TRANSPORTE MARÍTIMO INTERNACIONAL E MITIGAÇÃO CLIMÁTICA SOB A ÓTICA DE MODELOS DE AVALIAÇÃO INTEGRADA

Eduardo Miranda Müller Drumond Casseres

Tese de Doutorado apresentada ao Programa de Pós-graduação em Planejamento Energético, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Doutor em Planejamento Energético.

Orientadores: Alexandre Salem Szklo
Roberto Schaeffer

Rio de Janeiro
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Do you ever look at someone and wonder "What is going on inside their head?"

Joy

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Não fazemos nada sozinhos. Este trabalho leva meu nome, mas obviamente segue a mesma lógica. É fruto das intermináveis trocas que definem nossa vida.

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TRANSPORTE MARÍTIMO INTERNACIONAL E MITIGAÇÃO CLIMÁTICA SOB A ÓTICA DE MODELOS DE AVALIAÇÃO INTEGRADA

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Junho/2023

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Modelos de Avaliação Integrada (IAMs) têm sido utilizados para produzir cenários de longo prazo das emissões globais de gases de efeito estufa. Por seu amplo escopo, esses modelos tipicamente incluem representações agregadas do sistema energético e de uso do solo. Diante do papel crucial de emissões residuais em cenários de mitigação profunda, um maior detalhamento de setores de difícil descarbonização vem se tornando prioridade para a comunidade de modelagem integrada. Nesse contexto, esta tese busca aprofundar a representação do transporte marítimo (~3% das emissões anuais de CO_2) em IAMs, de forma a melhor compreender seu papel num mundo de baixo carbono. Para tanto, o trabalho se estrutura em torno de quatro publicações de complexidade crescente, culminando na adição de um módulo de transporte marítimo internacional totalmente integrado ao COFFEE, um IAM global desenvolvido no Brasil. Com foco na modelagem da demanda e de potenciais combustíveis alternativos, esse esforço permite a elaboração de cenários de consumo energético do setor sob a perspectiva de orçamentos de carbono (ou seja, de forma compatível com trajetórias sistêmicas de descarbonização). Os resultados indicam um papel decisivo de combustíveis de base renovável na redução de emissões do setor marítimo internacional entre 2030 e 2070, com destaque para óleos vegetais, bioálcoois, amônia verde e biocombustíveis avançados.

Abstract of Thesis presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

INTERNATIONAL SHIPPING AND CLIMATE MITIGATION THROUGH THE LENS OF INTEGRATED ASSESSMENT MODELS

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Integrated Assessment Models (IAMs) have been used to produce long-term scenarios of global greenhouse gas emissions. Due to their broad scope, these models typically include aggregated representations of the energy and land use systems. Given the crucial role of residual emissions in deep mitigation scenarios, a more detailed representation of hard-to-abate sectors has become a priority for the integrated modelling community. In this context, this thesis aims at deepening the representation of maritime transportation (~3% of annual CO_2 emissions) in IAMs to better understand its role in a low-carbon world. To that end, the work is structured around four increasingly complex publications, culminating in the addition of a fully integrated international shipping module to COFFEE, a global IAM developed in Brazil. Focusing on the modelling of demand and potential alternative fuels, this effort enables the development of energy consumption scenarios for the sector from the perspective of global carbon budgets (i.e., in line with systemic decarbonization pathways). Results indicate a decisive role of renewable-based fuels in reducing emissions from international shipping between 2030 and 2070, with a particular emphasis on vegetable oils, bioalcohols, green ammonia and advanced biofuels.

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1. Introdução

Esta tese de doutorado examina o papel do transporte marítimo internacional em cenários de mitigação climática. Para tanto, o trabalho se estrutura em torno de quatro publicações científicas[1] produzidas entre 2020 e 2023, cada uma associada a um capítulo (2-5) da tese. Neste primeiro capítulo, depois de uma breve introdução de temas fundamentais (itens 1.1 a 1.3), apresentam-se conceitualmente os Modelos de Avaliação Integrada (IAMs), principais ferramentas da pesquisa desenvolvida (item 1.4). Em seguida, discutem-se o papel crucial dos setores de difícil descarbonização em cenários de baixo carbono (item 1.5) e o peso do transporte marítimo como um desses setores (item 1.6). Por fim, aborda-se a lacuna de literatura científica que motivou a escolha da linha de pesquisa em questão, e apontam-se os principais objetivos da modelagem realizada no âmbito dos quatro artigos.

1.1. Mudança global do clima

O termo "Mudança Global do Clima" (MGC) diz respeito à alteração climática de escala planetária que vem sendo causada por atividades humanas, principalmente desde o século 19 [1]. A causa dessa alteração é a emissão de grandes quantidades de Gases de Efeito Estufa (GEEs), cuja origem é bastante diversa [2]. Parte dessas emissões é absorvida pela biosfera, mas uma fração significativa permanece no ar, acarretando concentrações atmosféricas de GEEs atípicas em comparação com os registros das últimas épocas geológicas [3]. Devido a propriedades moleculares dos GEEs, essas concentrações extraordinariamente altas fazem com que a Terra retenha uma parte maior da energia recebida como radiação solar[2], o que se traduz por um aumento sensível da temperatura

[1] Lideradas pelo autor da tese.

[2] De forma mais precisa: a Terra recebe radiação energia do Sol sob a forma de ondas eletromagnéticas concentradas na faixa do visível. Os gases presentes na atmosfera terrestre são transparentes a esse comprimento de onda, permitindo que a energia chegue à litosfera e ao oceano. Após uma absorção parcial, a Terra reemite energia, também sob a forma de radiação, com a maior parte dessa emissão ocorrendo na faixa do infravermelho. GEEs têm a capacidade de absorver radiação infravermelha, impedindo que uma parte dessa energia retorne ao espaço. A MGC é fruto da intensificação desse fenômeno (efeito estufa) [375].

superficial média global[3] do planeta (aquecimento global) [4]. Estima-se que a anomalia de temperatura em relação ao período de referência[4] seja hoje[5] da ordem de 1,1ºC [1].

Pelo menos desde os anos 1950, a MGC é apontada como um risco para as sociedades humanas [5], [6]. A compreensão da magnitude e da qualidade desse risco evoluiu ao longo das décadas e, hoje, vê-se o colapso ecológico protagonizado pela MGC como um dos grandes desafios da humanidade no século 21 [7]–[9].

De acordo com a compilação mais recente do Grupo de Trabalho II do IPCC, a MGC tem ocasionado o aumento da frequência e da intensidade de eventos extremos, como precipitação e ondas de calor. Além disso, seus impactos vêm se fazendo sentir por alterações de natureza mais sistêmica e gradual, como acidificação oceânica, aumento do nível do mar e reduções regionais de precipitação. Observa-se ainda uma deterioração generalizada do funcionamento, resiliência e capacidade adaptativa dos ecossistemas, refletida, por exemplo, por eventos atípicos de mortandade terrestre e oceânica. A MGC vem prejudicando também a segurança alimentar global, em particular por seu impacto sobre a produtividade agrícola. Ademais, a MGC vem afetando negativamente a saúde da população mundial por meio de calor extremo, aumento da ocorrência de doenças de veiculação alimentar e hídrica, infecções gastrointestinais associadas a enchentes (e.g., cólera), crescimento dos casos de desconfortos cardiorrespiratórios e desafios de saúde mental (e.g., traumas ligados à vivência de eventos extremos). Em áreas urbanas, os impactos concentram-se sobre saúde, meios de subsistência e infraestrutura, especialmente em áreas marginalizadas. Efeitos adversos da MGC têm sido identificados também em diversos setores da economia (e.g., agricultura, silvicultura, pesca, energia e

[3] Trata-se aqui da temperatura superficial média global (GMST, do inglês *Global Mean Surface Temperature*) [376].

[4] O período de referência em relação ao qual a anomalia é calculada é aquele compreendido entre 1850 e 1900 [2]. No contexto do IPCC, o termo “pré-industrial” é utilizado, a título de simplificação, como correspondente ao período 1850-1900. Esse intervalo de meio século é usado como linha de base da temperatura do planeta antes da interferência humana.

[5] Por “hoje”, entende-se, na verdade, o período compreendido entre 2010 e 2019 [1].

turismo). Além disso, alguns eventos extremos, como ciclones tropicais, reduzem o crescimento econômico em curto prazo. Prejuízos à equidade de gênero e social também têm sido registrados. Finalmente, a MGC vem agravando crises humanitárias e provocando migrações em todo o planeta [10].

Além de listar os principais efeitos já observados da MGC, o Grupo de Trabalho II do IPCC analisa os riscos da provável intensificação do aquecimento global em curto e médio/longo prazo. A Tabela 1 resume esses riscos, associados respectivamente aos períodos 2021-2040 e 2041-2100 [10].

Tabela 1 – Riscos associados à intensificação do aquecimento global

Curto prazo (2021-2040)	**Médio/longo prazo (2041-2100)**
Resumo: Um aquecimento de 1,5ºC traria um aumento de riscos imediatos para ecossistemas e seres humanos. O nível de tais riscos depende das tendências de vulnerabilidade, desenvolvimento e adaptação. Ações de curto prazo que limitem o aquecimento a 1,5ºC podem reduzir substancialmente perdas e danos causadas pela MGC.	**Resumo:** Para além de 2040, os riscos associados à MGC dependem do nível de aquecimento alcançado. De acordo com a quantificação de 127 riscos-chave, os impactos projetados são várias vezes superiores àqueles já observados. A magnitude dos riscos depende de ações de adaptação e mitigação em curto prazo. Há uma escalada de potenciais impactos adversos para cada incremento na temperatura média global.
Exemplos: • Aumento adicional da frequência, severidade e duração de eventos extremos, com altos riscos de perda de biodiversidade. • Aceleração da subida do nível do mar, comprometendo assentamentos e ecossistemas costeiros. • Agravamento dos desafios associados a energia e recursos hídricos em áreas urbanas. • Ultrapassagem do limiar de diversos impactos generalizados e irreversíveis na transição de 1,5ºC para 2,0ºC.	**Exemplos:** • Risco de extinção de 3 a 48% das espécies terrestres, a depender do nível de aquecimento (2-5ºC). • Impactos de enchentes entre 1,4 e 3,9 maiores em comparação com aqueles de um mundo de 1,5ºC, a depender do nível de aquecimento (2-3ºC). • Aumento da pressão sobre a produção de alimentos, impactando ainda mais a segurança alimentar de regiões vulneráveis. • Maior ocorrência de doenças e aumento do número de mortes prematuras globalmente. • Ameaça existencial para diversas pequenas ilhas pela subida do nível do mar.

