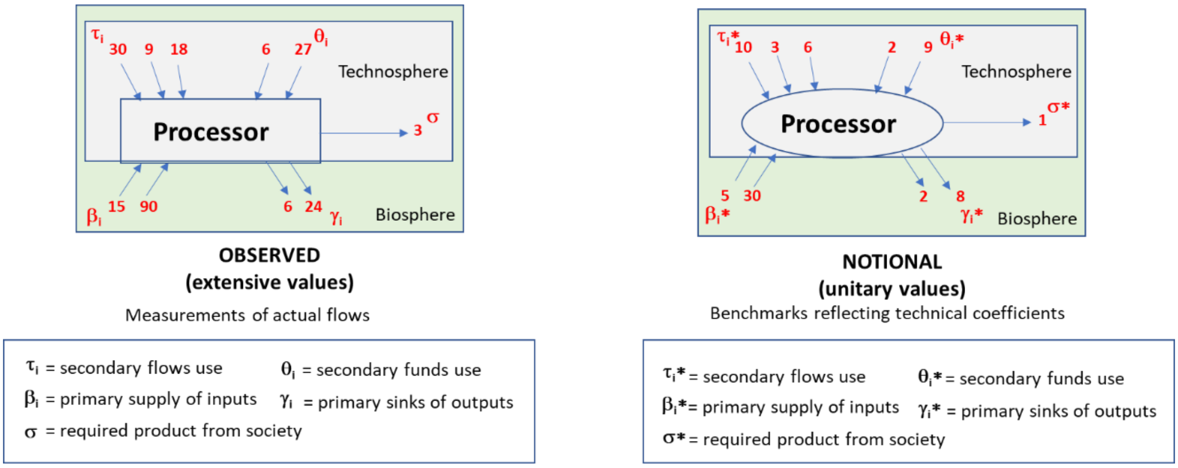
A3.4 Network scaling with Metabolic Processors

The semantic framework adopted by relational analysis is based on the four Aristotelian causes: (i) material cause, the material input coming from nature – this is useful to identify external constraints; (ii) formal cause, the organizational structure (recorded in blueprints/know-how) and the set of cybernetic controls that can be stored as recorded information – this is useful to study the role of technology and know-how; (iii) efficient cause, the agents of change expressing the required functions – this is the semantically open part of the representation, because the same function can be expressed by different combinations of material and formal causes; and (iv) final cause, defining the purpose of the energy system for the embedding social system.

The analysis of energy systems based on metabolic processors provides three important advantages:

1. The set of relations characterized by a processor avoids the simplifications typical of reductionism

A processor integrates a set of non-equivalent descriptions of the observed system in the form of a data array. The same structure of the data array can be used to characterize the metabolic attributes of both structural and functional elements and of functional elements generated by a combination of lower-level functional elements, when moving the analysis to upper levels. The data sources used to describe the various elements across levels are non-reducible to each other in a common metric. Thus, establishing congruent relations between processors describing structural elements and functional elements across levels allows to generate a coherent representation across scales inside the metabolic pattern. Data about the flows "coming from" and "going to" the technosphere (flows having a technical and an economic relevance) can be used to check the performance in terms of technical coefficients, labor requirement, economic costs and revenues. Data about the flows "coming from" and "going to" the biosphere (water, primary sources on the supply side and emissions and pollutants on the sink side) can be used to assess environmental pressures and, when georeferenced, to check potential environmental impacts. Combining structural and functional representations in a coherent analytical tool allows to track what is produced and consumed, how is produced and consumed, at what biophysical and environmental costs in relation to which societal purposes.



OBSERVED
(extensive values)
Measurements of actual flows

NOTIONAL
(unitary values)
Benchmarks reflecting technical coefficients

τ_i = secondary flows use
θ_i = secondary funds use
β_i = primary supply of inputs
γ_i = primary sinks of outputs
σ = required product from society

τ_i* = secondary flows use
θ_i* = secondary funds use
β_i* = primary supply of inputs
γ_i* = primary sinks of outputs
σ* = required product from society

Fig.A10 Representation of the data array associated with a metabolic processor

Five different categories of inputs and outputs are represented in Fig. A10:

τ_i = secondary flow inputs: circulating flow elements required by processes coming from the technosphere (processes under human control), e.g., electricity, fuels;

θ_i = secondary fund inputs: fixed fund elements required by processes coming from the technosphere (processes under human control), e.g., hours of workers, power capacity;

β_i = primary supplies of inputs coming from processes outside human control (biosphere): availability of primary sources (either fund-flow or stock depletion), e.g., oil, gas;

γ_i = primary sinks of outputs provided by processes outside human control (biosphere): availability of primary sink capacity (either fund-flow or sink filling), e.g., GHG emissions, polluting water;

σ = secondary flow outputs: products required from society determined in both quantity and quality, e.g., crude oil, refinery products.

The relations over the quantities of these different flow and fund elements can be expressed using two non-equivalent representations:

- Extensive values: the values observed for specific processes;
- Unitary values: technical coefficients calculated as benchmarks of given functional or structural elements.

2. It is possible to move the representation given by processors across different levels of analysis and scales, maintaining coherence between the various quantitative assessments

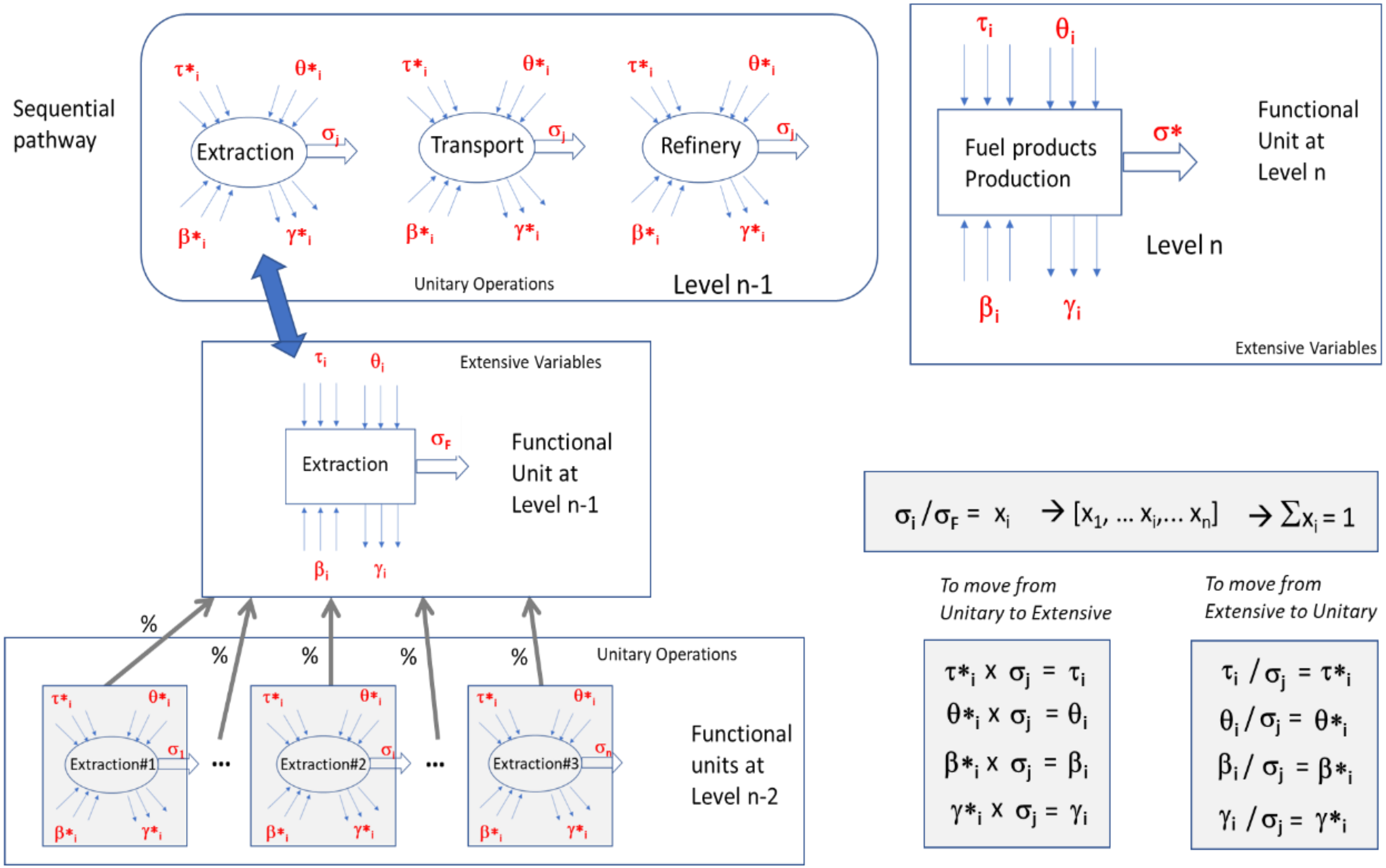


Fig. A11 Moving the assessment of the oil sector across different scales (non-equivalent definitions of functional units) and hierarchical levels

Different definitions of a functional unit, viewed as an effective combination of lower-level components, are illustrated in Fig. A5. On the lower-left corner, different functional units of extractions (e.g., different types of fields operating at level n-2) are combined together to generate a functional unit of “extraction” at the level n-1. On the upper left corner, we see a sequential pathway of processes (“extraction” → “transportation” → “refinery”), which can be considered as a functional unit “oil products production” at level n (on the right-upper corner). Each sequential pathway is composed by a series of functional units defined at level n-1 (blue double arrow).

Using this accounting framework, we can integrate non-equivalent descriptions referring to structural and functional elements: (i) the WHAT/HOW can be characterized by looking at the structural aspects of the elements: the “WHAT” is the specific transformation and the “HOW” is a characterization based on benchmarks of the processes carried out, i.e. the material infrastructures and the material flows coming in and getting out associated with the necessary know-how and the observed technical coefficients (bottom-up analysis); and (ii) the WHAT/WHY can be defined by looking at the functional role played by the element inside the rest of the system, i.e. the purposes justifying the expression of the process in the first place (why society supports the reproduction of it) and the specific combination of element in a functional units (top-down analysis).

3. It is possible to generate contextualization for the performance of the oil sector and its higher and lower-level components

The energy sector is a component interacting with the rest society, the oil sector is a component of the energy sector, and the compartment of extraction is just a component of the oil sector. Since complex socio-ecological systems are hierarchically structured (Allen and Starr, 1982; Pattee, 1973), keeping a holistic picture of the relations over hierarchical elements inside the metabolic pattern expressed at different levels is vital. This helps to check the correctness of the representation given and to grasp the meaning of different components inside the system (the big picture) (Giampietro et al., 2012).

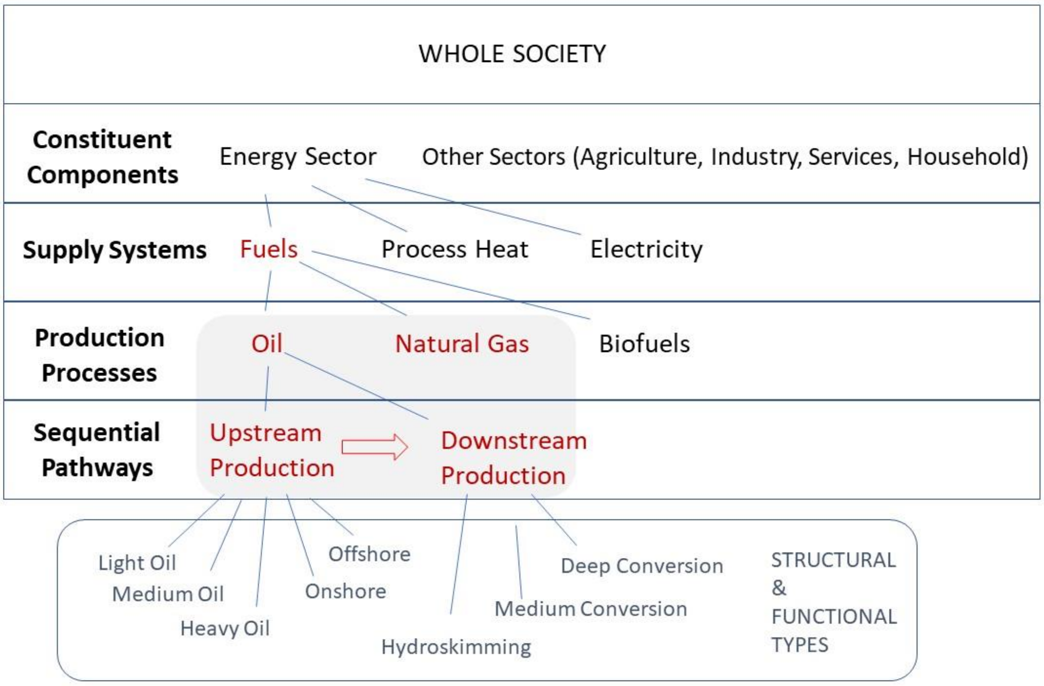


Fig. A12 Map contextualizing the role of structural and functional elements within the energy sector and within the rest of the society

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A4. Supplementary Material to Chapter 5

A4.1 The oil sector as a metabolic network

We characterized the oil metabolism and the associated multidimensional spaces using a bottom-up approach. In the pre-analytical step, we defined the categories of the oil taxonomy and the relevant biophysical and economic dimensions of the analysis (Fig. A13); then, we constructed the representation looking at single oil fields and refineries as reported in (Carnegie Endowment for International Peace, 2018). In this methodological study, the scope was not to provide an accurate numerical description, nor did we consider the dynamic variability in time of the metabolic benchmarks. Hence, our characterization of the oil sector across the multiple scales (extraction and refining benchmarks) is not a "true" representation of the real situation, but a reflexive tool useful to energy analysts (and stakeholders) to gain valuable insights in the societal metabolism of oil. The relations over numbers – the relational network – rather than the numbers themselves are the focal point of attention. Indeed, we sought to demonstrate the strength of a relational approach to the oil sector, as the oil sector is a metabolic network of structures and functions that needs to be reproduced in time for maintaining a functioning social-ecological system; technologies, investment, natural resources and sinks are merely 'becoming' and their benchmarks are always subject to change. If more accurate and recent numbers can be obtained, the metabolic representation can be updated without invalidating the relational matrix. For complementary information about the description of the oil sector with relational analysis, see (Manfroni et al., 2021).

Fig. A13 Multidimensional descriptive domain: selected dimensions for the characterization of the oil sector, represented in the form of multidimensional vectorial space (in algebraic terms)

This supplementary material not only details how the results presented in the main text were obtained, but that it also presents additional results that could not be included in the main text for reasons of space.

A4.2 Library of sequential pathways

A4.2.1 Energy carrier requirements and GHG emissions

The oil taxonomy defined in section 2.2.1 (main text) draws on the categories reported in (Carnegie Endowment for International Peace, 2018). 'Heavily depleted' extraction typology refers to Californian fields. The benchmarks of the requirements of energy carriers (natural gas, diesel, coke, electricity) and CO2 emissions were calculated using data from (Carnegie Endowment for International Peace, 2018), after mapping oil fields and refineries into our selection of extraction and refining typologies.

A4.2.2 Net water consumption

A4.2.2.1 Extraction

Net water consumption is the net amount of water withdrawn from the environment. It is the difference between the water injected and the recovery share of produced water. Due to the lack of a unified, complete and freely accessible water database, benchmarks for water consumption were calculated from data of five different sources (Carnegie Endowment for International Peace, 2018; Kondash and Vengosh, 2015; Rosenfeld et al., 2009; Veil, 2015; Wu et al., 2011): every oil field contained in the OCI dataset was associated with a water consumption profile of the most similar extraction typology.
The specification hierarchy for the *injected water* is the following:

US, Rest of the World (RoW) {Fracking, Middle East, Heavy, Extra-Heavy, Heavy depleted, Mexican, Nigerian, Primary recovery/Alaska {Iraqi, Ghawar}}

The specification hierarchies for the *produced water* are the following:

Low water {Nigerian, Heavy, Extra-heavy, Primary recovery, Middle East, Alaska {Fracking, Iraqi}}

Watery {US watery, Heavy, Heavy depleted}

The specification hierarchy for the *recycled water* is the following:

Low water, Watery {Offshore {US, Nigerian, Middle East, Heavy depleted}}

This means that the more specific benchmarks (right in the hierarchy) were used whenever available. Net water consumption for tar sands is directly reported in (Wu et al., 2011).