Dados: [10]

1.2. Acordo de Paris

Apesar de ter sido marginalmente abordada na Conferência de Estocolmo de 1972 [11], foi apenas no final dos anos 1980 que a MGC se tornou objeto proeminente do debate público sobre meio ambiente, especialmente a partir da criação do IPCC, em 1988 [12].

Em 1992, de posse do Primeiro Relatório de Avaliação do IPCC [13], as Nações Unidas convocaram a Conferência do Rio de Janeiro (Rio 92), que foi marcada pelo estabelecimento da Convenção-Quadro das Nações Unidas sobre a Mudança do Clima (UNFCCC, do inglês *United Nations Framework Convention on Climate Change*) [14].

Naquele momento, o objetivo da UNFCCC era, de acordo com a sua própria formulação, "estabilizar as concentrações atmosféricas de GEEs em um nível que pudesse evitar interferência antropogênica no sistema climático" [11]. Desde então, a convenção tem servido como principal referência institucional em termos de mitigação da MGC. Sua implementação é atualizada anualmente na chamada Conferência das Partes (COP), em que discussões e negociações entre países dão origem a metas e ações climáticas. Entre as 27 edições da COP, duas se destacaram por resultados mais marcantes. Em 1997, na COP3, formulou-se o Protocolo de Quioto, segundo o qual os países mais industrializados reduziriam suas emissões combinadas em pelos menos 5% até 2012 em comparação com os níveis de 1990. Embora tenha sido apenas parcialmente bem-sucedido, o Protocolo de Quioto representou a primeira ação concreta de mitigação da MGC em âmbito global [11], [15].

Em 2015, depois de muitos anos de progressos mais modestos, um novo marco foi alcançado na COP21 com o Acordo de Paris, considerado o primeiro consenso global a respeito do tema por ter sido adotado por quase todos os países do mundo, cobrindo mais de 98% das emissões mundiais de GEEs. O acordo tem como principal objetivo a manutenção da anomalia da temperatura média global bem abaixo dos 2ºC, buscando esforços para limitá-la a 1,5ºC [16].

O Acordo de Paris se baseia nas chamadas Contribuições Nacionalmente Determinadas (NDCs, do inglês *Nationally Determined Contributions*), planos nacionais voluntários de redução de emissões de GEEs que devem ser atualizados a cada cinco anos. A NDC brasileira original, por exemplo, incluía metas de erradicação do desmatamento, aumento da participação de biocombustíveis na matriz energética e redução das emissões associadas à agricultura [17].

Caso integralmente cumpridas, as atuais NDCs poderiam produzir uma trajetória de emissões compatível com um mundo ligeiramente abaixo de 2ºC [18]. Particularmente, os compromissos firmados na COP26 (Glasgow) indicam um aquecimento limitado à faixa 1,6-1,8ºC [19]. Uma trajetória de emissões mais próxima de 1,5ºC exigiria um rápido aprofundamento das atuais ambições [20], [21].

1.3. Emissões de gases de efeito estufa

Conforme explicado, a MGC é consequência de concentrações elevadas de GEEs na atmosfera terrestre, por sua vez causadas pela emissão desses gases por atividades humanas (Figura 1). A Figura 2 mostra as mais recentes estimativas do IPCC para a contribuição de componentes individuais para o aquecimento observado no período 2010-2019. O dióxido de carbono (CO_2) se destaca como principal GEE[6], respondendo por um efeito de +0,79ºC sobre a temperatura média global.

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[6] No contexto da MGC, o dióxido de carbono (CO_2) é o principal gás de efeito estufa. Esse gás faz parte de um contexto mais amplo de trânsito cíclico de átomos de carbono entre atmosfera, biosfera e litosfera (incluindo oceanos). Em condições normais, o chamado ciclo do carbono mantém a concentração atmosférica de CO_2 entre 170 e 300 ppm [377]. Desde o século 19, emissões antropogênicas de CO_2 têm conferido uma nova dinâmica a esse processo, incrementando a taxa de transferência de carbono da litosfera para atmosfera, o que ocorre principalmente por meio da produção e queima de combustíveis fósseis [2]. Ao contrário dos outros GEEs, o CO_2 possui longa vida média, aquecendo o planeta por um período entre 300 e 1.000 anos [377]. Essa longa vida média vem favorecendo o acúmulo de CO_2 na atmosfera e, hoje, sua concentração está em torno de 415 ppm, 48% acima da média da Era Comum. De acordo com os achados mais recentes da paleoclimatologia, trata-se da concentração atmosférica mais elevada em pelo menos 800 mil anos [1]. A contribuição do metano é a segunda mais significativa, em torno de +0,51ºC. Outros GEEs, como o óxido nitroso (N_2O) e os gases halogenados, têm efeitos de menor magnitude, ainda que relevantes. Já os aerossóis, formados a partir de moléculas como o SO_2, produzem um efeito de resfriamento, que mascara parcialmente o aquecimento associado aos GEEs [1].

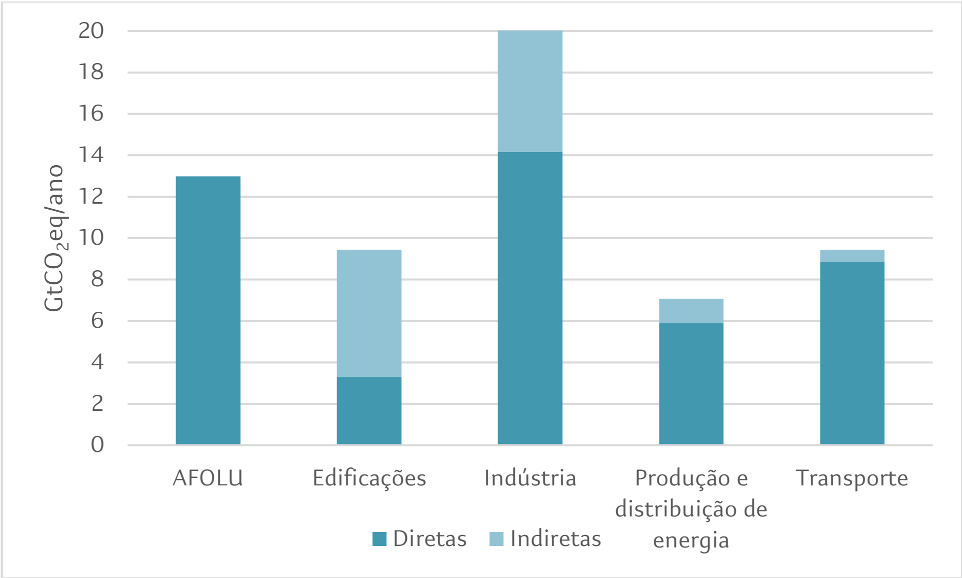

Figura 1: Emissões anuais de GEEs por setor em 2019

Nota: Dados reportados em termos de CO_2 equivalente. O setor de AFOLU responde atualmente por cerca de um quinto (22% em 2019) das emissões antropogênicas de GEEs, com destaque para CO_2 LULUCF (desmatamento) e CH_4 emitido por fermentação entérica e cultivo de arroz. No caso do setor de edificações (16% do total de GEE emitido em 2019), o peso das emissões indiretas é muito grande (cerca de dois terços), o que se deve principalmente à demanda residencial por eletricidade e calor. Já a indústria, além de emissões indiretas, contribui fortemente com emissões diretas de GEEs, originadas, por exemplo, nos setores cimenteiro e siderúrgico. Mais de um terço (34% em 2019) da emissão anual de GEEs vem desse setor, o mais relevante entre os cinco. A produção de energia (principalmente a explotação e o refinamento de combustíveis fósseis) emite 12% (valor de 2019) do CO_2eq anual, com uma pequena fração desse total advinda de seu autoconsumo. Finalmente, o transporte, principal destino dos derivados do petróleo, tem um peso total (15% em 2019) comparável ao do setor de edificações. Devido à sua estrutura baseada em combustíveis líquidos (com baixíssimo uso de eletricidade), quase todas as emissões do setor são classificadas como diretas. Fonte: elaboração própria. Dados: [22]

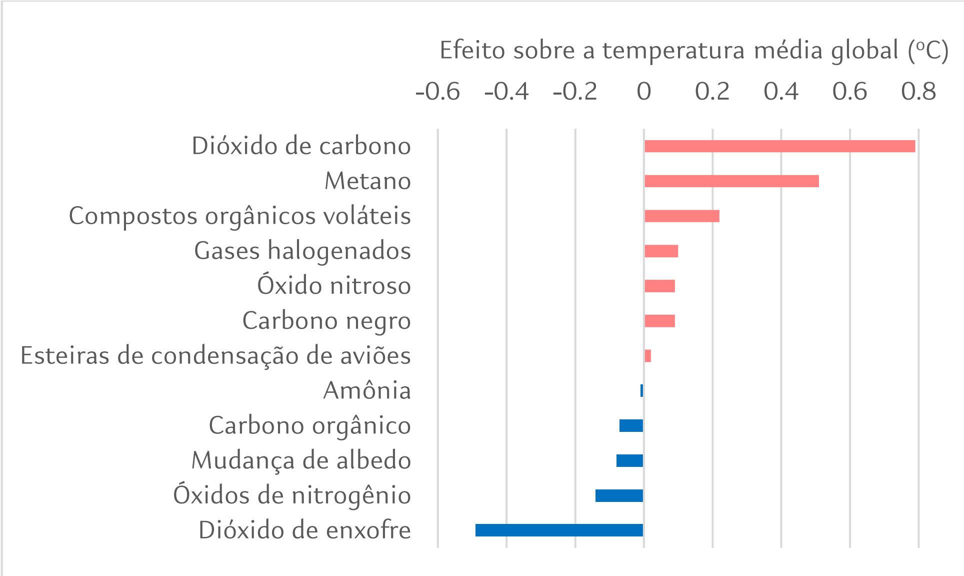

Figura 2: Contribuição de componentes individuais para o aquecimento global

Nota: Melhores estimativas disponíveis para a contribuição de componentes individuais de influência humana para a anomalia de temperatura observada no período 2010-2019 em relação ao período de referência (1850-1900). Fonte: elaboração própria. Dados: [1]

O fato de o CO_2 permanecer na atmosfera por um tempo muito superior ao horizonte de planejamento das sociedades humanas faz com que, sob a perspectiva da MGC, considere-se que o gás, uma vez emitido[7], incrementa o estoque de carbono por tempo indeterminado. Ou seja, para todos os efeitos, enquanto as emissões líquidas de origem antropogênica forem positivas, o estoque atmosférico de CO_2 só poderá aumentar [23].

Essa particularidade deu origem à ideia de orçamento de carbono, um conceito central em termos de política climática nos últimos 15 anos [24], [25]. Orçamentos de carbono procuram refletir a relação entre limites desejáveis de aquecimento global e a quantidade total de CO_2 emitida por atividades humanas desde o século 19. Tendo em vista a relação praticamente linear entre concentração de CO_2 na atmosfera terrestre e nível de aquecimento global em longo prazo [1], [26], estabilizar a temperatura média em dado patamar implica emitir, no máximo, um certo montante de CO_2. Embora tenha limitações

[7] Cabe ressaltar que uma parte das emissões antropogênicas de CO_2 é absorvida pela biosfera e pelos oceanos [1].

e envolva incertezas (como o papel de outros GEEs), essa abordagem tem se mostrado útil à ciência de mitigação climática, especialmente quando combinada à análise baseada em cenários [20], [21], [23], [27]–[30].

A Figura 3 mostra as melhores estimativas disponíveis para os orçamentos de carbono associados a 1,1ºC (atual nível de aquecimento), 1,5ºC e 2ºC (níveis tomados como referência desde o Acordo de Paris). Entre 1850 e 2021, o mundo emitiu cerca de 2.500 $GtCO_2$, acarretando um aquecimento de 1,1ºC. Para se limitar o aumento da temperatura superficial média global a 1,5ºC com 50% de probabilidade, o orçamento total é de 2.900 $GtCO_2$, o que implica um orçamento remanescente de 400 $GtCO_2$ a partir de 2022 (~14% do total). No caso de um limite de 2ºC com 66% de probabilidade[8], o orçamento total é de 3.600 $GtCO_2$ e o orçamento a partir de 2022, 1.100 $GtCO_2$ (~30% do total). A comparação dos orçamentos de carbono de 1,5ºC e 2ºC com o montante de CO_2 emitido desde 1850 evidencia a proximidade desses limites de temperatura: caso as emissões anuais de CO_2 se mantenham constantes a partir de 2022, o orçamento de 1,5ºC será esgotado em cerca de dez anos [2], [21].

[8] A escolha do nível de probabilidade de 66% corresponde a uma interpretação não oficial do termo "*well below 2ºC*" (advindo do Acordo de Paris).

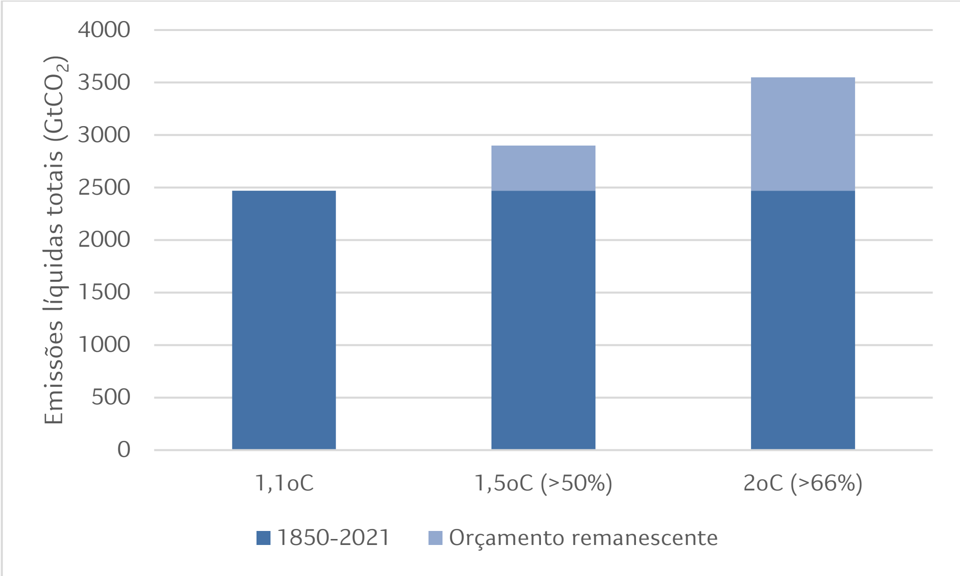

Figura 3: Orçamento de carbono para três diferentes patamares de temperatura média global

Fonte: elaboração própria. Dados: [2]

1.4. Modelos de avaliação integrada

Conforme abordado no item 1.1, A MGC se tornou um tópico cientificamente relevante na segunda metade do século 20, o que suscitou o desenvolvimento de uma governança global em torno do tema. Paralelamente, pesquisadores das áreas de ciências da natureza, economia e engenharia começaram a se debruçar sobre as possíveis trajetórias futuras de emissões de GEEs e sua relação com o aquecimento do planeta. Motivadas pela demanda por informação qualificada advinda das esferas políticas (como a UNFCCC), essas iniciativas produziram um novo campo científico cujo objetivo seria compreender as conexões entre a sociedade humana, a biosfera e o sistema climático, com foco numa abordagem quantitativa. Um aspecto central desse movimento foi o desenvolvimento dos chamados Modelos de Avaliação Integrada (IAMs, do inglês *Integrated Assessment Models*), ferramentas computacionais desenhadas para modelar matematicamente atividades humanas e sua interface com o meio ambiente em escala global [31], [32].

Embora o surgimento da modelagem global remonte às décadas de 1970 e 1980 (com modelos como World3[9], MARKAL[10] e RAINS[11]), foi apenas nos anos 1990 que a questão da MGC se tornou o foco dos IAMs, um processo que se confunde com a própria história do IPCC [31].

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[9] A maior parte dos IAMs surgiu nos anos 1990. No entanto, sua origem remonta à década de 1970, período durante o qual a consciência científica acerca da degradação ambiental expandiu-se para além da poluição local, passando a considerar o meio ambiente global, em seu conjunto, como objeto de estudo [31]. O principal marco dessa expansão de escopo foi a publicação do livro "Os Limites do Crescimento", patrocinado pelo Clube de Roma. Esse trabalho, desenvolvido por uma equipe de pesquisa do Instituto de Tecnologia de Massachussetts (MIT), concluiu que, mantendo-se as tendências populacionais e o ritmo de consumo de recursos observado à época, os limites biofísicos do crescimento econômico seriam alcançados em não mais que cem anos, o que provavelmente acarretaria declínio populacional e industrial [378]. As conclusões de "Os Limites do Crescimento" basearam-se no World3, um modelo computacional que representava a interação entre o crescimento demográfico, os sistemas alimentar e industrial, os estoques de recursos não renováveis e a poluição. Apesar de ter sido alvo de críticas por sua estrutura relativamente simples, é consenso no meio científico que o World3 representou uma mudança de paradigma: embora não tenha sido chamado de IAM, o modelo foi pioneiro na utilização da ciência da computação para simular a evolução, em longo prazo e escala planetária, de aspectos do desenvolvimento humano e do meio ambiente [31], [379], [380]. Conforme será discutido à frente, essa é a característica que define os atuais IAMs.

[10] Com o primeiro choque do petróleo, iniciado em 1973 [381], teve início uma preocupação global acerca da disponibilidade dos recursos energéticos fósseis. Isso suscitou o surgimento de inúmeras instituições e projetos voltados para a segurança energética ao redor do mundo. Nesse contexto, logo se percebeu que as simulações computacionais poderiam ser úteis, o que engendrou o advento da modelagem técnico-econômica do setor de energia, tendo o modelo britânico MARKAL [382] como maior símbolo.

[11] Um dos primeiros exemplos de aplicações práticas de IAMs foi seu uso para modelar o fenômeno da chuva ácida, inicialmente apontado como um problema pelo governo sueco, na Conferência de Estocolmo. Ao se compreender que a chuva ácida era decorrente das emissões de compostos sulfurados no continente europeu, logo surgiu a necessidade de definição de metas de redução dessas emissões com alguma base científica [383]–[385]. Nesse contexto, o IIASA começou a desenvolver, em 1984, o modelo *Regional Acidification Information and Simulation* (RAINS), que, em poucos anos, se tornou a principal ferramenta de suporte ao tratado europeu sobre o assunto (LRTAP, do inglês *Long-Range Transboundary Air Pollution*). O RAINS é visto como um dos modelos de maior sucesso da história na interface com as políticas públicas, uma vez que foi usado explicitamente para definir metas europeias de redução de emissões de enxofre [31], [386]. É seguro dizer que o RAINS constituiu uma fonte de inspiração considerável para os IAMs climáticos que apareceriam em seguida [31].

Após a Rio 92, houve uma onda de desenvolvimento de cenários de emissões de GEEs baseados em IAMs [33]. Apesar da baixa maturidade científica da modelagem integrada, o IPCC rapidamente adotou essa abordagem como uma referência, tomando os IAMs como a ferramenta ideal para o estudo da relação entre aquecimento global, economia e políticas públicas [32]. A influência do novo campo científico se fez sentir já no Protocolo de Quioto (1997) e se consolidou na virada para o século 21, com a publicação de um relatório do IPCC focado em cenários de longo prazo produzidos por IAMs [31]–[34].

A partir desse ponto, a modelagem global com foco em mitigação climática se estabeleceu definitivamente como uma área de pesquisa à parte. Desde então, os IAMs vêm crescendo em número e complexidade, enquanto seus cenários vêm servindo como ilustração dos possíveis futuros das emissões antropogênicas de GEEs. Esse conhecimento tem cumprido um papel importante na definição de metas e ambições na esfera política. O exemplo mais evidente é a influência dos cenários do Quinto Relatório de Avaliação do IPCC (AR5) sobre a formulação do Acordo de Paris [31].