The assumptions are summarized in Table A9. The first column (“Level”) refers to the level of the ‘injected water’ specification hierarchy.

Table A9. Water use assumptions

Level	Oil field typology	Injected water	Produced water	Recycled water	Net water consumption	Source
0	Low water		1.3	0%		Carnegie Endowment for International Peace, 2018
0	Watery		4	0%		Carnegie Endowment for International Peace, 2018
0	Offshore			9.8%		Veil, 2015
0	Tar sands				1.3/2.2[**]	Wu et al., 2011, p.59
1	US	8	1.3/6.8	45%		Rosenfeld et al., 2009, Veil, 2015,, Wu et al., 2011
1	RoW	8.6				Wu et al., 2011[*]
2	Fracking, Eagle Ford	0.37	0.56			Kondash and Vengosh, 2015
2	Fracking, Bakken	0.22	0.36			Kondash and Vengosh, 2015
2	Heavy	13	13			Rosenfeld et al., 2009, p.8
2	Extra-heavy	1.7	1.7			Rosenfeld et al., 2009, p.12
2	Heavy depleted	15.5	15.5			Veil, 2015
2	Primary recovery	0.2	0.2			Wu et al., 2011
2	Middle East	2.9	0.39			Rosenfeld et al., 2009, p.9
2	Mexican	0				Rosenfeld et al., 2009, p.10
2	Nigerian	2.3	1.5			Rosenfeld et al., 2009, p.13
2	Alaska	2.6	2.6			Rosenfeld et al., 2009, p.5
3	Iraq	5	2.5			Rosenfeld et al., 2009
3	Ghawar	1.4				Wu et al., 2011

**Water-flooding, secondary recovery benchmark ** CSS or SAGD technologies*

A4.2.2.2 Refining

Net water consumption in refining (Table A10) is from (Sun et al., 2018) :

Table A10. Refining net water use benchmarks

Refining typology	Net water consumption bbl_w/bbl_{oil}
Hydroskimming	0.336
Medium conversion	0.336
Deep conversion coking	0.442
Deep conversion hydrocracking	0.468

A4.2.3 Land use

A4.2.3.1 Extraction

Land use extraction data are from (Royal Ductch Shell, 2020). *Net developed, total acreage in 2019* was divided by *net number of oil productive wells* and converted into square kilometers:

$$Land\ intensity\ =\ net\_ac/n\_wells\ *4.05$$

We assumed the following well productivities (Table S3) to obtain land use intensity per barrel (right column):

Table A11. Assumptions on well productivities and land use intensities

Extraction typologies	*Well productivity bbl/well*	*Land use intensity ha/bbl*
Light Low water Onshore	1190	4,51E-03
Light Watery Onshore	595	9,02E-03
Light Low water Offshore	13400	4,00E-04
Light Watery Offshore	6700	8,01E-04
Medium Low Water Onshore	1190	4,51E-03
Medium Watery Onshore	595	9,02E-03
Medium Low Water Offshore	13400	4,00E-04
Medium Watery Offshore	6700	8,01E-04
Ultra-deep	13400	4,00E-04
Depleted	297,5	1,80E-02
Heavily depleted	148,75	3,61E-02
Fracking	550	9,76E-03
Heavy & Extra-heavy	595	9,02E-03
Tar sands	530*	1,01E-02

**10% less productive in comparison to heavy oil extraction, according to (Canada, 2015)*

The average well productivity estimates are derived from typical values in the Uppsala Giant Oil Field Database (described further in (Höök et al., 2014; Sällh et al., 2015)) and from (Wachtmeister et al., 2017) for tight oil. The used estimates are based on the average of a subset of global wells and serve to illustrate the methodological approach but should not be considered accurate. The real variability is not taken into account in this conceptual study.

A4.2.3.2 Refining

Land use in refining was not considered in the representation.

A4.2.4 Capex and Fixed assets

A4.2.4.1 Extraction

For conventional fields, extraction capital expenditures (capex) per barrel were calculated as the average over the period 2017-2019 (Shell, 2019) referring to costs sustained by the Royal Dutch Shell company, and dividing by the averaged total hydrocarbon production (Royal Dutch Shell, 2020). The same was done for fixed assets, mining data of "Net property, plant & equipment" (WSJ, 2020a).

For unconventional light oils we used data referring to Chesapeake Energy Corp. and the 2019 average daily production (Chesapeake Energy, 2019; WSJ, 2020b, 2020c).

For unconventional heavy oils we used Suncor Energy data from (Suncor Energy, 2019), available at (Suncor Energy, n.d.).

The exchange rate used is 0.84 USD/EUR and 0.67 CAD/EUR (updated at 08/04/2021).

The results are reported in Table S4:

Table A12. Capex and fixed assets extraction benchmarks

Extraction typologies	***CapEx €/bbl***	***Fixed assets €/bbl***
Conventional	9.8	69.4
Unconventional light	10.7	68.4
Unconventional heavy	12.5	157.0

A4.2.4.2 Refining

For hydroskimming and medium conversion refining, capital expenditures (ENI, 2019) and fixed assets (WSJ, 2020d) per barrel were calculated taking the average over 2017-2018-2019 and dividing by averaged refinery intake (ENI, 2019). For deep conversion, either coking or hydrocracking, data are from (Royal Dutch Shell, 2020; Shell, 2019).

Table A13. Capex and fixed assets refining benchmarks

Refining typologies	***Capex €/bbl***	***Fixed assets €/bbl***
Hydroskimming Medium conversion	5.0	37.0
Deep conversion coking Deep conversion hydrocracking	7.9	56.4

A4.2.5 Labor

A4.2.5.1 Extraction

Labor requirements per barrel were calculated by multiplying the average number of employees in extraction per year over the period 2017-2019 by the total working hours (2000 hrp.c./y), then dividing by the average production over the same time frame.

$$hr_{barrel} = {n\_empl\_extr * workload}\big/{production}$$

For conventional, unconventional light and heavy fields data are respectively from (Chesapeake Energy, 2019; Royal Ductch Shell, 2020; Suncor Energy, 2019). Shell is the reference for conventional extraction, Chesapeake Energy Corp. for unconventional light and Suncor Energy for unconventional heavy fields.

Table A14. Extraction labor intensities

Extraction typologies	**Labor intensity hr/bbl**
Conventional	0.024
Unconventional light	0.026
Unconventional heavy	0.094

A4.2.5.2 Refining

Labor requirements per barrel were calculated by multiplying the average number of employees in refining per year over the period 2017-2019 by the total working hours (2000 $hr_{p.c.}/y$) and dividing by the average refining intake in the same time frame:

$$hr_{barrel} = {}^{n\_empl\_ref \, * \, workload}\!/_{ref\_intake}$$

For refining, Shell is the reference for deep conversion, ENI for hydroskimming and medium conversion (ENI, 2019; Royal Ductch Shell, 2020).

Table A15. Refining labor intensities

Refining typologies	**Labor intensity** **hr/bbl**
Hydroskimming Medium conversion	0.13
Deep conversion coking Deep conversion hydrocracking	0.08

A4.2.6 Constructing sequential pathways

Possible sequential pathways were constructed using the benchmarks calculated in the previous sections (Table 1 main text). The combined production functions were generated by combining the established sequential pathways according to a set of different relative compositions (Tables S10-S11). As extraction typologies can be associated with multiple refining types, we established (i) a fixed relative composition of extraction typology in the production mix (Table S8); and (ii) a fixed coupling between extraction and refining (Table S9).

Table A16. Relative contributions of extraction typologies to the total oil supply in the current situation (2018) and in the three (unconventional) simulations. Unconventional oils are reported in red.

Extraction typologies	**Current**	**Unconventional light**	**Unconventional heavy coking**	**Unconventional heavy hydrocracking**

Light low water onshore	16%	4%	4%	4%
Light low water offshore	3%	4%	4%	4%
Medium low water onshore	28%	4%	4%	4%
Medium low water offshore	13%	4%	4%	4%
Light watery onshore	2%	4%	4%	4%
Light watery offshore	1%	4%	4%	4%
Medium watery onshore	4%	4%	4%	4%
Medium watery offshore	4%	4%	4%	4%
Depleted	9%	9%	9%	9%
Heavy depleted	1%	1%	1%	1%
Ultra-deep	4%	**30%**	0%	0%
Fracking	4%	**30%**	0%	0%
Heavy & Extra heavy	11%	0%	**40%**	**40%**
Tar sands	2%	0%	**20%**	**20%**
Total	**100%**	**100%**	**100%**	**100%**

Table A17. Refining compositions associated with extraction typologies.

Extraction typologies	Hydroskimming	Medium conversion	Deep conversion
Light low water onshore	74%	26%	0%
Light low water offshore	74%	26%	0%
Medium low water onshore	0%	100%	0%
Medium low water offshore	0%	100%	0%
Light watery onshore	74%	26%	0%
Light watery offshore	74%	26%	0%
Medium watery onshore	0%	100%	0%
Medium watery offshore	0%	100%	0%
Ultra-Deep	37%	63%	0%
Fracking	100%	0%	0%
Depleted	0%	100%	0%
Heavy depleted	0%	0%	100%

Heavy & Extra heavy	0%	19%	81%
Tar sands	50%	0%	50%

Once the relative compositions of extraction and refining typologies were defined, considering benchmarks reported in Table 1, we calculated the combined production functions (Table 4-5, main text). The output of oil products (gross and net) is reported in Table 2 of the main text.

A4.3 Societal requirements of oil products

World consumption is assumed equal to world production as reported in (ENI, 2018).

A4.3.1 US requirement

US consumption data are from the US Energy Information Administration (EIA), specifically the EIA's data API (US Energy Information Administration, 2021a). We selected the following US oil products, supplied for 2018 and averaged on a monthly base, from the categories "*U.S. Product Supplied of [label of the product] Oil, 4 Week Avg*":

1. Finished motor gasoline;
2. Total distillate;
3. Kerosene-type jet fuel;
4. Propane and propylene;
5. Residual fuel oil;
6. Other oils;
7. Petroleum products (total).

The 'total distillate category' in the EIA dataset consists of the following subcategories:

- No 1 distillate;

- No 2 diesel;
- No 2 Fuel oil/heating oil;
- No 4 distillate;
- Distillate other.

All these categories were matched with supply categories from the OCI dataset. Coke and Other oils OCI categories have been grouped and labelled as 'Other products'. We assumed the following mapping scheme:

Table A18. Mapping categories of oil products between EIA (consumption) and OCI (supply) accounting schemes.

US societal consumption - EIA dataset	**Supply categories – OCI dataset**
Finished motor gasoline	Gasoline
Kerosene-type jet fuel	Jet fuel
No 1 distillate + No 2 diesel	Diesel
No 2 Fuel oil/heating oil + No 4 distillate + Distillate other + Residual fuel oil	Fuel oil
Other oils + Propane and propylene	Coke + Other oils = Other products

To obtain the diesel and fuel oil shares, we disentangled the 'total distillate' consumption among the different subproducts. Sales of specific subproducts are reported under the '*U.S. [label of the product] Adj Sales/Deliveries to [label of the societal sector], Annual'* categories across US sectors and oil products.

The US societal sectors selected are the following:

- Commercial consumers;
- Electricity utility consumers;
- Farm consumers;
- Industrial consumers;

- Military consumers;
- Off-highway construction;
- Off-highway other;
- Off-highway consumers;
- Oil company consumers;
- On-highway consumers;
- Rail road consumers;
- Residential consumers;
- Transportation total.

We assumed zero stocks, hence the sales equal the consumption. Summing up the consumption of each oil product across the US societal sectors and dividing by the ‘total distillates’ amount previously defined, we obtained the societal shares for each distillate:

- No 1 distillate = 3.4%;
- No 2 diesel = 96.4%;
- No 2 Fuel oil/heating oil = 0.15%;
- No 4 distillate = 0.06%;
- Distillate other = 0.13%.

The shares are referred to the percentage of ‘total distillates’ inside the whole societal consumption pattern (they sum up to 100%).
The US requirement of oil products is reported in Table 3 (main text).

A4.3.2 EU requirement

EU consumption data are from the Energy balance 2020 (Eurostat, 2020). The year of reference is 2018. Again, we established a coherent mapping between our taxonomy of oil products and the one used by Eurostat as reported in Table S11. Only values of products (in the first column of Table S10) referring to "Energy sector", "Final energy consumption" and "Final non energy consumption" have been considered.

Table A19. Mapping categories of oil products between EU Energy Balance 2020 (consumption) and OCI (supply) accounting schemes

EU societal consumption	Supply categories – OCI dataset
Motor gasoline (excluding biofuel portion) + Aviation gasoline + Naphtha (final energy consumption)	Gasoline
Gasoline type jet fuel + Kerosene type jet fuel (excluding biofuel portion) + Other kerosene	Jet fuel
Gas oil and diesel oil (excluding biofuel portion)	Diesel
Fuel oil + Petroleum coke	Fuel oil
Crude oil + Natural gas liquids + Refinery feedstocks + Additives and oxygenates (excluding biofuel portion) + Other hydrocarbons + Refinery gas + Ethane + Liquefied petroleum gases + Naphtha (final non-energy consumption and energy sector) + White spirit and special boiling point industrial spirits + Lubricants Bitumen + Paraffin waxes + Other oil products	Other products

The final result is reported in Table 3, main text.

A4.4 Energy-for-energy internal requirement and coupling factors

Before coupling supply to requirement, we assessed the internal consumption of the oil sector itself, and subtracted it from the gross supply output to obtain the net production available to society. The internal energy loop depends on the performance of the oil sector and hence on the specific combination of sequential supply pathways (the combined production functions). We therefore obtained different values for different oil products across different supply pathways.

We assumed that electricity is 100% produced with fuel oil; diesel and coke are used directly as fuels. First, we calculated the inputs of diesel, fuel oil and coke (energy carriers) required to produce a whole barrel of oil products (bbl_{EC}/bbl_{oil}, %). The OCI dataset provides these values in MJ/bbl (numerator of the right side of the equations), so we applied the following conversions to obtain the desired ratio:

$$\frac{diesel_{input}}{whole\_barrel_{output}} = \frac{Diesel\_requirement\ [MJ/bbl_{oil}]}{diesel\_conversion\_efficiency\ [\%] * Lower\_Calorific\_Value\ [MJ/l_{diesel}]}/159.9\ \left[\frac{l_{diesel}}{bbl_{diesel}}\right]$$

$$\frac{fuel\_oil_{input}}{whole\_barrel_{output}} = \frac{Electricity\_requirement[MJ/bbl]}{fueloil\_conversion\_efficiency[\%] * Lower\_Calorific\_Value\left[MJ/l_{fueloil}\right]}/159.9\left[\frac{l_{fueloil}}{bbl_{fueloil}}\right]$$

$$\frac{coke_{input}}{whole\_barrel_{output}} = \frac{coke\_requirement\ [MJ/bbl]}{coke\_conversion\_efficiency\ [\%] * Lower\_Calorific\_Value\ [MJ/kg_{coke}]}/161.05\ \left[\frac{kg_{coke}}{bbl_{coke}}\right]$$

We made the following assumptions:

- 50% conversion efficiency for large diesel (compression-spark) engines (Breeze, 2019);
- 70% conversion efficiency for combined heat-electricity (CHP) production in steam turbines – fuel oil to electricity (US Department of Energy, 2015; US Energy Information Administration, 2021b);
- 80% conversion efficiency for industrial heater and burners (coke) (US Department of Energy, 2015; US Energy Information Administration, 2021b);
- Lower calorific values: diesel = 36 MJ/l, fuel oil = 39.2 MJ/l, coke = 29.5 MJ/kg (Engineering Toolbox, 2021).