Um IAM é um programa computacional que modela uma parte ou a totalidade do sistema econômico global, com foco nas emissões de GEEs. Como essas emissões estão ligadas às mais diversas atividades humanas (Figura 1), o modelo deve conter algum tipo de representação de cada uma (ou ao menos da maior parte) dessas atividades. Respondendo pelo grosso das emissões globais de GEEs, o sistema energético é inevitavelmente a espinha dorsal de todo IAM. Assim, esses modelos geralmente incluem uma representação dos diferentes recursos energéticos (e.g., curvas de custo de extração de petróleo, curvas de potencial eólico e solar), bem como dos conversores energéticos intermediários e finais (e.g., destilarias, refinarias, usinas geradoras de eletricidade, processos industriais, frotas veiculares, residências) [20], [21], [35]–[41]. A fim de cobrir a totalidade das emissões de GEEs, alguns IAMs incluem ainda uma representação detalhada do sistema de agricultura e uso do solo (origem de cerca de um quinto das emissões - Figura 1) [20], [42]–[47].

Em relação a estrutura e método de solução, IAMs são bastante heterogêneos [48], mas sua formulação tipicamente reflete o objetivo de prover informações úteis ao desenho de políticas climáticas. Em IAMs modernos, é particularmente importante a lógica de orçamentos de carbono (item 1.3) como restrição da trajetória futura de emissões de GEEs, uma abordagem que dialoga de maneira direta com limites específicos de aquecimento [27], [31], [35], [40], [49], [50].

Hoje, os IAMs são utilizados primordialmente para traçar cenários de emissões de GEEs e, por conseguinte, de variação da temperatura média global. Seu horizonte temporal é o médio e longo prazo, sendo os anos de 2030, 2040, 2050 e 2100 os marcos comumente adotados [2], [48]. De forma geral, os IAMs de escopo mundial procuram responder ao seguinte par de questões:

- **Q1**: "Para se limitar o aquecimento global a determinado patamar, com dado grau de confiança, que trajetória de emissões anuais de GEEs deveria ocorrer entre 2020 e 2100?"
- **Q2**: "Levando-se em conta restrições tecnológicas, econômicas, demográficas e socioambientais, que transformações poderiam ocorrer nos sistemas globais de energia, agricultura e uso do solo para que se pudesse seguir essa trajetória de emissões?"

Apesar de a formulação da pergunta Q1 ter caráter genérico ("determinado patamar"), na prática, os IAMs têm tido as metas de Paris (item 1.2) como referência. Assim, os patamares em questão frequentemente se resumem aos limites de 1,5ºC e 2ºC, com boa parte da literatura se concentrando em cenários associados a esses dois níveis de aquecimento [36]. Particularmente, trajetórias de 1,5ºC foram objeto de um relatório especial do IPCC, em 2018 [50].

1.5. Setores de difícil de descarbonização

Em cenários produzidos por IAMs, o grau e a velocidade de descarbonização da economia global são função da disponibilidade de opções de mitigação, de seu custo e principalmente da magnitude da restrição imposta às emissões cumulativas de CO_2 ao longo do período considerado (i.e., do orçamento de carbono) [21]. Naturalmente, os possíveis caminhos de mitigação variam de setor para setor, e a própria natureza dos serviços energéticos envolvidos implica maior ou menor dificuldade de transposição de barreiras técnico-econômicas. Cenários têm indicado, por exemplo, que emissões de CO_2 ligadas à mobilidade urbana e ao conforto térmico residencial podem ser abatidas com relativa facilidade até 2050 usando tecnologias já maduras e escaláveis [21], [36], [39], [51]–[56].

Por outro lado, cerca de um terço das emissões globais anuais de CO_2 tem origem em setores cuja especificidade traz desafios adicionais, como a inexistência de opções de mitigação que combinem elevado potencial, boa prontidão tecnológica e custo razoável[12]. Esses setores de difícil descarbonização (*hard-to-abate sectors*, na literatura internacional) representam hoje cerca de 11 $GtCO_2$/ano e incluem uma fração da produção de eletricidade, da indústria pesada e dos transportes[13] [53], [57], [58].

No caso da produção de eletricidade, o desafio vem da necessidade de flexibilidade para acompanhamento da carga. Para se garantir energia elétrica confiável, é necessário contar com um sistema de geração capaz de responder às crescentes variações diárias de demanda. Em âmbito global, essa modulação é provida principalmente por usinas a gás natural, cujo baixo tempo de *ramp-up* permite suprir picos de demanda. A substituição desse uso da energia fóssil não é trivial, especialmente em uma matriz elétrica cada vez mais dependente de fontes intermitentes [59]. Por isso, embora a maior parte das emissões de CO_2 da geração elétrica não pertença ao grupo *hard-to-abate*, o alto custo de capital das tecnologias de armazenamento de energia [60] (que possibilitariam um sistema flexível inteiramente baseado em fontes renováveis) faz com que ao menos 30% dessas emissões possam ser assim categorizadas [53].

Já na indústria, emissões *hard-to-abate* estão presentes principalmente nos setores cimenteiro e siderúrgico que, juntos, respondem por cerca de 5 $GtCO_2$/ano. Além de grandes consumidoras de energia térmica fóssil (emitindo, portanto, CO_2 associado a serviços energéticos), essas indústrias se baseiam em reações químicas que têm o dióxido

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[12] No caso dos transportes aéreo e marítimo, há ainda a dificuldade de atribuição de responsabilidade sobre as emissões [98].

[13] Expandindo-se a análise para além do CO_2, pode-se considerar também a agricultura como *hard-to-abate*, já que esse setor responde por emissões de difícil abatimento de metano e óxido nitroso [54].

de carbono como produto, a redução do minério de ferro usando carvão metalúrgico e a calcinação do calcário para formar clínquer. A presença dessas emissões não energéticas de CO_2 faz com que níveis profundos de descarbonização dos setores cimenteiro e siderúrgico exijam uma completa reestruturação dessas indústrias [53], [61].

Transporte rodoviário de longa distância, aviação e navegação completam o grupo de emissões de difícil descarbonização, respondendo por quase 2,5 $GtCO_2$/ano [53], [55], [62], [63]. Atualmente, esses meios de transporte são movidos por derivados de petróleo de elevada densidade energética volumétrica, o que lhes confere uma considerável autonomia. Ao contrário do que ocorre com o transporte urbano de passageiros, a substituição desses produtos (diesel, querosene de aviação – QAv, e bunker marítimo[14]) por eletricidade de base renovável não é factível diante das atuais perspectivas tecnológicas, especialmente no caso de aeronaves e embarcações [64]–[67]. Mesmo o hidrogênio verde[15], que poderia ser visto como um vetor energético capaz de promover uma "eletrificação indireta" desses setores, enfrenta uma série de restrições técnicas (incluindo densidade energética) que praticamente inviabilizam seu uso direto em larga escala na aviação e na navegação[16] [68], [69].

Em cenários de mitigação, IAMs tipicamente indicam uma sobrevivência de emissões de CO_2 em setores *hard-to-abate*, mesmo com orçamentos de carbono bastante restritivos (e.g., 400-600 $GtCO_2$) [20], [21], [39]. Em geral, essas emissões residuais são compensadas por estratégias de Remoção de Dióxido de Carbono (CDR, do inglês

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[14] O termo "bunker" pode se referir a combustíveis marítimos em geral ou, mais especificamente, àqueles constituídos por frações pesadas do petróleo. Ao longo da tese, utiliza-se o termo "bunker" como sinônimo de Óleo Combustível Pesado - HFO (*Heavy Fuel Oil*).

[15] Aqui, adota-se a convenção amplamente difundida na literatura recente segundo a qual o hidrogênio verde corresponde àquele produzido por meio de eletrólise a partir de fontes renováveis [387].

[16] Por outro lado, há a possibilidade de uso do hidrogênio para produção de amônia e combustíveis sintéticos (e.g., eletrodiesel, eletrometanol) [121].

Carbon Dioxide Removal)[17]. Esse resultado se deve a critérios internos de custo-efetividade dos IAMs, segundo os quais seria vantajoso produzir emissões negativas em vez de levar as emissões positivas residuais a zero [21]. Ocorre que, devido ao extenso escopo da modelagem integrada, IAMs frequentemente possuem uma representação pouco detalhada de setores de difícil descarbonização, o que poderia levá-los a subestimar seu real potencial de mitigação. Diante dessa relação direta entre emissões residuais e CDR, nos últimos anos, o interesse da comunidade de modelagem integrada tem se voltado para uma representação mais acurada de emissões *hard-to-abate* e do potencial de mitigação a elas associado [20], [21], [66], [70]–[73]. Esta tese de doutorado é fruto desse contexto, em um esforço especificamente direcionado para o setor de transporte marítimo.

1.6. Transporte marítimo internacional

Com uma história que remonta a pelo menos 50 mil anos atrás, o transporte marítimo teve papel central no desenvolvimento comercial e militar das sociedades humanas [74]–[82]. No contexto da Revolução Agrícola (a partir de ~9.000 AEC), embarcações passaram por uma primeira transição energética, em que a vela substituiu o músculo humano como motor primário da navegação de longa distância. Isso possibilitou a formação de redes mercantes complexas já na Antiguidade e, mais tarde, criou as condições para a formação de impérios coloniais de extensão mundial [75], [78], [83]. Com a consolidação da tecnologia a vapor no século 19, o transporte marítimo passou por uma nova transição, encontrando no carvão mineral uma confiável e eficiente fonte de energia propulsiva. Aliada a inovações como cascos de aço e redes telegráficas, essa transição aumentou a velocidade média das embarcações e proporcionou ganhos de escala sem precedentes, criando as bases de uma indústria marítima global [74], [78], [79]. Um novo salto de eficiência ocorreu a partir do começo do século 20, quando a maturação da indústria do

[17] Um exemplo de CDR natural é o florestamento. Alguns exemplos de CDR baseado em tecnologia são: Bioenergia com Captura e Armazenamento de Carbono (BECCS, do inglês *Bioenergy with Carbon Capture and Storage*), Captura Direta do Ar com Armazenamento de Carbono (DACCS, do inglês *Direct Air Capture with Carbon Storage*) e Intemperismo Melhorado (EW, do inglês *Enhanced Weathering*) [388].

petróleo e da combustão interna tornou evidentes as vantagens do uso de hidrocarbonetos líquidos como combustíveis marítimos[18] [78], [84], [85]. Sucessivas inovações técnicas ao longo do século[19] reduziram drasticamente os custos de frete marítimo, criando as condições para um crescimento exponencial do mercado global de commodities e, mais tarde, para uma revolução do transporte de carga geral[20]. Na virada para o século 21, o comércio marítimo internacional movimentava 6 milhões de toneladas de carga por ano (crescimento de ~900% em relação a 1950), incluindo quantidades de carvão, petróleo, grãos e minérios da mesma ordem de grandeza do consumo anual global dessas commodities [86], [87]. Hoje, mais de 80% da carga comercializada internacionalmente passa por navios mercantes[21] [88].

Conforme ilustra a Figura 4, em anos recentes, a atividade marítima praticamente dobrou em relação ao ano 2000, com a massa trocada internacionalmente via embarcações atingindo cerca de 11 Gt/ano em 2019. Embora a carga geral conteinerizada seja a principal origem desse crescimento, produtos de baixo valor agregado ainda representam a maior parte do comércio marítimo internacional, respondendo por quase 60% da massa total embarcada anualmente [86]. Particularmente, o mercado de produtos energéticos (e.g., petróleo) e agrícolas (e.g., grãos) depende fortemente da eficiência econômica proporcionada pelo transporte a granel de longo curso [89], [90].

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[18] Como, por exemplo, maior espaço para carga, uma conversão termodinâmica mais eficiente e uma logística de operação mais simples (e.g., sem a necessidade de foguistas) [85].

[19] Como, por exemplo, o surgimento do motor de dois tempos (com melhor relação peso/potência), o aumento do porte das embarcações e a adaptação de motores marítimos para trabalhar com frações menos nobres do petróleo [123].

[20] A revolução a que se faz referência é o processo de conteinerização observado a partir dos anos 1980 [87].

[21] Este percentual é baseado em dados de volume [88].

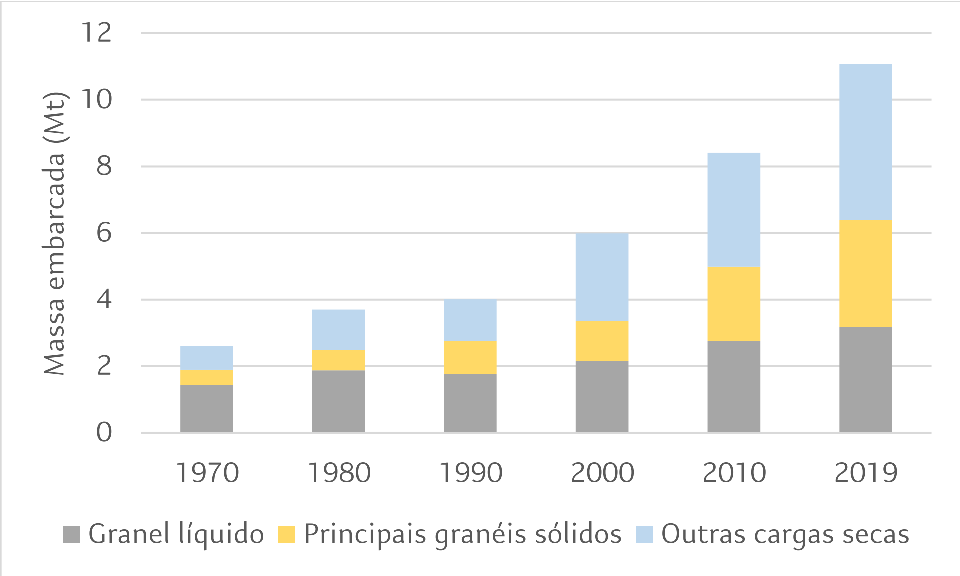

Figura 4: Comércio marítimo internacional

Nota: Atividade do comércio marítimo internacional entre 1970 e 2019, em termos de massa. Fonte: elaboração própria. Dados: [91]

Naturalmente, o "milagre" do comércio internacional proporcionado pelo transporte marítimo nos últimos 70 anos veio a custo de externalidades socioambientais. No século passado, isso se expressou de forma mais evidente por desastres como aquele ocorrido com o petroleiro Torrey Canyon, em 1967, que provocou o derramamento de 120 mil toneladas de óleo bruto no oceano [92], [93]. Posteriormente, durante o período histórico inaugurado pela Conferência de Estocolmo (1972), questões associadas a poluentes atmosféricos também se tornaram relevantes no âmbito do transporte marítimo, especialmente a partir dos anos 1990. Nesse sentido, a evolução da regulação de emissões de óxidos de enxofre (SOx) é o principal exemplo [94]. Por estarem entre os derivados mais pesados do petróleo, combustíveis marítimos são tipicamente ricos em enxofre, o que faz com que sua queima libere quantidades significativas de SOx. Os impactos negativos desses compostos sobre a saúde humana[22] motivaram o desenvolvimento de uma regulação específica sobre o tema, que culminou com a obrigatoriedade, a partir do

[22] Notadamente sobre o sistema respiratório [389].

ano 2020, de se utilizar globalmente combustíveis com teor máximo de enxofre igual a 0,5% em base mássica[23] (daqui em diante, IMO2020) [94]–[96].

Já discussões envolvendo a contribuição do transporte marítimo para a MGC são mais recentes. Conforme ilustra a Figura 5, a navegação mercante vem emitindo algo em torno de 1,0 $GtCO_2$/ano, com cerca de 70% desse total associado especificamente ao transporte marítimo internacional. Nos últimos anos, isso representou aproximadamente 3% das emissões anuais globais de CO_2 e 2% das emissões de GEEs (em base equivalente, emissões de CH_4 e N_2O são pouco relevantes no setor marítimo[24]) [62], [97]. Além de representar uma fração menor das emissões de transportes (historicamente dominadas pelo setor rodoviário, que hoje responde por ~6 $GtCO_2$/ano [55]), o transporte marítimo possui a peculiaridade de operar majoritariamente em águas internacionais, o que torna desafiadora a alocação de suas emissões a Estados específicos [98]. Isso fez com que o setor (juntamente com a aviação) não fosse abarcado pelos mais importantes tratados de mitigação climática, incluindo o Acordo de Paris [99], [100]. No entanto, desde a assinatura do acordo (em 2015), a pressão por ações de descarbonização na navegação mercante vem aumentando, já que um possível crescimento dessas emissões em longo prazo poderia comprometer os objetivos de Paris [62], [99]–[101].

[23] Em contraste com um teor natural médio por volta de 2,5% [125].

[24] Contudo, o bunker gera emissões significativas de carbono negro (especialmente na região do Ártico). O papel desse poluente é relevante do ponto de vista de MGC por seu potencial de alteração do albedo [390]. De forma mais geral (i.e., considerando todas as emissões de carbono negro, e não apenas aquelas originadas no bunker), isso é ilustrado pela Figura 2.

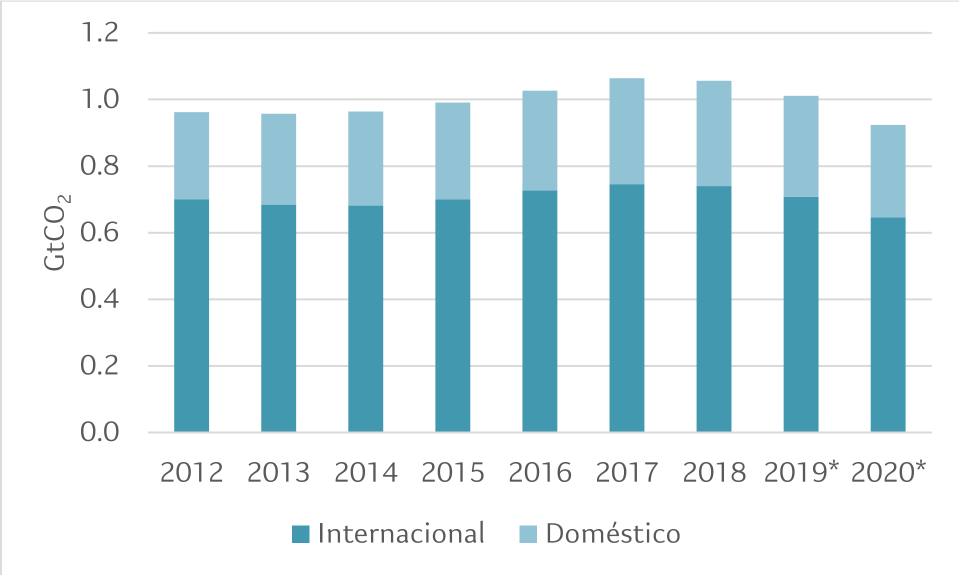

Figura 5: Emissões de CO_2 do transporte marítimo

Nota: Emissões de CO_2 do transporte marítimo doméstico e internacional entre 2012 e 2020 (para 2019 e 2020, o valor das emissões do transporte marítimo doméstico é uma estimativa baseada na proporção média dos três anos anteriores). Fonte: elaboração própria. Dados: [62], [97]

A regulação das emissões de GEEs do transporte marítimo internacional é responsabilidade de uma agência especializada das Nações Unidas, a Organização Marítima Internacional (IMO, do inglês *International Maritime Organization*). Embora as discussões sobre mitigação climática no âmbito da IMO remontem a 1997 (na esteira do Protocolo de Quioto), as primeiras iniciativas da agência se limitaram à inventariação das emissões de GEEs do setor [102]. Uma primeira medida concreta foi o estabelecimento, em 2011, de uma política de redução da intensidade de carbono[25] da frota. Essa política, baseada no índice EEDI (do inglês *Energy Efficiency Design Index*), exigiu reduções progressivas da intensidade de carbono de novas embarcações no período 2013-2025, com aprofundamento da ambição a cada período de cinco anos [103]–[105]. Na prática, esses requisitos vêm sendo cumpridos por meio de ganhos de eficiência

[25] Apesar de ter sido anunciada como um programa de eficiência energética, essa política baseia-se num indicador cuja formulação envolve uma relação de emissões de CO_2 e serviço de transporte. Trata-se, portanto, de uma intensidade de carbono [104].

energética proporcionados por melhorias construtivas e operacionais [62], [105]–[107]. Mais recentemente, a IMO expandiu sua política de eficiência energética a fim de incluir exigências para embarcações existentes [108], [109].