Results are reported in Table A20:

Table A20. Internal requirement of EC to supply one barrel of oil products (% $barrel_{EC}/barrel_{oil}$).

Oil-for-oil internal loop	Diesel	Fuel oil	Coke	*Total*
Current situation	0,8%	0,6%	0,7%	**2,1%**
Unconventional light	0,7%	0,5%	0,3%	**1,5%**
Unconventional heavy - coking	5,4%	1,0%	1,5%	**7,9%**
Unconventional heavy - hydrocracking	5,4%	1,0%	1,4%	**7,8%**

Then, we calculated the output/input ratios for each EC across the set of combined production functions, using the following formulas:

$$\frac{diesel_{output}}{diesel_{input}} = \frac{diesel\_output\ [\%] * Lower\_Calorific\_Value\ [MJ/l] * diesel\_conversion\_efficiency\ [\%] * 159.9\ [l/bbl]}{diesel\_requirement\ [MJ/bbl]}$$

$$\frac{fuel\_oil_{output}}{fuel\_oil_{input}} = \frac{diesel\_output\ [\%] * Lower\_Calorific\_Value[MJ/l] * fueloil\_conversion\_efficiency\ [\%] * 159.9\ [l/bbl]}{electricity\_requirement\ [MJ/bbl]}$$

$$\frac{coke_{output}}{coke_{input}} = \frac{coke\_output\ [\%] * Lower\_Calorific\_Value[MJ/kg] * coke\_conversion\_efficiency\ [\%] * 159.9\ [kg/bbl]}{coke\_requirement\ [MJ/bbl]}$$

Results are reported in Table A21:

Table A21. Supply/requirement ratio for specific ECs across scenarios: the higher the value, the higher the efficiency in using the specific EC, the lower is the PES requirement to produce that EC.

Supply/requirement ratio	Diesel	Fuel oil	Coke
Current situation	21	4	2
Unconventional light	20	10	**0,4**
Unconventional heavy coking	3	2	4
Unconventional heavy hydrocracking	4	2	3

Gross societal requirement shares (Table 3, main text) were multiplied by total supply (105 million barrels per day) to obtain the absolute size of energy carrier requirements for the World, the US, and the EU consumption patterns. Net societal requirement values (Table 3) were calculated subtracting the oil sector requirements of diesel, fuel oil and coke (Table S12). Coupling factors were calculated comparing

the net supply composition across combined production functions (Table 2) with net requirement patterns, according to the mapping in Table S10 and S11 and using the definition of coupling factors detailed in section 2.3.3, main text.
Overall required production was calculated (Fig. 6) by multiplying coupling factors by nominal production (105 million bbl/d); the integrated performance space ***IP*** was obtained in the same way, multiplying coupling factors by supply benchmarks (Fig. 7).

A4.5 Exploring the multidimensional supply spaces: performance indicators

Visualization of the multidimensional space across scales is complex. It needs a variety of indicators and two non-equivalent description domains (intensive or extensive) to be handled. We used here three types of indicators:

1. Funds and/or flows, intensive description (e.g., Fig. A16);

2. Funds and/or flows, extensive description (e.g., Fig. A17);

3. Flow-fund ratios (e.g., Fig. 3-4-S20-21);

The switch between intensive and extensive metrics is possible using the factor of size, that is barrels produced per day (Fig. 6, main text).

The flow-fund indicators are useful to describe the internal structure of the oil sector and assess its quality in relation to the sustainability dimensions defined in section 2.1 (only feasibility and viability in this study). They highlight how the biophysical and economic funds, that constitute the oil sector, are functionally used and at what ‘metabolic rate’.

A4.5.1 Intensive and extensive metabolic benchmarks, space D_{cs}

The intensive description refers to metabolic benchmarks normalized per barrel. The extensive description of the flows and funds employed in the oil sector was obtained by combining the intensive supply benchmarks across simulations with the total number of barrels produced per day, which are assumed equal to the nominal level of consumption required (105 million barrels daily) multiplied by the coupling factor.

As stated earlier, our metabolic representation is time-invariant (in a strictly system dynamics sense). However, in Fig. S2 and S3 we show how supply benchmarks vary in proportion to the share of unconventional pathways (respectively light and heavy) in the supply mix, starting from the current share (22%).

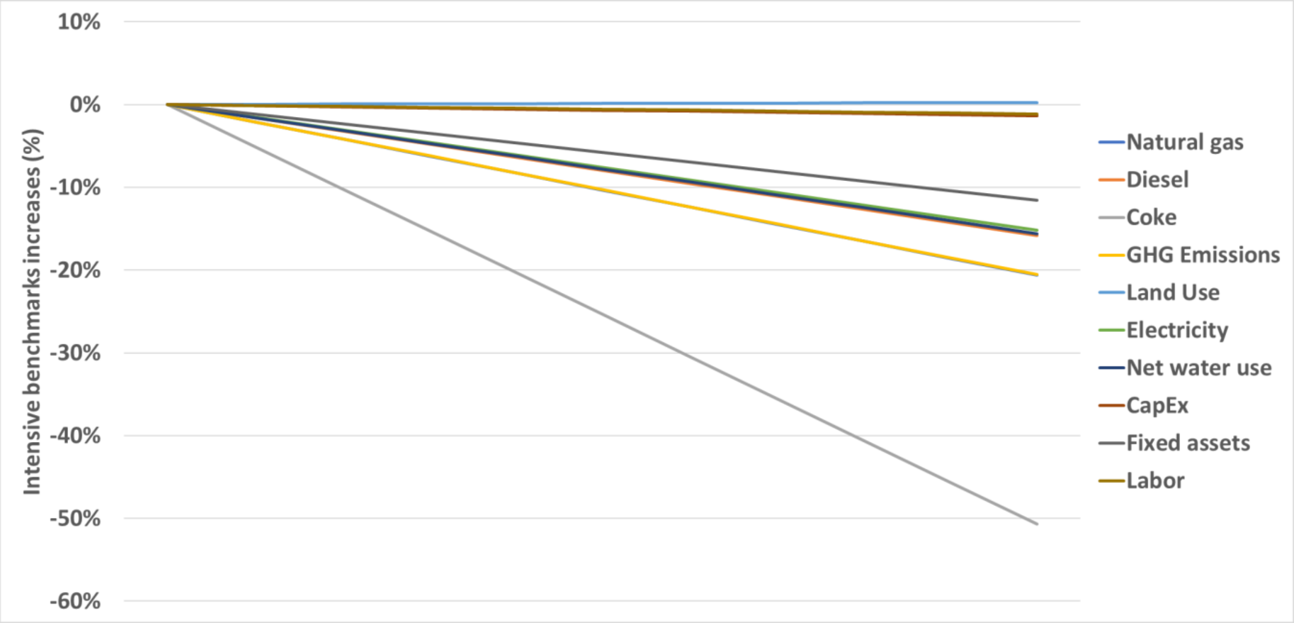

Fig. A14 Percentual variation of intensive metabolic benchmarks associated with the increasing share of unconventional light pathways in the combined production functions, from 22% (current total unconventional production) to 60% (only unconventional light)

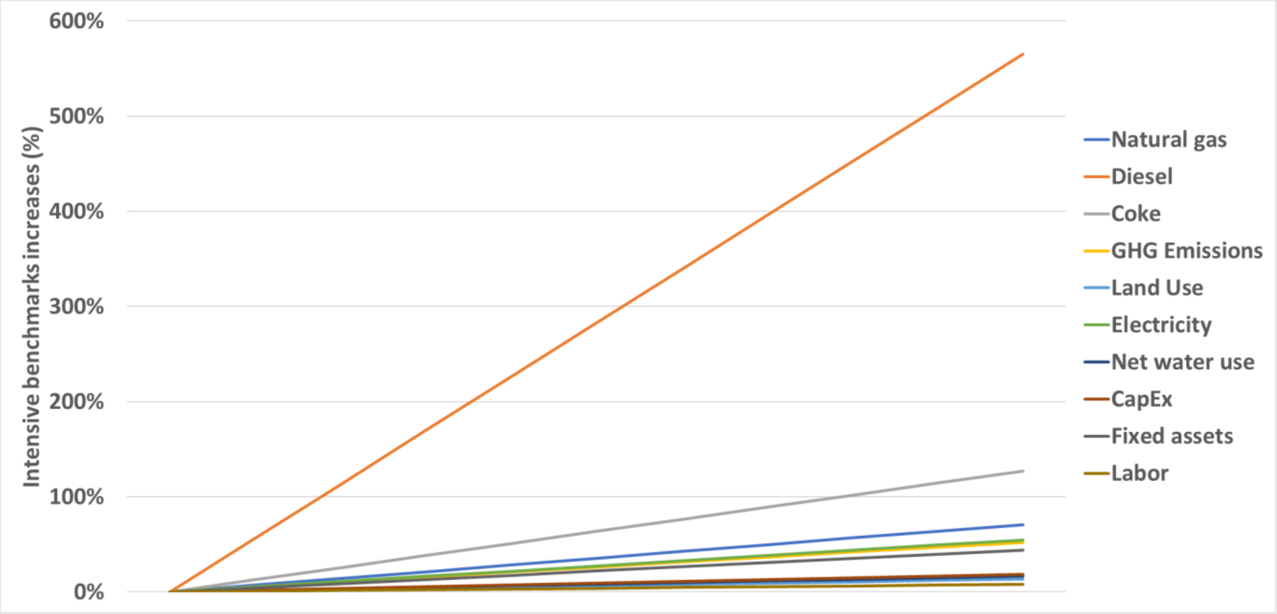

Fig. A15 Percentual variation of intensive metabolic benchmarks associated with the increasing share of unconventional heavy pathways in the combined production functions, from 22% (current total unconventional production) to 60% (only unconventional heavy)

A4.5.1.1 Viability

The complete set of intensive and extensive supply benchmarks related to the viability dimension is shown in Figures A16 – A21, except for the labor benchmarks which are shown in Fig. 8 of the main text.