Apesar de a política de eficiência energética da IMO ter tido claro impacto sobre a curva de emissões de CO_2 do transporte marítimo internacional (estabilidade do montante total emitido em contraste com um crescimento da atividade entre 2010 e 2020) [62], em longo prazo, sua contribuição para a descarbonização do setor tende a ser limitada, pois boa parte do potencial de eficiência já foi consumido desde o século 19 (Figura 6) [79].

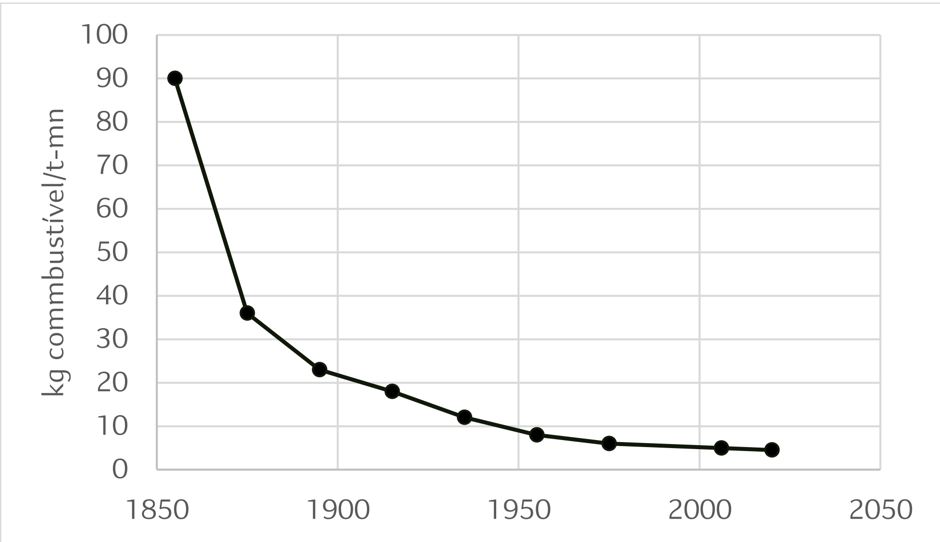

Figura 6: Consumo de combustível por unidade de serviço de transporte

Nota: Curva de evolução do consumo de combustível por unidade de serviço de transporte (tonelada-milha) entre 1850 e 2010, tomando como base navios graneleiros de pequeno porte. A figura ilustra o caráter decrescente dos ganhos marginais de eficiência energética em embarcações mercantes. Fonte: elaboração própria. Dados: [79]

Assim, desde a assinatura do Acordo de Paris, a adoção de medidas de mitigação adicionais vem sendo objeto de debate na IMO. Em 2018, a agência publicou uma estratégia preliminar de descarbonização, cujo principal objetivo é promover, até 2050, uma redução de 50% das emissões anuais do transporte marítimo internacional em relação ao nível de 2008 (daqui em diante, IMO2050) [110]. Tal estratégia será revisada ainda em 2023 a fim de incluir medidas mais rigorosas, com chances de se aumentar o valor da redução de emissões pretendida para 2050 [111]–[113].

Dadas as tendências de crescimento da demanda por transporte marítimo e saturação dos ganhos de eficiência energética nas embarcações, é muito provável que a viabilização de uma redução de emissões de pelo menos 50% até 2050 dependa do uso em larga escala de combustíveis de baixo carbono [66], [68], [101], [114].

A navegação mercante internacional consome atualmente cerca de 9 EJ/ano (Figura 7) e, conforme ilustra a Figura 8, depende inteiramente de recursos fósseis. Derivados de petróleo respondem por mais de 95% da energia final consumida pelo setor, com destaque para o Óleo Combustível Pesado (HFO, do inglês *Heavy Fuel Oil*), que representa cerca de 7 EJ/ano. O HFO é um energético formulado a partir de frações residuais do refino de petróleo, cujo valor é inferior ao do próprio óleo cru[26]. Originalmente utilizados em motores auxiliares ou de menor porte, combustíveis destilados (e.g., MDO – do inglês *Marine Diesel Oil*) têm ganhado mais espaço no setor nos últimos anos, especialmente com o estreitamento do nível máximo de teor de enxofre trazido pela IMO2020. Já o Gás Natural Liquefeito (LNG, do inglês *Liquefied Natural Gas*) é um combustível marítimo mais recente, cujo impulsionamento na indústria também esteve associado a seu baixo teor de enxofre [115]. Embora tenha performance climática igual ou ligeiramente superior[27] ao HFO e ao MDO [116], o LNG tem perspectiva de aumentar consideravelmente sua participação na matriz energética do transporte marítimo internacional em curto e médio prazo. Uma parte considerável do *orderbook*[28] global atual

[26] Com a IMO2020, esse cenário vem se alterando em alguma medida, já que o bunker com baixo teor de enxofre tem maior custo (cerca de 20% acima do bunker comum). Ainda assim, seu preço é bastante inferior ao do MDO [124].

[27] O impacto do LNG como combustível depende do nível de emissões de metano não queimado no exausto de motores marítimos. Quando utilizado em motores de alta pressão, o LNG apresenta certa vantagem em termos de mitigação, já que seu fator de emissão de CO_2 é inferior ao de hidrocarbonetos líquidos [116].

[28] Aqui, o termo *orderbook* se refere à lista de navios em fase de construção ou com construção planejada.

é composta por navios equipados com motores duais aptos a operarem com LNG como combustível principal [117].

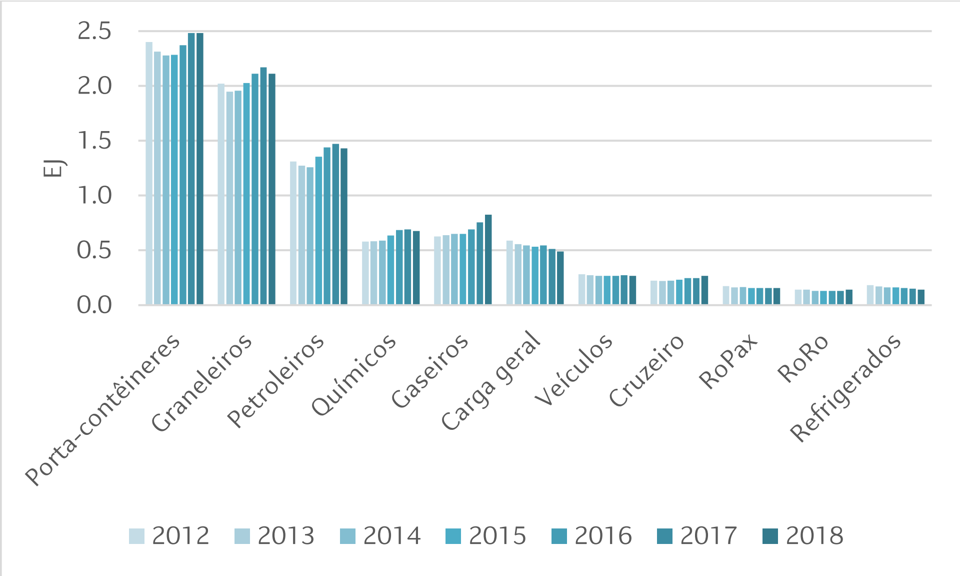

Figura 7: Consumo de combustíveis marítimos por classe de embarcação

Nota: Consumo de combustíveis marítimos do transporte marítimo internacional, por classe de embarcação, entre 2012 e 2018. Em média, porta-contêineres, graneleiros e petroleiros representam 67% do consumo anual de combustíveis pelo setor. Fonte: elaboração própria. Dados: [62]

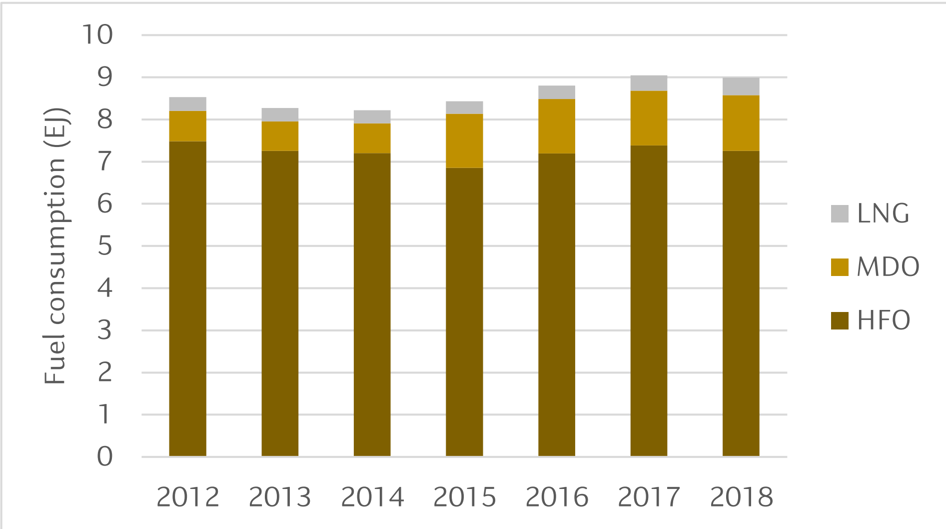

Figura 8: Consumo de combustíveis marítimos por energético

Nota: Consumo total de HFO, MDO e LNG pelo transporte marítimo internacional entre 2012 e 2018. Fonte: elaboração própria. Dados: [62]

A substituição do petróleo como fonte energética do transporte marítimo internacional não é uma tarefa simples. Apesar de potenciais combustíveis marítimos alternativos de baixo carbono serem diversos tanto em termos de rotas de produção como de vetores finais (Tabela 2), todos eles enfrentam barreiras que, sob o ponto de vista estritamente econômico, os tornam pouco atrativos ante o baixo custo e as vantagens técnicas dos combustíveis marítimos convencionais.

Tabela 2 – Potenciais combustíveis marítimos alternativos

Grupo	**Exemplos**
Biocombustíveis *drop-in* baseados em oleaginosas ou gordura animal	Biodiesel FAME Óleo vegetal direto (SVO) Óleo vegetal hidrotratado (HVO)
Biocombustíveis sintéticos *drop-in*	Diesel de *Biomass-to-Liquids* Diesel de *Alcohol-to-Diesel*
Eletrocombustíveis sintéticos *drop-in*	Diesel baseado em hidrogênio de eletrólise renovável
Bioálcoois e biogases[29]	Bio-LPG, Bio-LNG, biometanol, etanol
Eletroálcoois e eletrogases	LNG e metanol baseados em hidrogênio de eletrólise renovável
Hidrogênio e amônia	Amônia verde

O SVO, por exemplo, envolve rotas de produção dominadas (e.g., extração de óleo de soja) e tem densidade energética volumétrica comparável à do HFO. No entanto, sua aplicação como combustível *drop-in* é limitada por motivos técnicos[30]. Já o HVO, oriundo da hidrogenação do SVO, é um combustível de qualidade superior e quimicamente similar ao diesel fóssil [68], [69]. Ainda assim, o HVO pode ter seu emprego restringido pela competição com o uso alimentício e incertezas quanto a seu impacto sobre o desmatamento. Biocombustíveis sintéticos como aqueles produzidos pela

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[29] A título de coerência com os demais combustíveis marítimos (e com os artigos), adotam-se, ao longo da tese, as nomenclaturas em inglês para o Gás Natural Liquefeito (LNG, *Liquefied Natural Gas*) e para o Gás Liquefeito de Petróleo (LPG, *Liquefied Petroleum Gas*).

[30] Como, por exemplo, sua acidez e viscosidade [68], [391].

síntese de Fischer-Tropsch são inteiramente *drop-in* e podem utilizar resíduos como matéria-prima [68], [90], [118], mas enfrentam problemas de maturidade tecnológica na etapa de gaseificação, além de possuírem custo elevado. Já amônia verde (advinda de hidrogênio de eletrólise renovável) se baseia num processo tecnologicamente dominado (síntese de Haber-Bosch), mas não é aplicável à frota existente, baseada em motores de ignição por compressão. Além disso, a amônia tem densidade energética volumétrica quase 70% inferior à do diesel (Figura 9) e envolve riscos associados à sua toxicidade [68], [119], [120]. Com densidade energética ainda menor, o hidrogênio tem seu uso direto inviabilizado em aplicações de larga escala [64], [68]. No entanto, o gás pode ser utilizado para a produção de eletrocombustíveis *drop-in*, como o eletrodiesel. Essa rota envolve custos ainda mais elevados e depende da disponibilidade de CO_2 capturado para formulação do gás de síntese [68], [121]. O metanol, por sua vez, tem rotas de produção baseadas tanto em biomassa como eletricidade renovável, além de possuir vantagens de tancagem em comparação com o LNG. Contudo, sua densidade energética volumétrica é 55% inferior à do diesel e sua aplicabilidade depende da conversão da frota para novas motorizações[31] [68], [69].

[31] A discussão acerca de densidade energética e novas motorizações é aprofundada ao longo da tese.

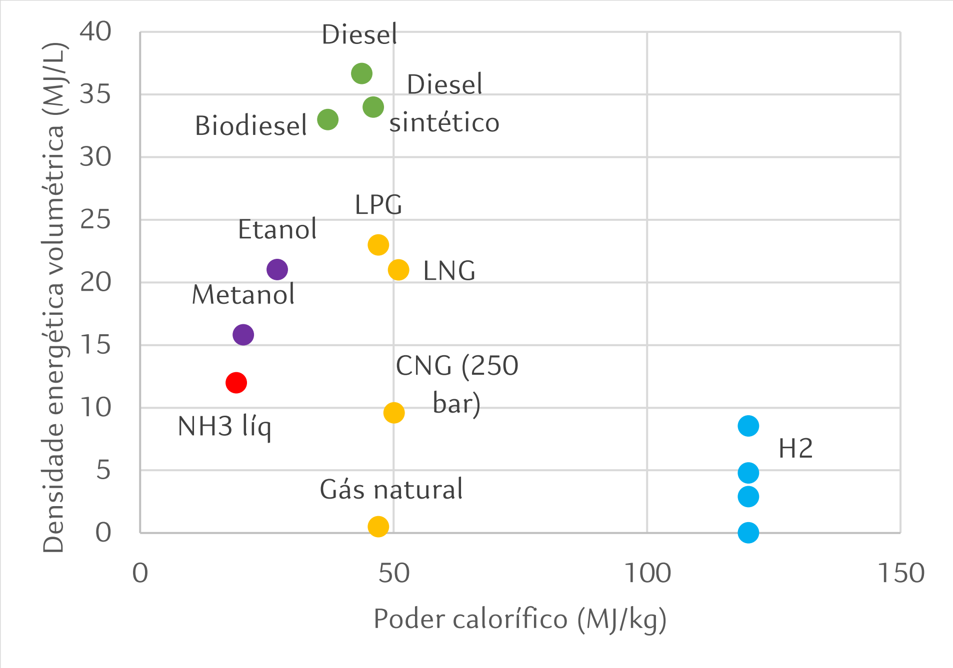

Figura 9: Densidade energética de combustíveis selecionados

Nota: CNG = Gás Natural Comprimido (do inglês *Compressed Natural Gas*). A presença de múltiplos círculos azuis reflete a variação da densidade energética volumétrica do hidrogênio molecular de acordo com o método de armazenamento. O ponto inferior indica a densidade do hidrogênio natural nas condições normais de temperatura e pressão. O ponto superior indica a densidade do hidrogênio liquefeito. Fonte: elaboração própria. Dados: [64], [68], [69], [120], [122]

A grande diversidade de combustíveis candidatos à substituição dos derivados de petróleo em embarcações mercantes contrasta com a atual configuração da indústria marítima global, caracterizada por grandes centros de abastecimento (e.g., Singapura, Roterdã, Fujairah) que oferecem um produto homogêneo e relativamente barato [123]–[125]. As possibilidades de transição dessa infraestrutura energética para um suprimento de baixo carbono são objeto de investigação desta tese de doutorado.

1.7. Objetivo desta tese

Desde os anos 2010, e especialmente após o estabelecimento da IMO2050, a literatura técnico-científica ligada a ciências náuticas, comércio internacional e engenharia naval vem se debruçando sobre as alternativas de descarbonização do transporte marítimo. De forma geral, esses estudos se dividem em três grandes áreas.

Uma primeira área se concentra na identificação e descrição de medidas de redução de emissões ligadas a aspectos construtivos e operacionais das embarcações [62], [126], [127]. Tais estudos investigam detalhadamente o potencial de medidas específicas ou promovem uma revisão sistemática das diferentes medidas existentes (construindo, por exemplo, curvas de custo de abatimento marginal [62], [128]). Essa parte da literatura aborda temas como redução da velocidade de navegação (*slow steaming*) [129]–[133], otimização de rotas segundo condições meteorológicas (*weather routing*) [126], [134]–[136], tratamento/pintura do casco (*hull coating*) [137]–[139], manutenção do hélice, designs inovadores de casco [140]–[142], uso de redutores de arrasto [126], uso de materiais leves [126], [143], recuperação de calor residual [144]–[146], propulsão eólica auxiliar [142], [147]–[149], conexão com energia de terra (*cold ironing*) [126], [150], [151] e, mais recentemente, captura de CO_2 a bordo [152]–[154].

A segunda área é composta por artigos e relatórios que analisam combustíveis marítimos alternativos de baixo carbono e sua aplicação à frota atual ou a novas motorizações. Esses estudos procuram revelar as vantagens e desafios ligados a cada vetor energético (e.g., biocombustíveis *drop-in*, amônia, etanol, metanol) ou simplesmente caracterizá-los do ponto de vista técnico [68], [69], [114], [119], [121], [155]–[160].

Finalmente, uma terceira área desenvolve cenários do consumo de energia do transporte marítimo internacional e de suas emissões de CO_2 entre 2015 e 2050 [62], [101], [161]–[164]. Tipicamente, esses estudos se baseiam em premissas exógenas de demanda e têm o aumento da participação de combustíveis ou a redução de emissões do setor determinadas *ex ante* (por exemplo, tratando a IMO2050 como um objetivo a ser cumprido). Embora esses cenários setoriais usualmente possuam bom detalhamento da frota global e de medidas de mitigação construtivas e operacionais, sua arquitetura implicitamente considera que a descarbonização do setor marítimo é um objetivo em si, e não parte do desafio mais abrangente de limitar o aquecimento global a 1,5ºC ou 2ºC. Em contraste, o transporte marítimo representa menos de 10% do consumo mundial de petróleo e cerca de 3% da energia final demandada globalmente (Figura 10). Cenários do setor deveriam, portanto, ser colocados no contexto mais amplo da transição energética global, já que é altamente provável que tendências de descarbonização dos combustíveis marítimos sejam ditadas por padrões mais estruturais de uso e conversão de energia[32].

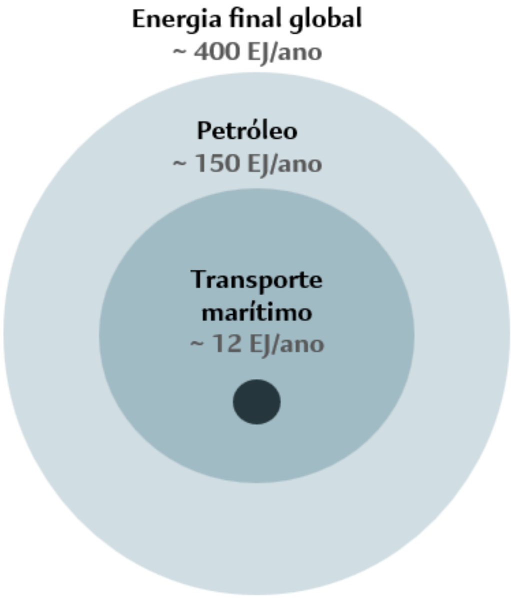

Figura 10: O transporte marítimo internacional no contexto do setor energético

Fonte: elaboração própria. Dados: [21], [62]

Assim, uma lacuna relevante da atual literatura é a ausência de cenários energéticos do transporte marítimo internacional concebidos sob uma lógica sistêmica que considere as numerosas conexões do setor com o restante da economia global. Idealmente, essa lacuna poderia ser preenchida por IAMs, cujo objetivo é exatamente produzir cenários integrados de descarbonização. Entretanto, conforme discutido, a representação do transporte marítimo nesses modelos tende a ser bastante agregada e simplificada.