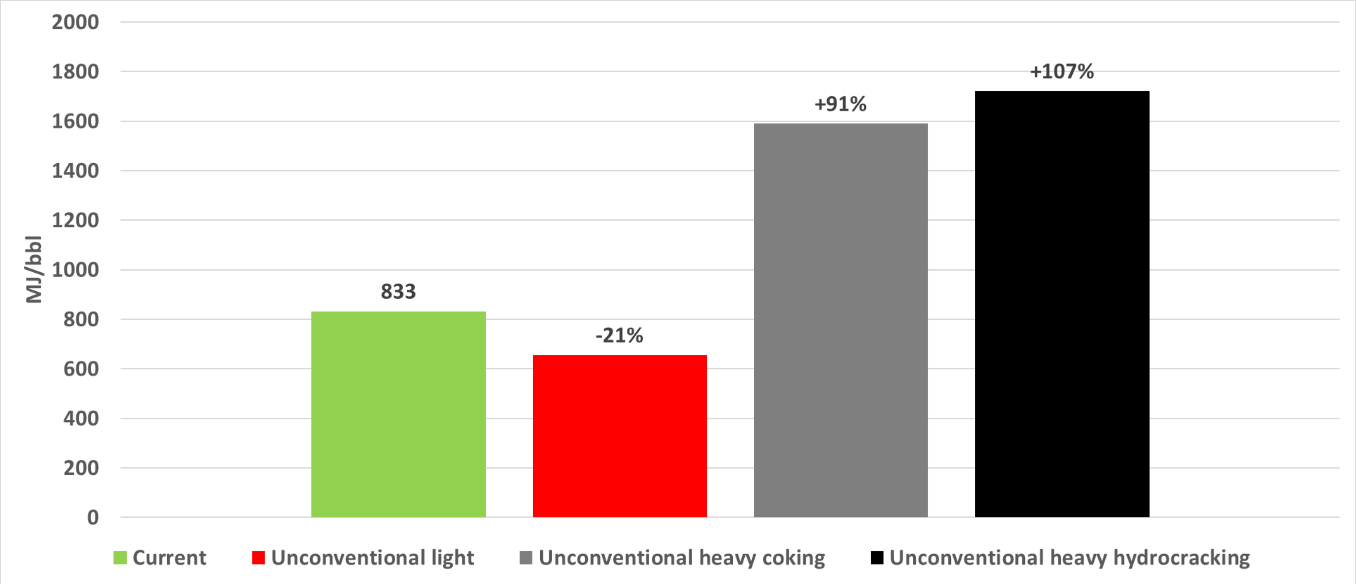

Fig. A16 Combined energy carrier intensities

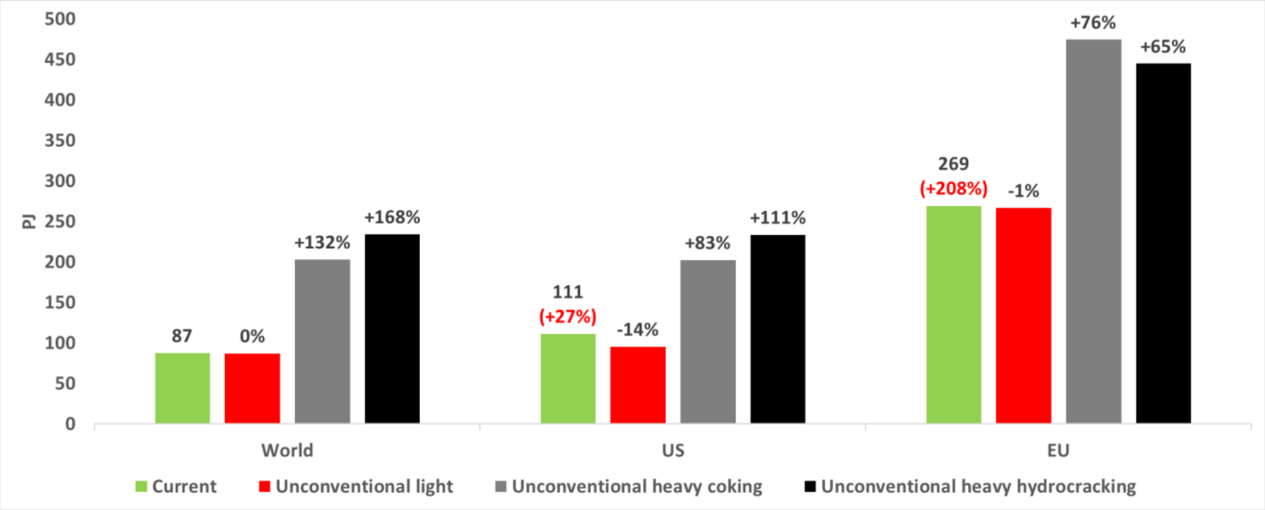

Fig. A17 Extensive daily requirements of energy carriers

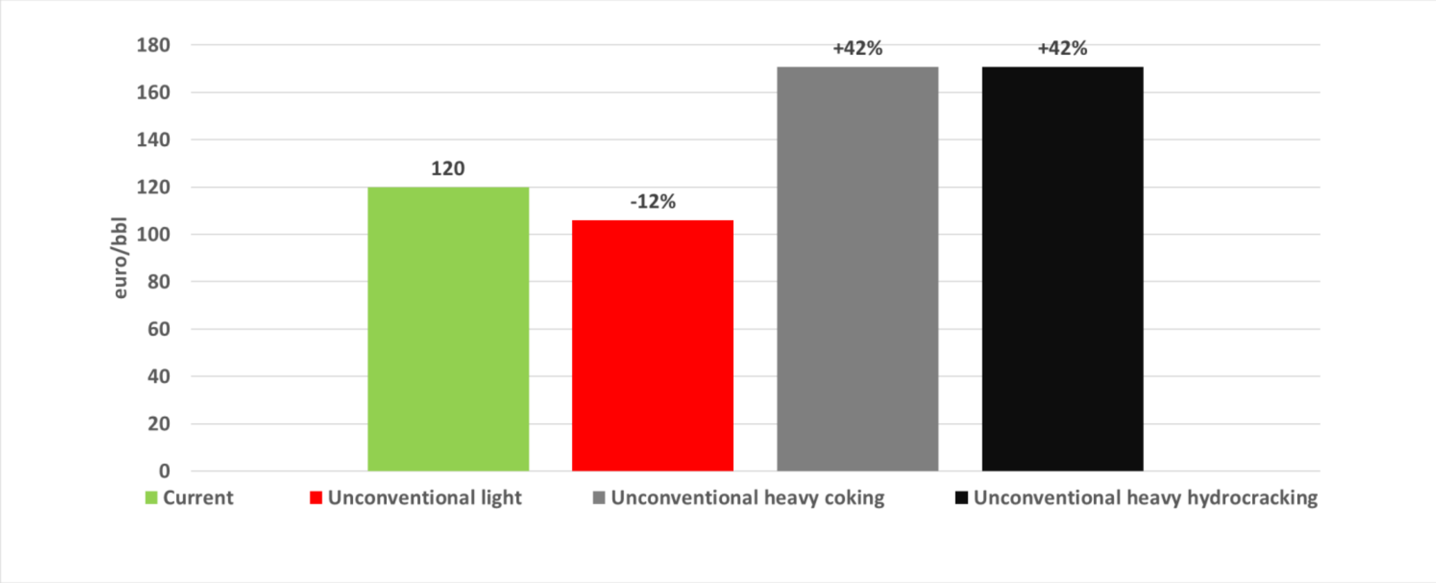

Fig. A18 Fixed assets intensities

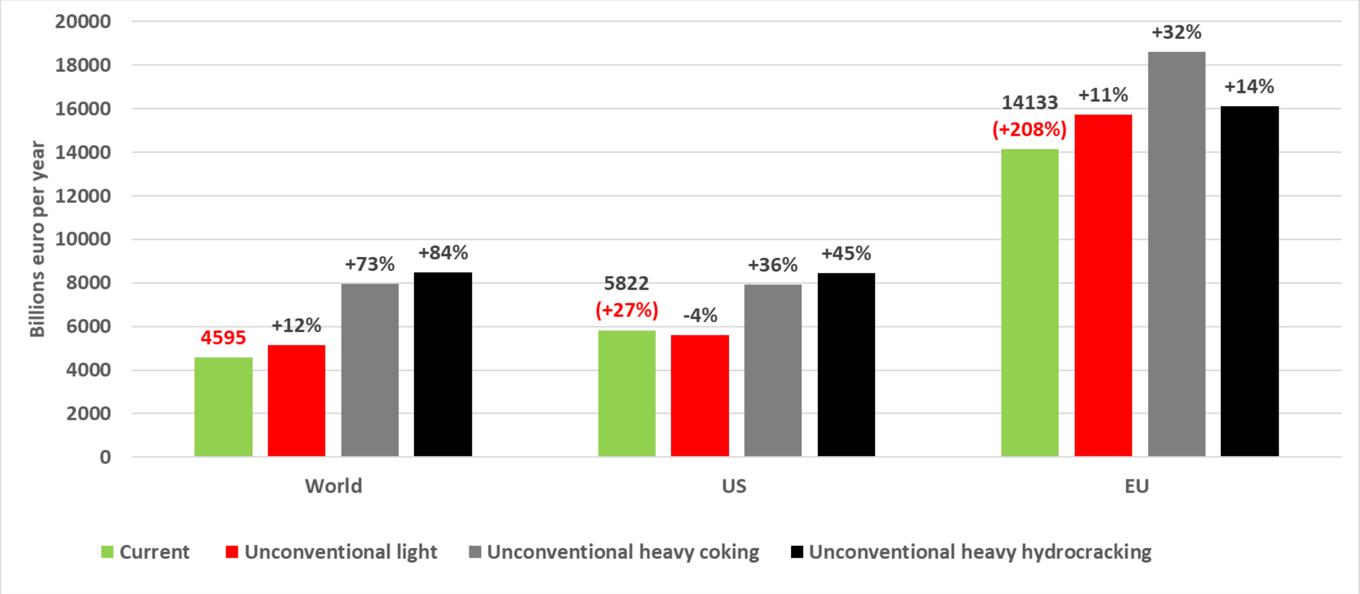

Fig. A19 Fixed assets, extensive annual requirement

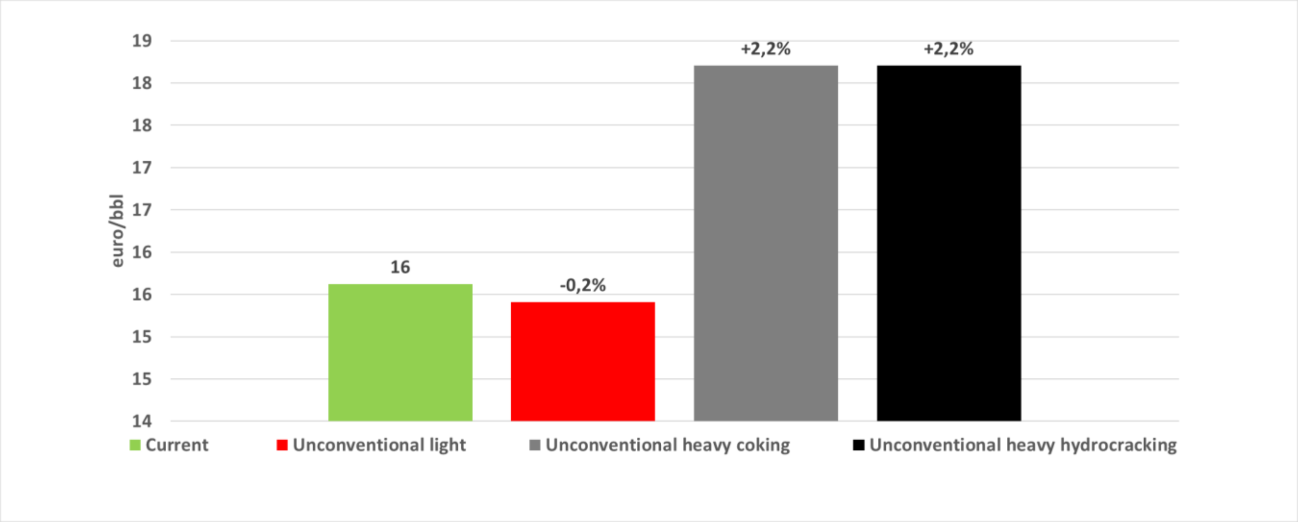

Fig. A20 Capex intensities

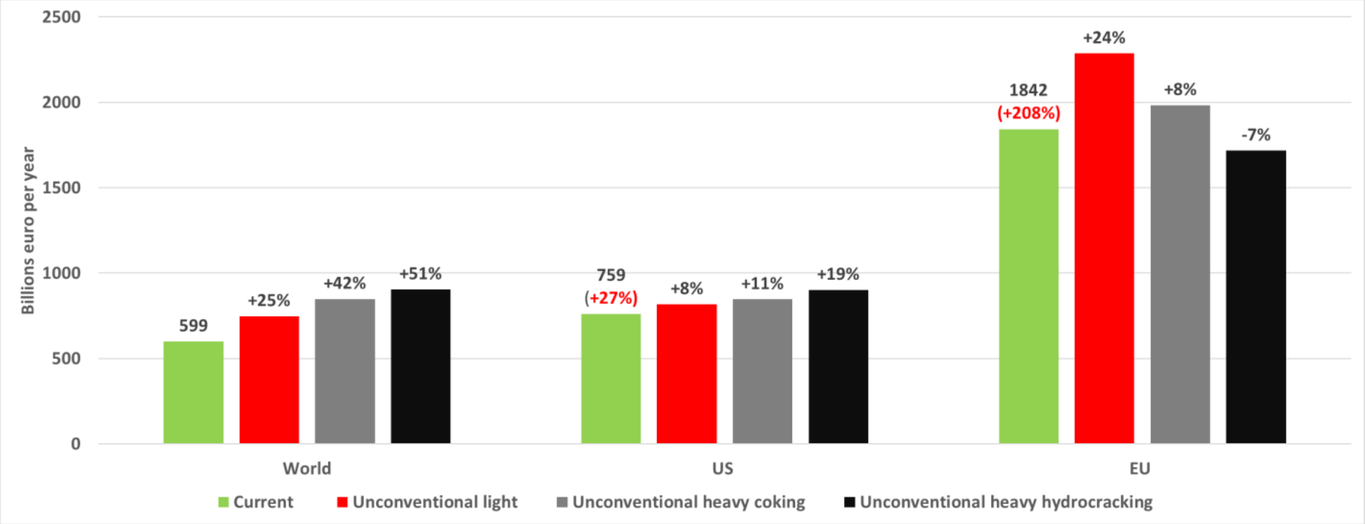

Fig. A21 Capex, extensive annual requirement

A4.5.1.2 Feasibility

The intensive and extensive supply benchmarks related to the feasibility dimension are reported in Figures A22 – A27.

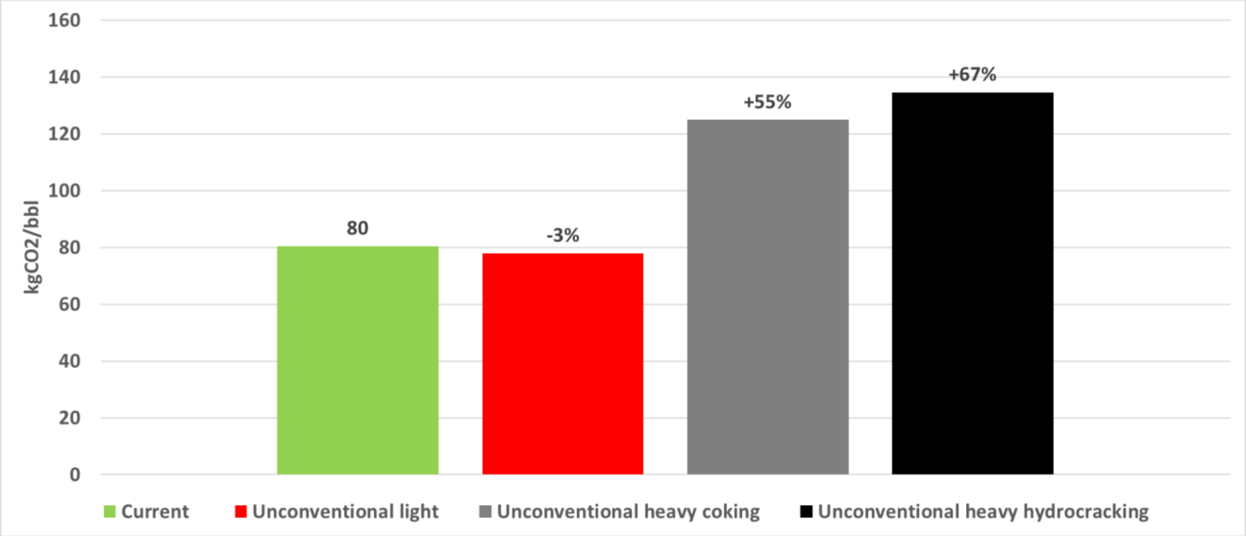

Fig. A22 GHG emission intensities

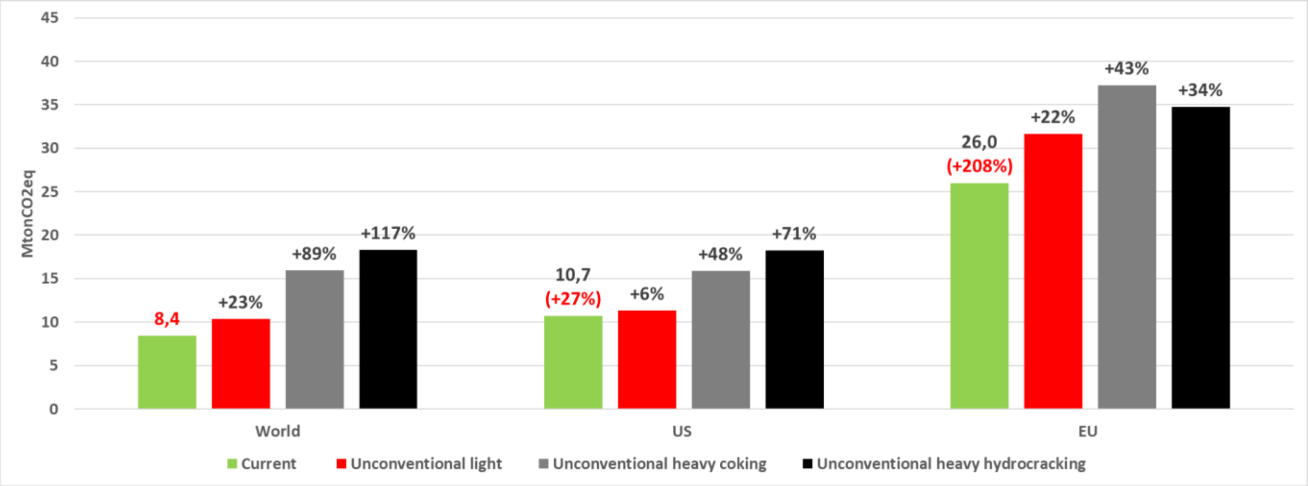

Fig. A23 Extensive daily GHG emissions

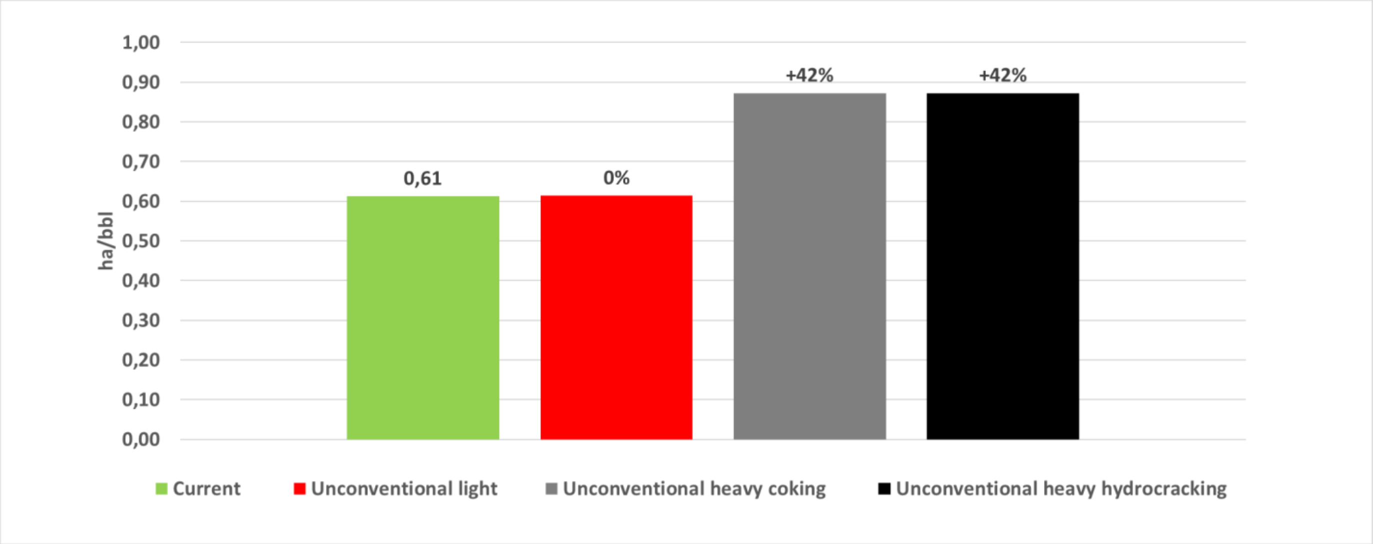

Fig. A24 Land use intensities

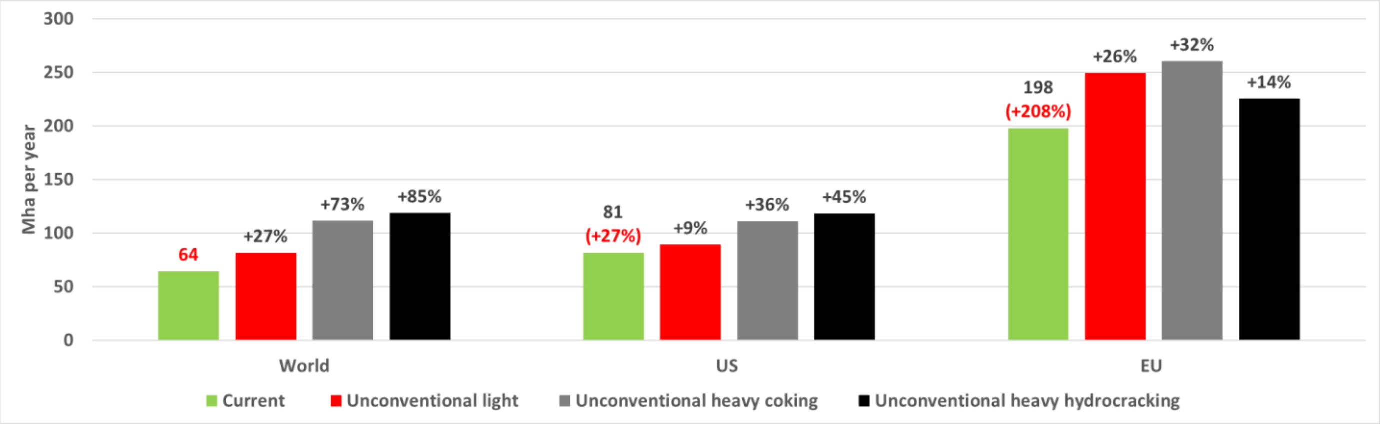

Fig. A25 Extensive annual land use

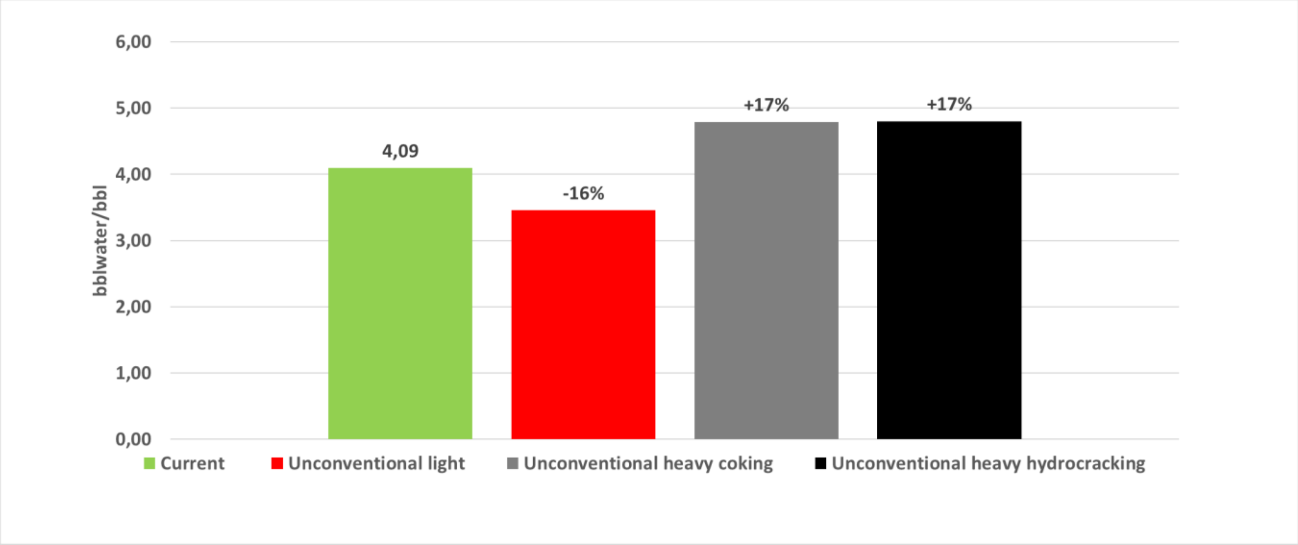

Fig. A26 Net water use intensities

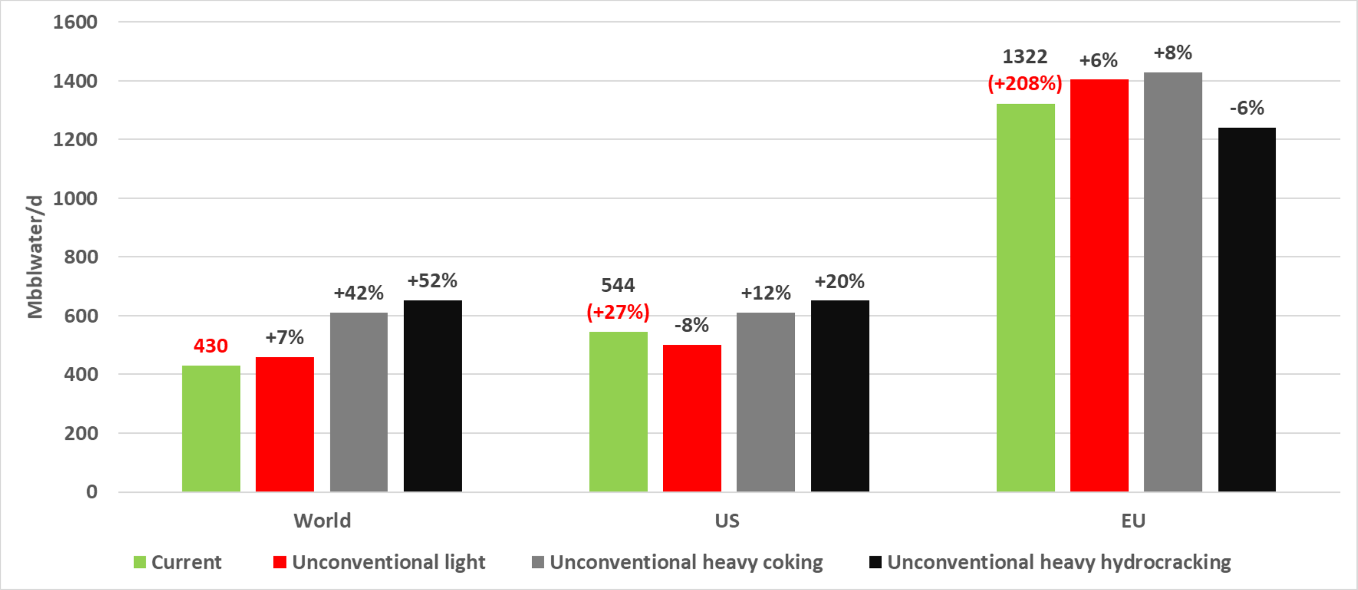

Fig. A27 Extensive daily net water use

A4.5.2 Integrated performance indicators (space IP) and flow-fund ratios

Flow-fund and intensive benchmarks inform us about the internal structure and functioning of the oil sector. The extensive descriptions inform us about the size and boundaries of the system. The multidimensional space representing the current supply situation in face of different consumption scenarios is shown in Fig. A28. The forced coupling between the supply and the requirement patterns is the main driver of the actual size of the oil sector, defining its pressures on both the biosphere and the anthroposphere. The available set of PES and the library of sequential pathways play a minor role in defining the size of the biophysical and economic pressures in comparison to the effect of consumption patterns (the space resulting from the adoption of an EU-type demand is systematically larger).

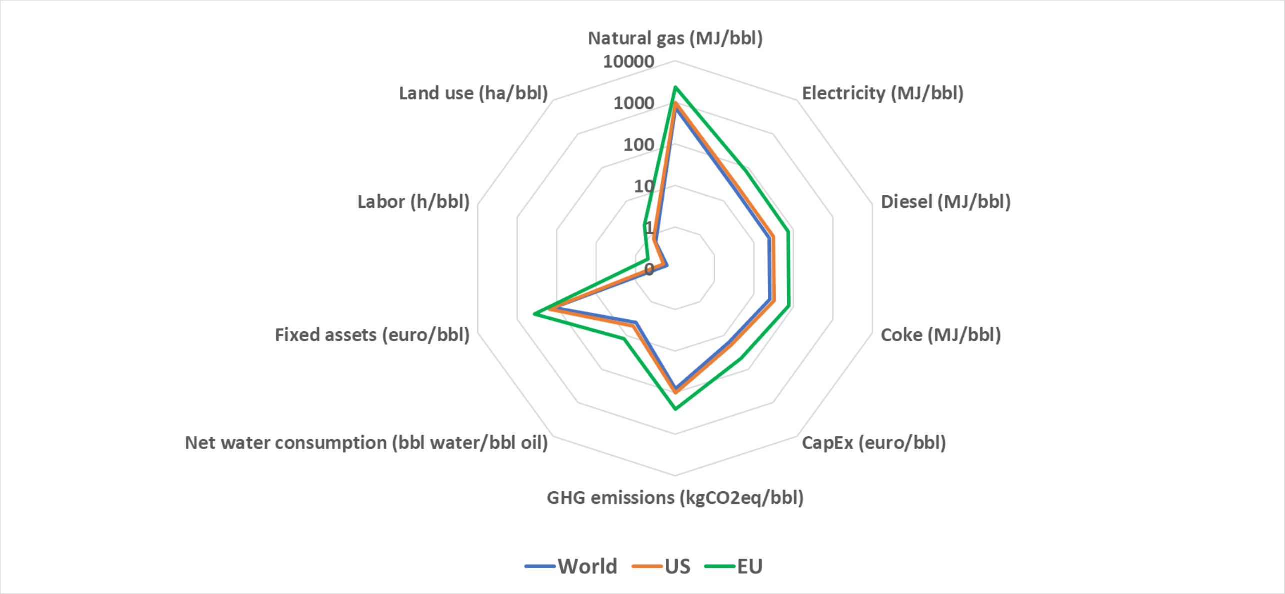

Fig. A28 Integrated performance spaces – Indicators of social-ecological (total) pressures adjusted to the daily production that guaranteed the equilibrium point between supply and consumption

A4.5.2.1 Indicators characterizing the biophysical and technological performance

The complete set of the indicators related to the biophysical and technological performance is shown in Figures A29 – A32.

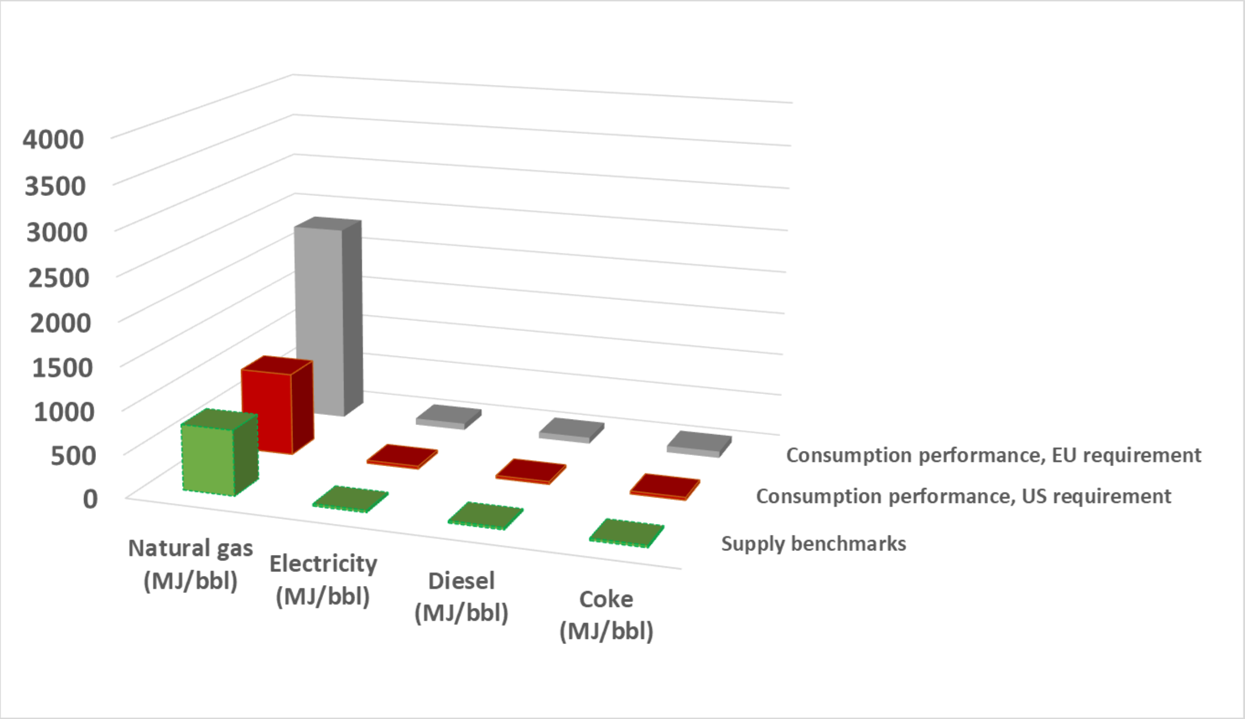

Fig. A29 Biophysical and technological performance (energy carrier requirement) of an US and EU demand-driven enlargement of the global oil sector under the current production pattern, to respectively match the requirement of gasoline and diesel, compared to supply benchmarks (baseline consumption)

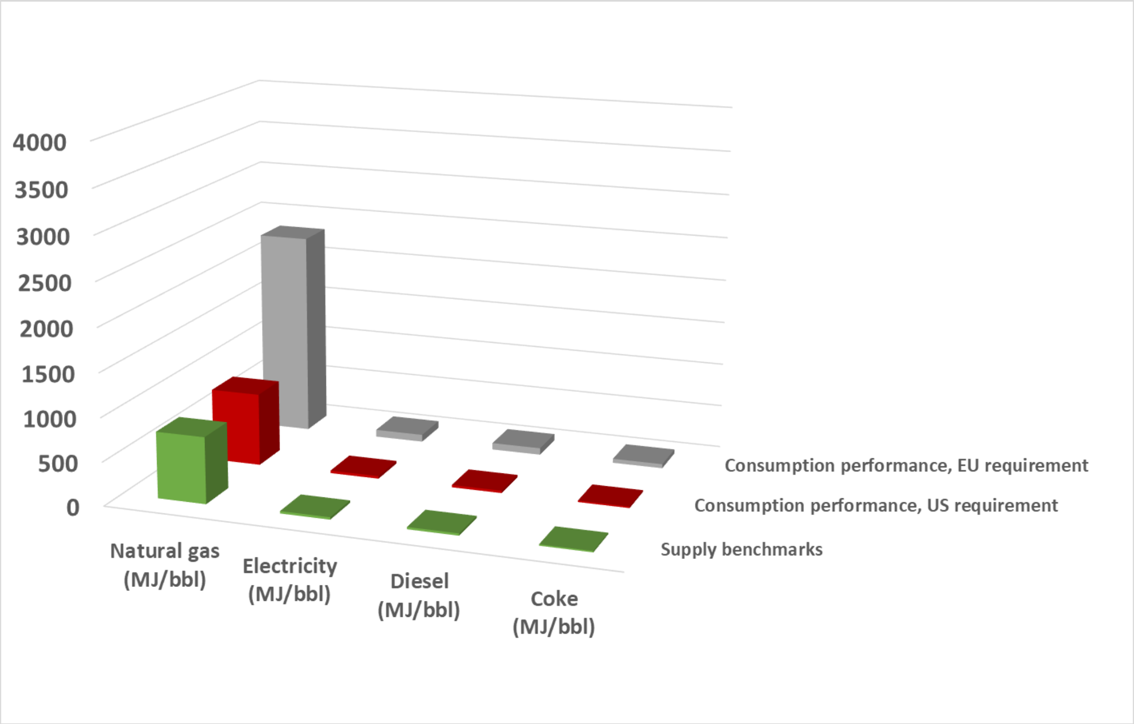

Fig. A30 Biophysical and technological performance (energy carrier requirement) of an US and EU demand-driven enlargement of the global oil sector under the unconventional light supply pattern, to match the requirement of diesel, compared to supply benchmarks (baseline consumption)

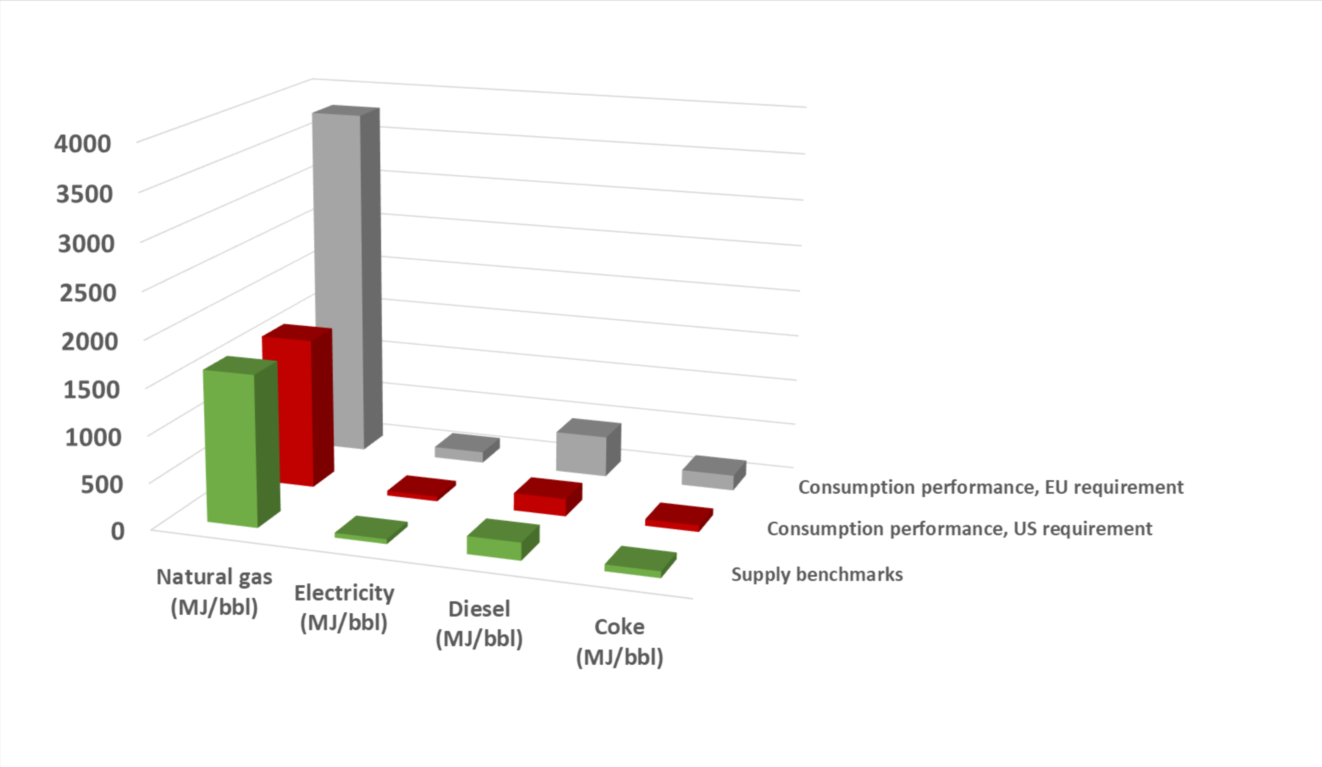

Fig. A31 Biophysical and technological performance (energy carrier requirement) of an US and EU demand-driven enlargement of the global oil sector under the unconventional heavy coking supply pattern, to respectively match the requirement of other products and diesel, compared to supply benchmarks (baseline consumption)

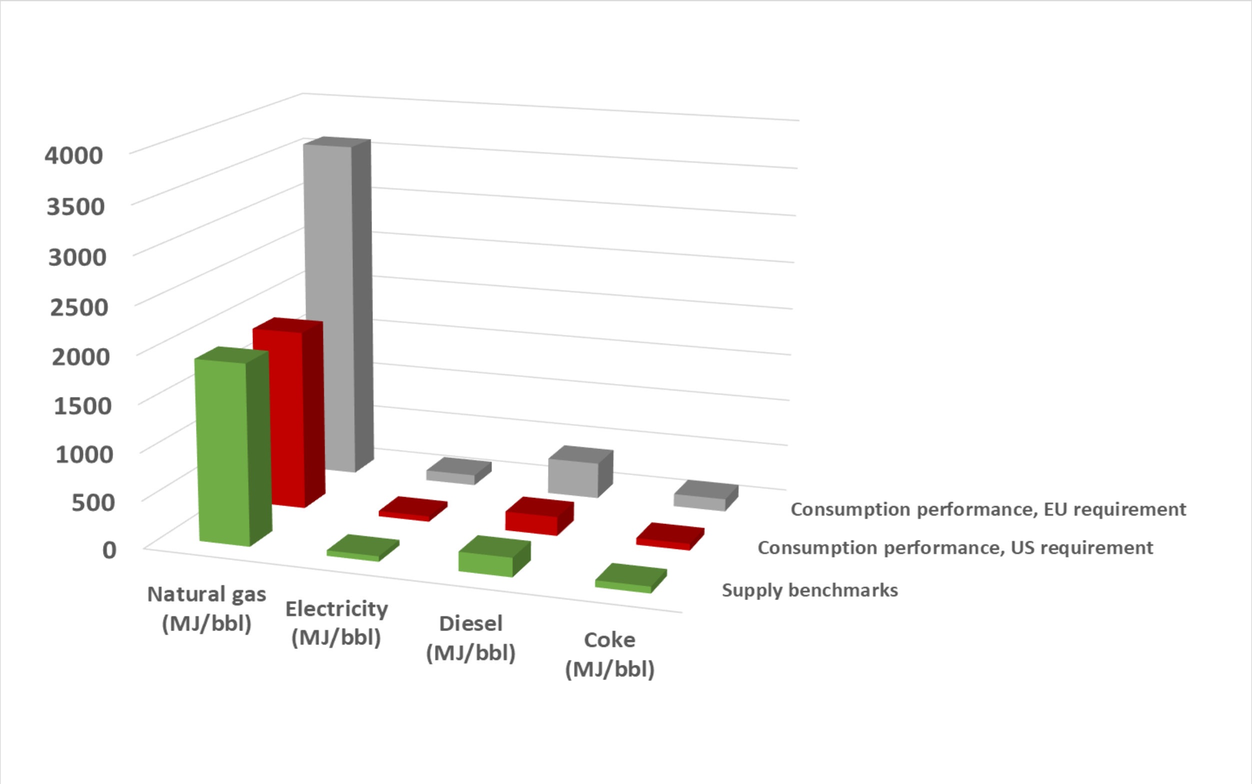

Fig. A32 Biophysical and technological performance (energy carrier requirement) of an US and EU demand-driven enlargement of the global oil sector under the unconventional heavy hydrocracking supply pattern, to respectively match the requirement of other products and fuel oil, compared to supply benchmarks (baseline consumption)

A4.5.2.2 Indicators characterizing the environmental performance

The complete set of the indicators related to the environmental performance is shown in Figures A33 – A36.

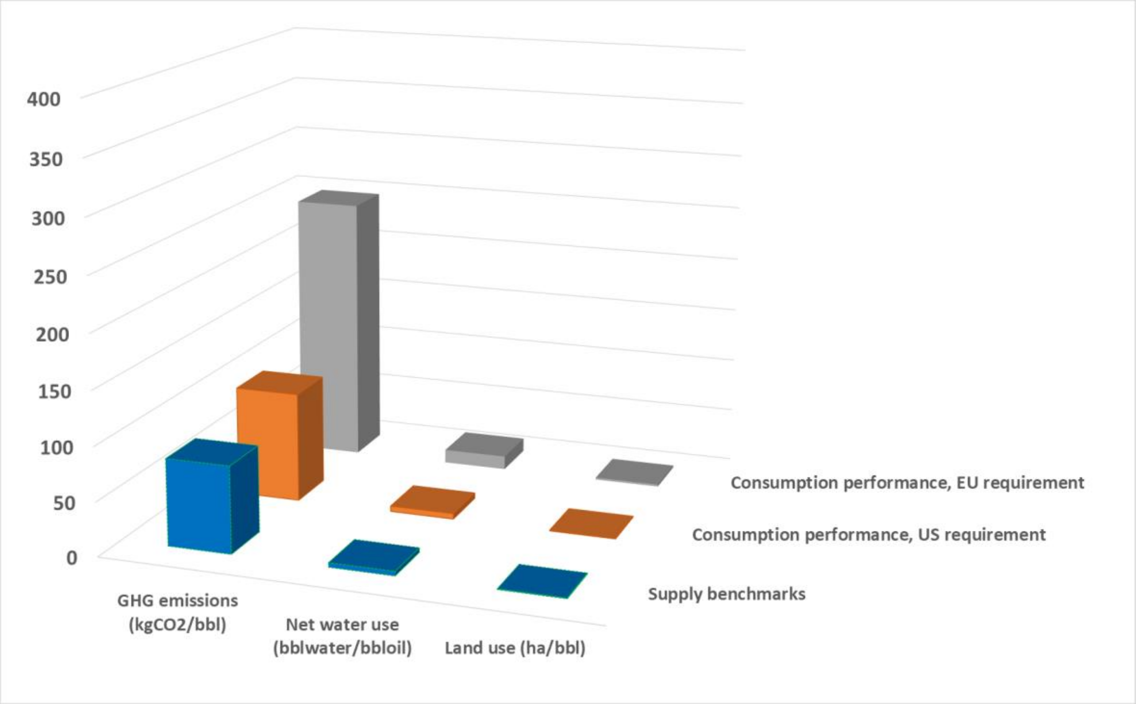

Fig. A33 Environmental performance (land use, GHG emissions and water use) of an US and EU demand-driven enlargement of the global oil sector under the current production pattern, to respectively match the requirement of gasoline and diesel, compared to supply benchmarks (baseline consumption)

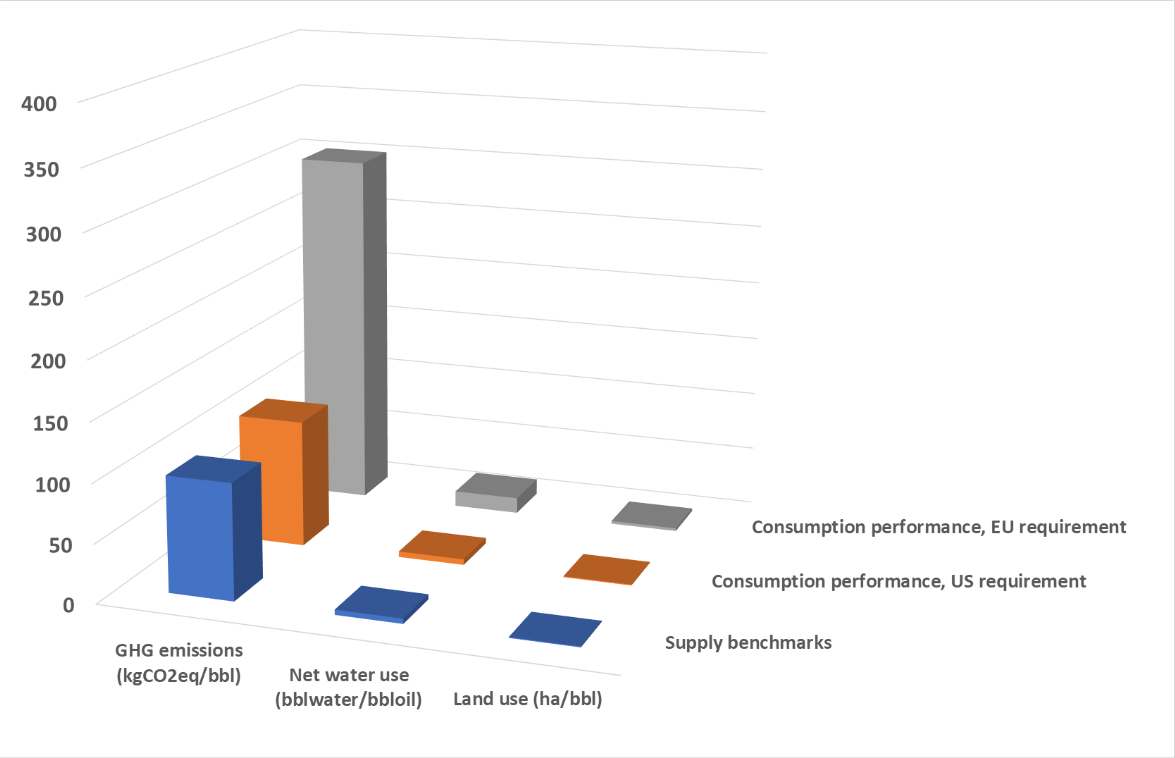

Fig. A34 Environmental performance (land use, GHG emissions and water use) of an US and EU demand-driven enlargement of the global oil sector under the unconventional light supply pattern, to match the requirement of diesel, compared to supply benchmarks (baseline consumption)

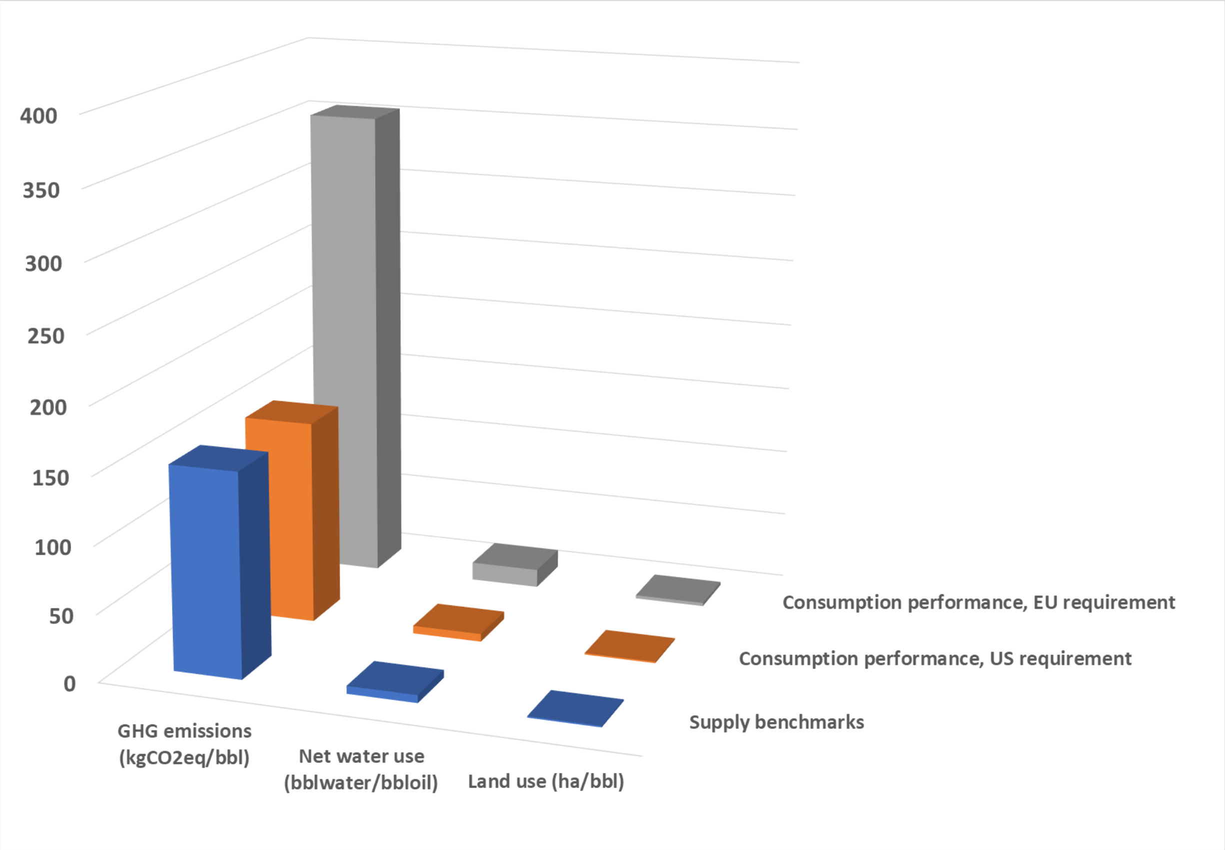

Fig. A35 Environmental performance (land use, GHG emissions and water use) of an US and EU demand-driven enlargement of the global oil sector under the unconventional heavy coking supply pattern, to respectively match the requirement of other products and diesel, compared to supply benchmarks (baseline consumption)

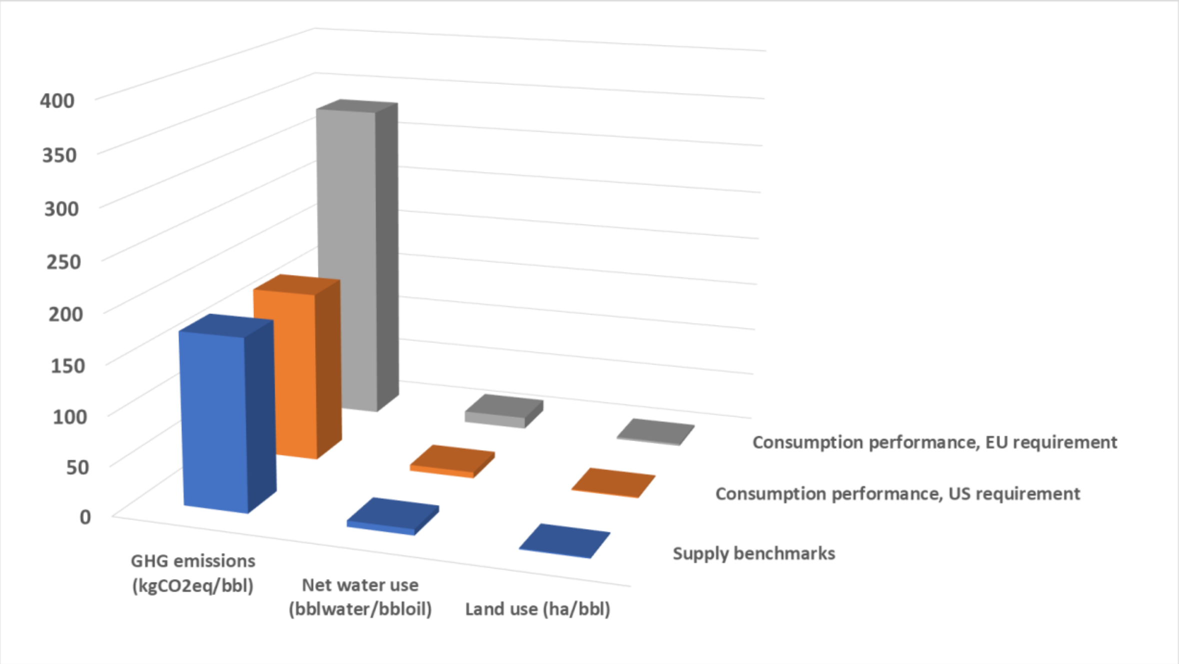

Fig. A36 Environmental performance (land use, GHG emissions and water use) of an US and EU demand-driven enlargement of the global oil sector under the unconventional heavy hydrocracking supply pattern, to respectively match the requirement of other products and fuel oil, compared to supply benchmarks (baseline consumption)

A4.5.2.3 Indicators characterizing the environmental performance

The complete set of the indicators related to the socio-economic performance is shown in Figures A37 – A40.

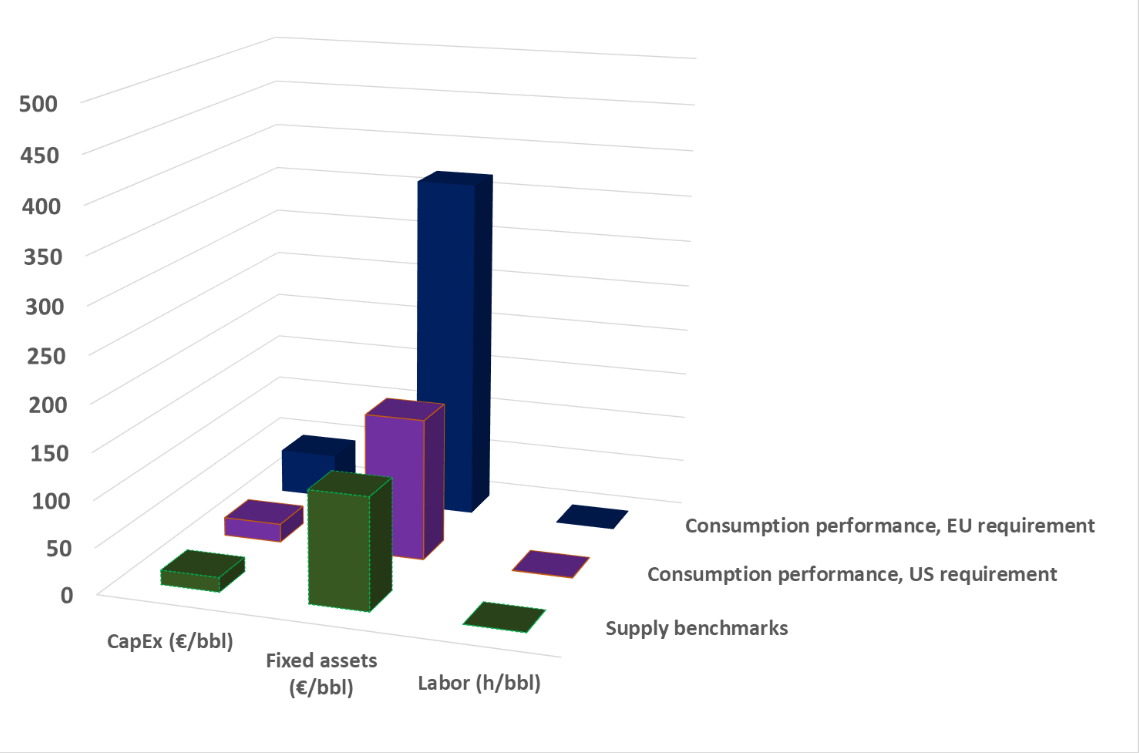

Fig. A37 Socio-economic performance (labor and capital investments) of an US and EU demand-driven enlargement of the global oil sector under the current production pattern, to respectively match the requirement of gasoline and diesel, compared to supply benchmark (baseline consumption)

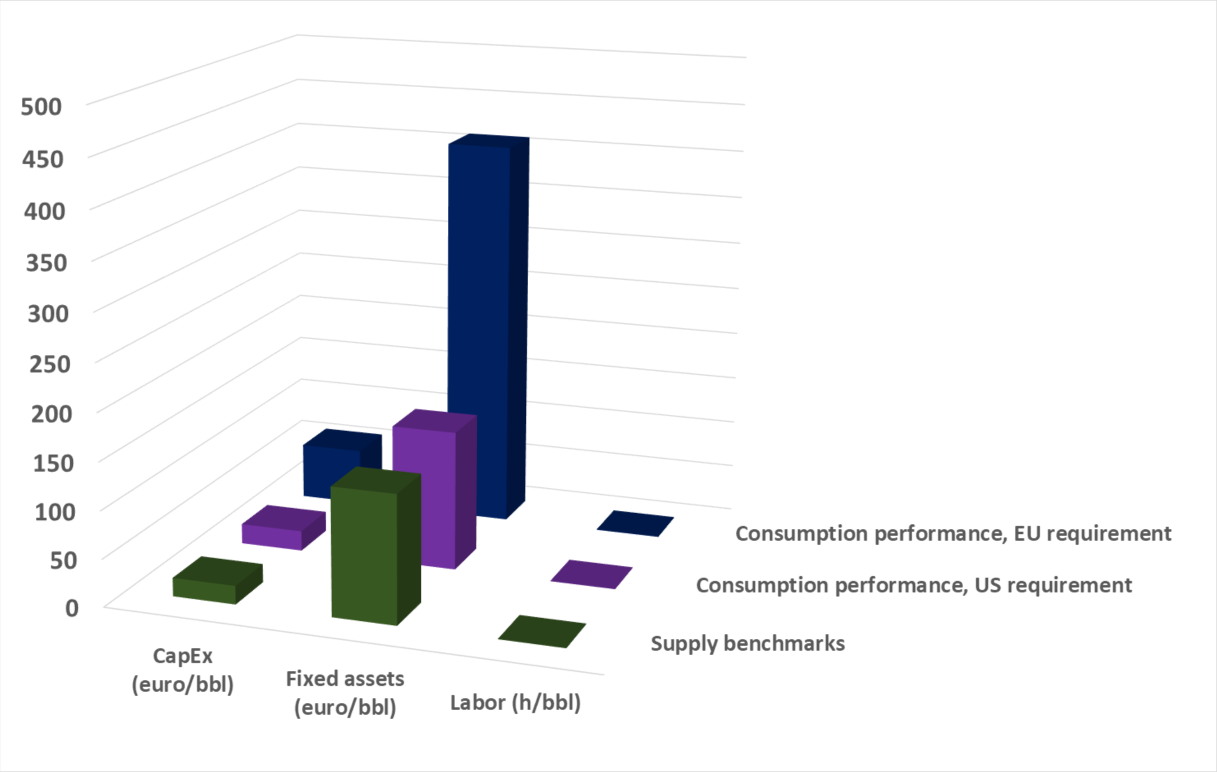

Fig. A38 Socio-economic performance (labor and capital investments) of an US and EU demand-driven enlargement of the global oil sector under the unconventional light supply pattern, to match the requirement of diesel, compared to supply benchmarks (baseline consumption)

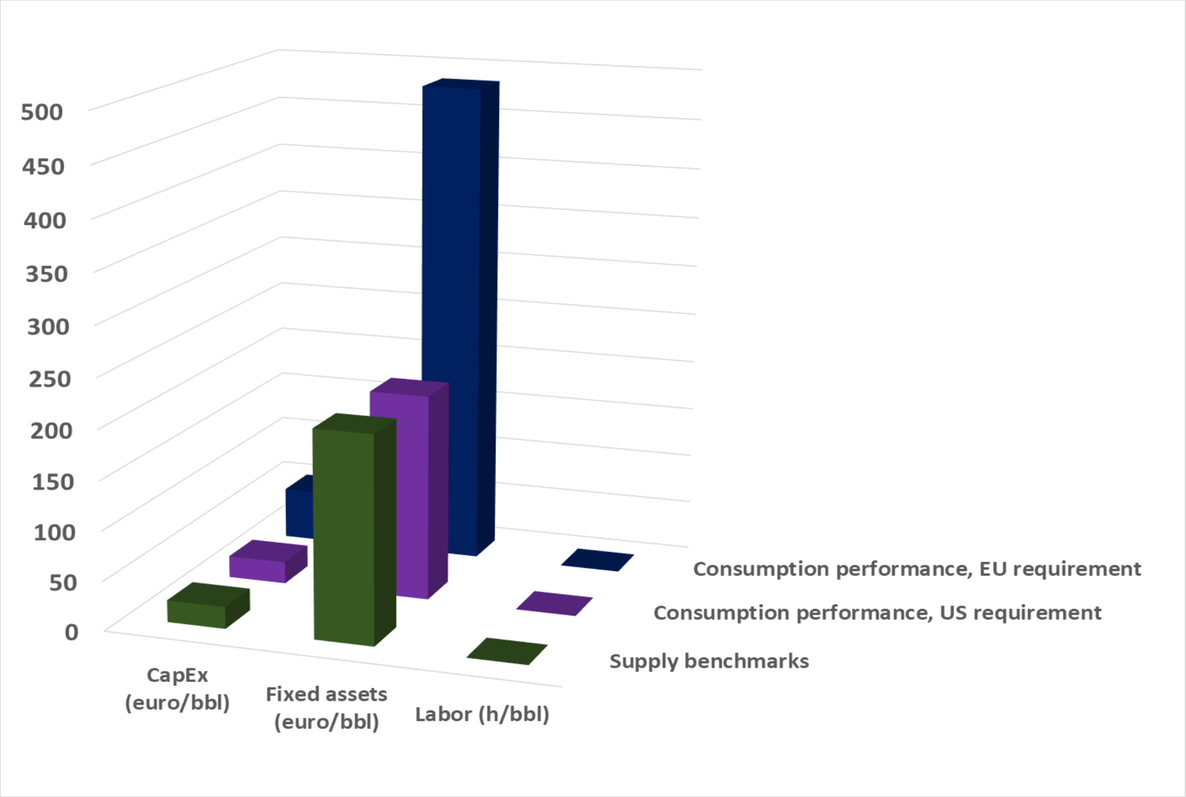

Fig. A39 Socio-economic performance (labor and capital investments) of an US and EU demand-driven enlargement of the global oil sector under the unconventional heavy coking supply pattern, to respectively match the requirement of other products and diesel, compared to supply benchmarks (baseline consumption)

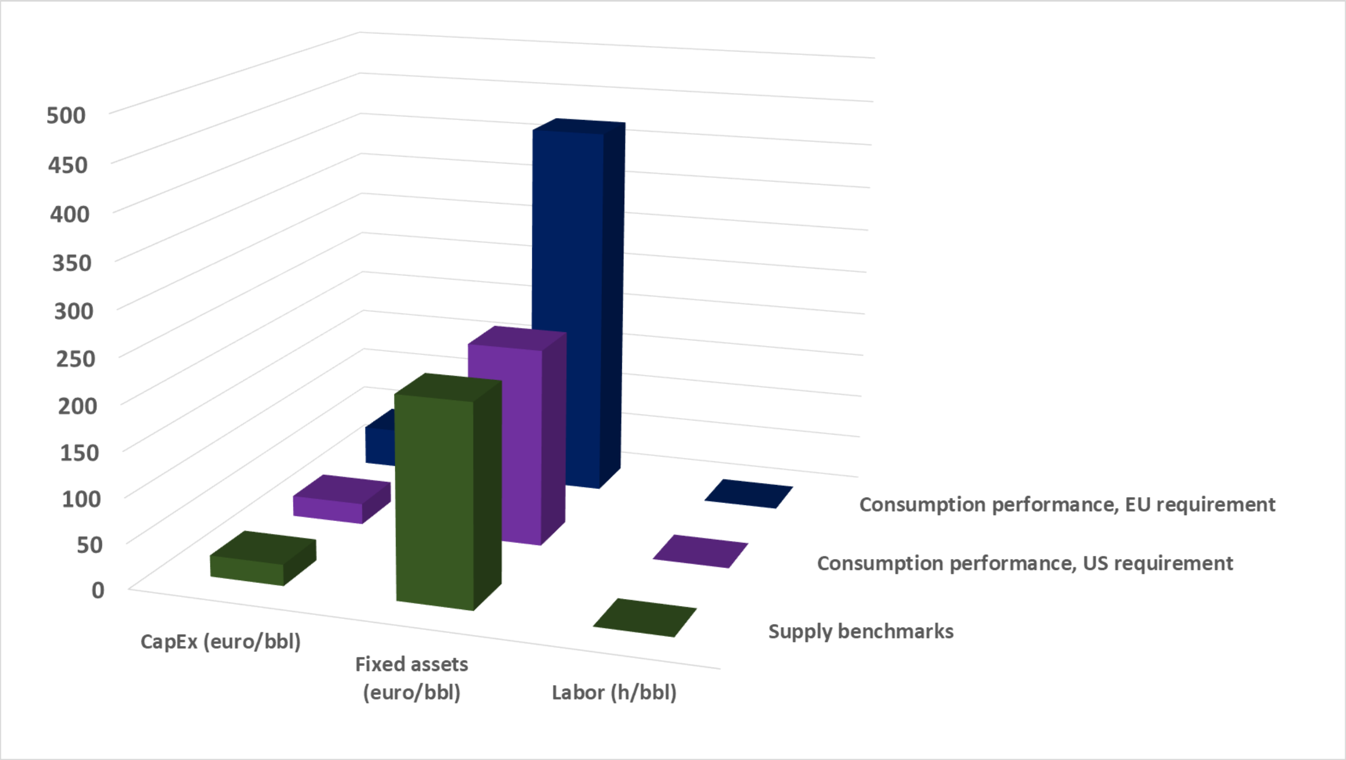

Fig. A40 Socio-economic performance (labor and capital investments) of an US and EU demand-driven enlargement of the global oil sector under the unconventional heavy hydrocracking supply pattern, to respectively match the requirement of other products and fuel oil, compared to supply benchmarks (baseline consumption)

A4.5.2.4 Special indicators

Flow-fund indicators can be used to assess the oil sector performance in relation to specific dimensions, useful to interested stakeholders. We report as explicative example: (i) the ratio between capex and fixed assets, that gives a rough measure of annual investments needed for the maintenance/upgrading of the technical capital – high in tight oil, due to the rapid economic cycle involved in its extraction (Wachtmeister and Höök, 2020); and (ii) the emission intensity of labor, that can complement the information from the Energy Metabolic Rates (EMRs, Fig. 3 of the main text) to have a rough measure of the typologies of technology employed –

using natural gas instead of diesel/coke will show different GHG emissions to perform the same functions.

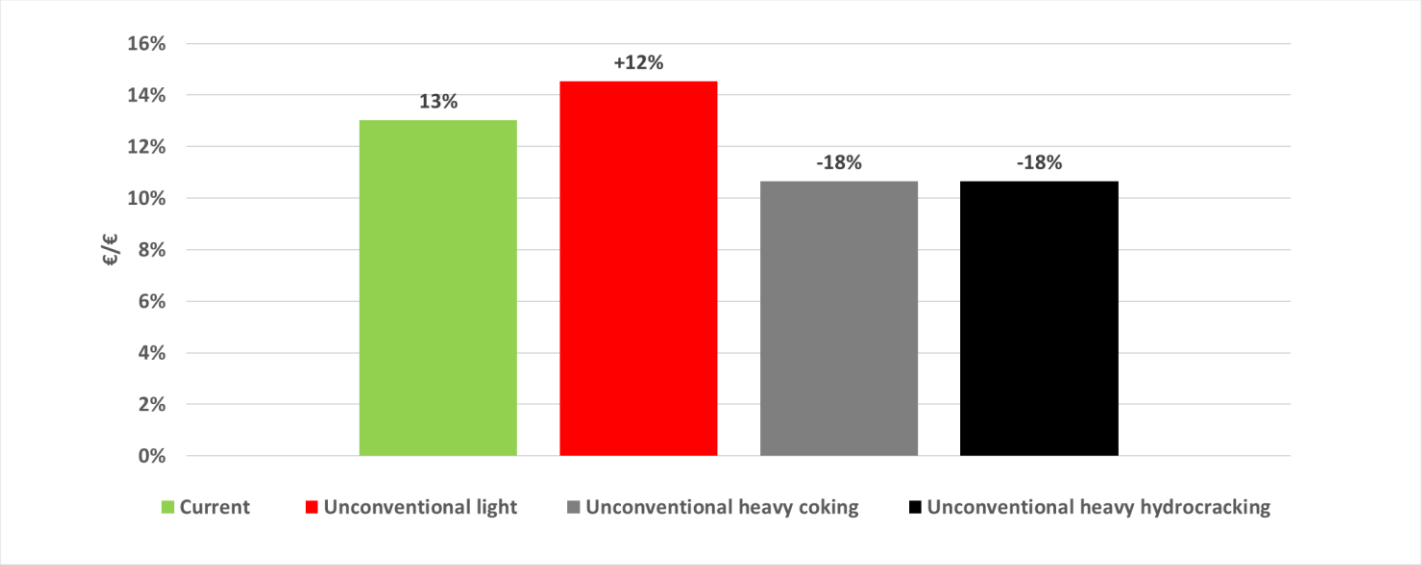

Fig. A41 Flow-fund indicators, capex/fixed assets

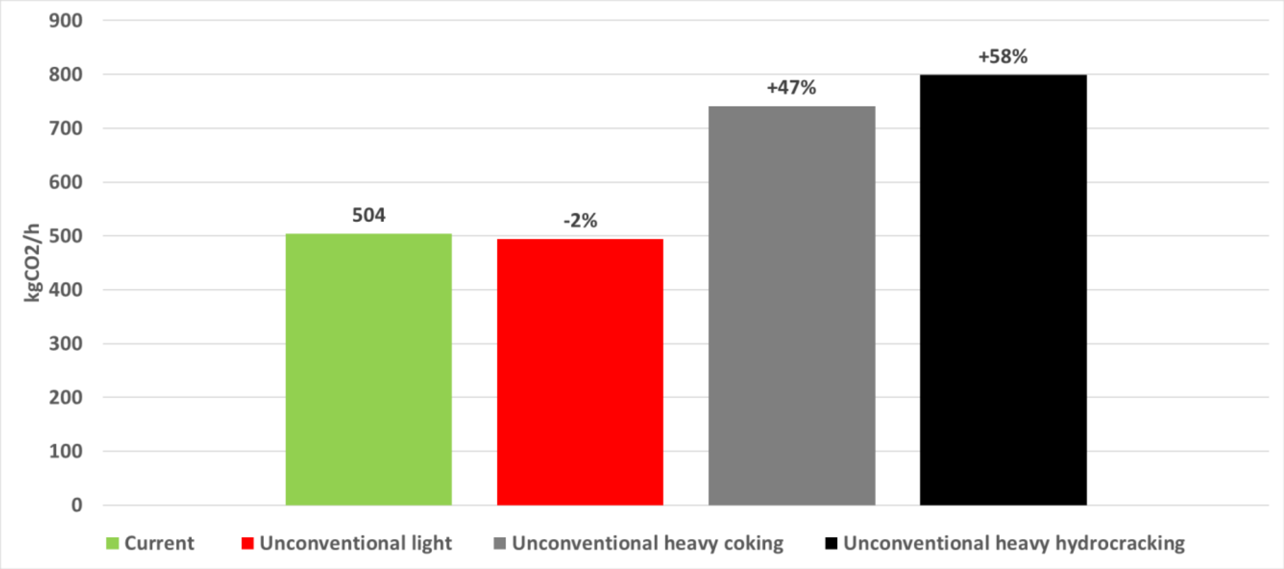

Fig. A42 Flow-fund indicators, GHG emission intensity of labor (kgCO$_2$/h)

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Collection of dissemination articles and essays

Publications

1. Manfroni, Bukkens and Giampietro. 2022. "**Securing Fuel Demand with Unconventional Oils: A Metabolic Perspective.**" Energy 261, 125256, https://doi.org/10.2139/ssrn.3965537

2. Manfroni, Bukkens and Giampietro. 2021. "**The Declining Performance of the Oil Sector: Implications for Global Climate Change Mitigation.**" *Applied Energy* 298: 117210. https://doi.org/10.1016/j.apenergy.2021.117210.

3. Manfroni et al. 2021. "**The Profile of Time Allocation in the Metabolic Pattern of Society: An Internal Biophysical Limit to Economic Growth.**" *Ecological Economics* 190: 107183. https://doi.org/10.1016/j.ecolecon.2021.107183

4. Giampietro et al. 2021. **Report on the Experience of Applications of the Nexus Structuring Space in Quantitative Storytelling**. MAGIC (H2020–GA 689669) Project Deliverable 4.4, revision (version 2.0). First published 30 August 2020, revised 25 January 2021.

Publications under review

5. Di Felice LJ, et al., "**Energy systems as holarchies: complexity and sustainability across scales".** *Energy, under review*

Ongoing works

6. Manfroni, 2022: **A smooth transition away from fossil fuels? Sociotechnical lock-in mechanisms across the EU oil metabolism**

7. Willerström, Manfroni, Wacthmeister and Höök, 2023**: Energy Crises: Risk or Chance?**

8. Willerström, Manfroni, Wacthmeister and Höök, 2023**: Explaining reserve growth: uniting contrasting perspectives from the Peak oil debate?**

Conferences, Workshops & Seminars

1. Participation in the **Energy Modelling Platform for Europe 2019 (EMP-E 2019), Modelling the implementation of A Clean Planet For All Strategy.** October 8 -9th, 2019,

European Commission, DG Research& Innovation, 21 rue du Champ de Mars – Marsveldstraat, 1050 Brussels

2. Oral presentation at the conference **ERSCP 2019 – Circular Europe for Sustainability: Design, Production and Consumption.** October 15-18th, 2019, Barcelona

3. **Invited expert to the International Workshop Extreme events and energy transitions: tackling the challenges of climate change by integrating social and complex systems science**. September 22-27th 2019, at the Joint Research Centre (JRC), Ispra site (Italy). Facilitator for the session on "Parallel exercises on multiscale integrated analysis of societal and ecosystem metabolism (MuSIASEM) performed at households, national and EU level"

4. **Invited speaker at the "Climate Change and Business Carbon Footprint" seminar**, Faculty of Petroleum & Mining Engineering, Geology and Environment (FIGMPA), Universidad Central de Ecuador (Quito). 13-23th December, 2021

5. **Invited Speaker by Federmanager & Confindustria Puglia** on the topic **Surfing the complexity of energy systems: a systemic perspective on the green transition.** March 16th, 2022 (online webinar)

6. Oral presentation **Surfing the oil hierarchy: a multiscale assessment of decarbonization pathways for the EU oil sector** at the **ICEE 2022 Conference. Energy & Environment: Bringing together Economics and Engineering – Technologies, Markets and Policies.** June 2-3rd, 2022, Porto, Portugal

7. Speaker at the **Auditing Metabolic Pattern Special Session, "Metabolic energy auditing to inform the transition away from fossil fuels"** of the **ESEE 2022, 14th Conference of the European Society for Ecological Economics. "Will Achilles catch up with the tortoise? It's high time for transformative action on sustainability".** June 14-17th 2022, Pisa, Italy

Dissemination pieces

1. Michele Manfroni 2022, **"Shale oil: shortages in the midst of abundance**". Essay protected by copyright.
2. Michele Manfroni, 2022, **"Waking up from the renewable dream: an increasingly carbon-intensive society",** https://www.rivistaenergia.it/2022/05/risvegliarsi-dal-sogno-rinnovabile-una-societa-sempre-piu-carbon-intensive/
3. Michele Manfroni, 2022, **"Waking up from the renewable dream: pillars and gaps in the green narrative"**, https://www.rivistaenergia.it/2022/05/risvegliarsi-dal-sogno-rinnovabile-pilastri-e-lacune-della-narrativa-verde/
4. Michele Manfroni, 2021, **"The cost of complexity: Soddy's prophecy and the acceptance of biophysical limits",** https://www.rivistaenergia.it/2021/12/il-costo-della-complessita-3-la-profezia-di-soddy-e-laccettazione-dei-limiti-biofisici/

5. Michele Manfroni, 2021, **“The cost of complexity: green rhetoric will not save us from today's and tomorrow's crises”**, https://www.rivistaenergia.it/2021/12/il-costo-della-complessita-2-la-retorica-verde-non-ci-salvera-dalle-crisi-di-oggi-e-domani
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7. Michele Manfroni, 2021, **“Energy cannibalism and the Red Queen effect: checkmate to decarbonization?”**, https://www.rivistaenergia.it/2021/10/cannibalismo-energetico-ed-effetto-regina-rossa-scacco-matto-alla-decarbonizzazione/
8. Michele Manfroni, 2021, **“The senescence of the oil sector”,** https://www.rivistaenergia.it/2021/04/la-senescenza-del-settore-petrolifero/
9. Michele Manfroni, 2021**, “Is techno-optimism the perfume of the ecological transition?”,** https://www.rivistaenergia.it/2021/03/il-tecno-ottimismo-e-il-profumo-della-transizione-ecologica/
10. Michele Manfroni, 2021, **“The Chinese “Dual Circulation Strategy”: a possible blow to the global climate agenda”,** https://www.rivistaenergia.it/2021/02/la-dual-circulation-strategy-cinese-un-possibile-brutto-colpo-per-lagenda-climatica-globale/

Final remarks

In the Ancient Greece, Science was understood as a contemplative activity: the purpose of "natural philosophers[34]" was to unravel the deep laws of Nature in order to live in harmony with the world. Nature was the eternal flowing background that, using the words of Heraclitus, "no man and no god made". It was the space within which the city, the habitable space for humans in practical and psychological terms, could be built and thrive; but only if citizens respected Nature's rules. Nature thus represented a bounded space for human action: ancient Greeks were deeply aware of being unavoidably part of the eternal cycle of Life and Death, and of being tragically mortals. Death was the ultimate Limit which gave the "right measure[35]" to the lives of men. There was nothing beyond this immanent world: they conceived themselves as one more species, not as the masters at the apex of Creation. Ancient Greek myths warned people that the laws of Nature, defined by the category of Necessity, constrain the space of action of human *tékhnē*, and that human *hubris* would lead to ruin.

"The just man is the one who internalizes his mortality. And starting from here he internalizes his limit. And from his limit his just measure." (Liberally translated by the author from Umberto Galimberti, Italian philosopher, during a speech).

The thoughts of Tim Jackson express similar arguments:

"As Aristotle pointed out in Nicomachean Ethics, the good life is not a relentless search for more, but a continual process of finding a "virtuous" balance between too little and too much. Capitalism not only fails to recognize the point where balance lies. It has absolutely no idea how to stop when it gets there" (Jackson, 2021).

Behind neoliberal capitalism, there is a pervasive and neglected anxiety about our mortality. "*Instead of addressing the underlying fear (lack of meaning (ed.), we*

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[34] Scientists are a modern conception: they do not contemplate, they force Nature to respond through experiments, trying to dominate it.

[35] From the ancient Greek *Katà Métron*, "*according to the right measure*", a fundamental virtue in the ancient Greek worldview.

turn for comfort to the things which make us feel good. Capitalism itself is a massive comfort blanket, designed to help us never confront the mortality that awaits us all" (ibid.). The only wise way to cope with the tragedy of our individual and collective transient condition is acceptance[36]. At the end of the day, we westerners are all desperately starving of meaning, not wealth. Accepting the tragedy of change means accepting the responsibility to contribute to create, and live for, something beyond us, wonderful and full of life and joy, to emerge from relativism and nihilism, something meta-stable at higher hierarchical levels, where the meaning of our lives subsume. And bearing the existential burden of the irremediable loss of the same structures of meaning in an eternal flowing process.

All living biological and eco-social organisms are shaped by their limits. Development and evolution, growth and senescence, stability and change are evolutionary strategies that complex systems developed to flourish despite their ultimate and unescapable death, made possible by the presence of constraints. In a universe free of constraints, where energy could flow liberally, equilibrium would be reached immediately; followed by total paralysis, and death. Limits create freedom, because they open up the space of possibilities for living organisms, hence an indeterminate future. And if the future is radically indeterminate, every decision is an instance of madness. For which me must assume risks and responsibility.

"All ecosystems involve "interactive flows of energy, matter, and information" (S. E. van der Leeuw, unpublished manuscript) […]. In infodynamics, information is defined in a very general sense as constraints on entropy production, that is, whatever configurations interrupt the flow […] of entropy from energy gradient dissipations are informational. Anything that might have been different is information, providing that it delays energy dissipation to the effect of dissipating it more completely." (Salthe, 2003).

Instead, we are going down deeper and deeper in the rabbit hole of Post Modernity, neglecting more and more the biophysical realities and generating the delirium of urban elites.

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[36] One may say that Complexity is insipid, if it weren't tragic

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