O trabalho realizado no contexto desta tese visa ao aprimoramento do transporte marítimo em IAMs, com a finalidade de desenvolver cenários para o setor ancorados na modelagem

[32] Ademais, políticas de redução das emissões do transporte marítimo podem levar a vazamento de emissões caso não sejam concebidas sob uma perspectiva sistêmica. Essa discussão será aprofundada no capítulo 2.

da totalidade do sistema energético. Assim, como objetivo geral, esta tese procura responder à pergunta destacada no Quadro 1.

Quadro 1 – Objetivo geral da tese

“Examinando-se o transporte marítimo global à luz de suas conexões com o restante do sistema energético, como evoluem a demanda e oferta de energia do setor em cenários integrados de descarbonização ao longo do século 21?”

A esse objetivo geral se associa uma série de objetivos específicos:

- A avaliação de fontes energéticas alternativas para o transporte marítimo;
- A avaliação das possíveis rotas tecnológicas de produção desses energéticos marítimos alternativos, com especial atenção a rotas baseadas em recursos renováveis;
- O estudo do impacto de diferentes cenários de demanda sobre o esforço de descarbonização do setor marítimo internacional;
- O desenvolvimento de uma modelagem total ou parcialmente endógena da demanda por transporte marítimo em IAMs;
- A produção, em nível nacional, de cenários de descarbonização do transporte marítimo concebidos sob a lógica sistêmica de IAMs;
- A produção, em nível global, de cenários de descarbonização do transporte marítimo concebidos sob a lógica sistêmica de IAMs;
- A análise da dinâmica de substituição dos combustíveis marítimos fósseis em cenários integrados de descarbonização do suprimento energético do transporte marítimo global;
- A avaliação do papel de combustíveis marítimos alternativos específicos em cenários de descarbonização do setor;

- A comparação do resultado de cenários energéticos integrados do transporte marítimo com o nível de redução de emissões representado pela IMO2050;

Diante desses objetivos, este trabalho envolveu esforços especificamente associados a três IAMs:

- BLUES (*Brazilian Land Use and Energy Systems model*), um modelo de escopo nacional desenvolvido desde os anos 2000 pelo Centro de Economia Energética e Ambiental (CENERGIA), laboratório ligado ao Programa de Planejamento Energético da COPPE/UFRJ;
- COFFEE (*Computable Framework for Energy and the Environment*), um modelo com estrutura semelhante à do BLUES, mas de escopo global, também desenvolvido pelo CENERGIA desde 2015;
- IMAGE (*Integrated Model to Assess the Global Environment*), um dos primeiros IAMs globais com foco em mitigação climática, desenvolvido pela Agência Ambiental dos Países Baixos (PBL, do holandês *Planbureau voor de Leefomgeving*) desde os anos 1980.

O aperfeiçoamento da modelagem energética do transporte marítimo nesses modelos deu origem a quatro artigos científicos, que correspondem aos próximos capítulos desta tese.

- **Artigo #1**: *Production of alternative marine fuels in Brazil: An integrated assessment perspective* (Capítulo 2), publicado na revista *Energy,* volume nº 219, identificação nº 119444, sob o DOI 10.1016/j.energy.2020.119444. Tradução livre do título: “Produção de combustíveis marítimos alternativos no Brasil: uma perspectiva de avaliação integrada”.
- **Artigo #2**: *Are there synergies in the decarbonization of aviation and shipping? An integrated perspective for the case of Brazil* (Capítulo 3), publicado na revista *iScience*, volume nº 25, fascículo n° 10, sob o DOI 10.1016/j.isci.2022.105248. Tradução livre do título: “Há sinergias na descarbonização da aviação e do transporte marítimo? Uma perspectiva integrada para o caso do Brasil”.
- **Artigo #3**: *Global futures of trade impacting the challenge to decarbonize the international shipping sector* (Capítulo 4), publicado na revista *Energy,* volume nº 237, identificação n° 121547, sob o DOI 10.1016/j.energy.2021.121547.

Tradução livre do título: “Impacto de futuros globais do comércio sobre o desafio de descarbonizar o setor marítimo internacional”.

- **Artigo #4**: *International shipping in a world below 2ºC* (Capítulo 5), submetido para a revista *Nature Climate Change* e atualmente em fase de revisão por pares. A mais recente versão do manuscrito está disponível em uma base de dados de *preprints* (https://www.researchsquare.com/article/rs-2958063/v1), sob o DOI 10.21203/rs.3.rs-2958063/v1. Tradução livre do título: “O transporte marítimo internacional num mundo abaixo de 2ºC”.

Cada um desses trabalhos representou um passo adiante na tentativa de aprimorar o setor marítimo em IAMs, com a complexidade metodológica aumentando a cada capítulo (Figura 11). Nos artigos #1 e #2, que podem ser vistos como frutos de um mesmo esforço, utilizou-se o modelo BLUES para analisar possíveis trajetórias de descarbonização dos combustíveis marítimos no caso específico do Brasil. Tendo em vista o escopo nacional dessa modelagem, a análise realizada se restringiu a rotas de navegação associadas ao comércio exterior brasileiro e se baseou em demandas exógenas.

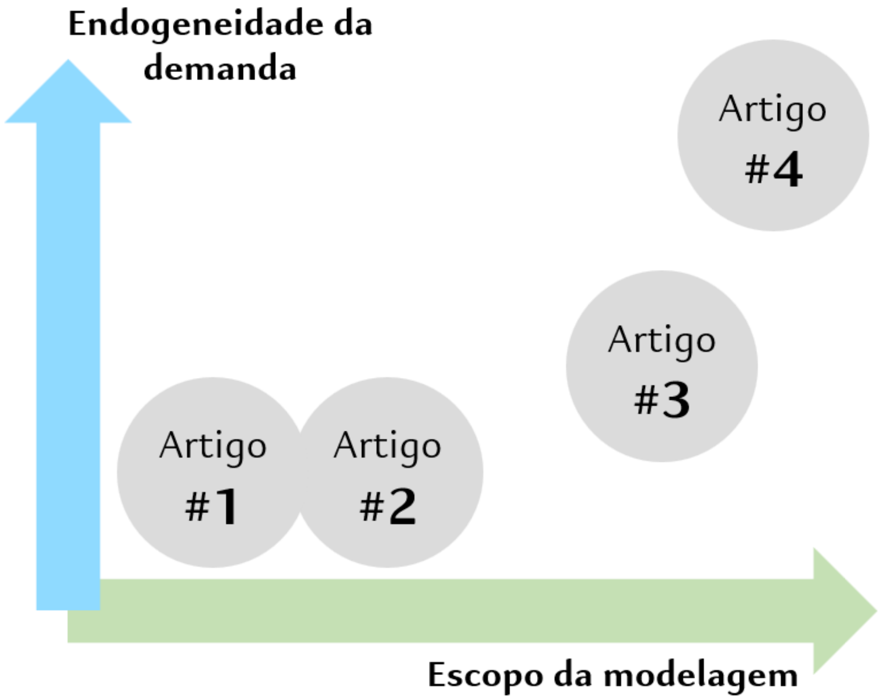

Figura 11: Ilustração da progressão metodológica desta tese

Nota: Na figura, o eixo das abscissas (verde) representa o escopo geográfico e tecnológico das produções científicas. Já o eixo das ordenadas (azul) reflete a endogeneidade da demanda por transporte marítimo na modelagem realizada. O crescimento desse segundo eixo indica, portanto, demandas produzidas cada vez mais internamente nos IAMs. Os artigos #1 e #2, por exemplo, focam sua análise no Brasil e possuem demandas essencialmente apriorísticas. Por isso, encontram-se perto da origem. Já o artigo #3 tem escopo geográfico global. Nesse trabalho, as demandas por transporte marítimo são geradas por um IAM e, assim, há um ganho de endogeneidade em comparação com os dois primeiros. Contudo, trata-se de ainda de um estágio intermediário de integração com IAMs (análise de pós-processamento). Finalmente, o artigo #4, além de realizar uma análise em nível global, envolve a modelagem integrada do suprimento energético marítimo. Em termos de endogeneidade da demanda, esse artigo é também o mais destacado, uma vez que os vetores de atividade são fruto da otimização geral do IAM. Fonte: elaboração própria

Já no artigo #3, cenários integrados do IMAGE foram utilizados para projetar a demanda global por transporte marítimo até o fim do século segundo cinco diferentes narrativas socioeconômicas. Em seguida, avaliaram-se os impactos dessas possíveis trajetórias de demanda sobre a quantidade requerida de energia marítima de base renovável para cumprimento da IMO2050. Ainda que tenha se baseado em um IAM de escopo mundial, com amplo detalhamento de rotas marítimas globais associadas a dezenas de produtos, o artigo #3 limitou-se a uma análise de pós-processamento, em que resultados do IMAGE serviram como entrada para uma modelagem essencialmente setorial da navegação.

Por fim, o artigo #4 concretizou o objetivo central desta tese de doutorado ao integrar plenamente uma modelagem mais detalhada do transporte marítimo internacional à estrutura de um IAM de escopo global. Nesse trabalho, o modelo COFFEE foi aprimorado a fim de incluir uma representação do transporte marítimo desagregada em 31 produtos/grupos de produtos, com a maior parte deles tendo a demanda determinada endogenamente. Além da representação da demanda, essa modelagem ofereceu ao COFFEE diferentes possibilidades de motorizações marítimas alternativas, cada qual associada a grupos de potenciais combustíveis marítimos. Por sua vez, tais combustíveis tiveram seu consumo vinculado a cadeias energéticas preexistentes no modelo.

Cabe ressaltar uma particularidade referente ao artigo #4. Embora seja a primeira publicação oficial refletindo a integração do módulo detalhado de transporte marítimo ao COFFEE, essa publicação não se resume aos resultados do modelo. Por se situar no contexto de um projeto internacional de modelagem integrada[33], o artigo #4 apresenta também os resultados de outros cinco IAMs. Assim, em vez de uma detalhada descrição da modelagem do COFFEE, essa publicação prima pela comparação de resultados dos seis modelos. Com base nessa maior diversidade de IAMs, o artigo busca conclusões mais robustas sobre o papel do transporte marítimo internacional num mundo de mitigação climática. Por isso, a fim de evitar falta de informação, no capítulo 5, antes da transcrição do artigo #4, inclui-se uma breve descrição do módulo de transporte marítimo internacional no COFFEE.

Em seguida à introdução, a tese se estrutura em torno dos quatro artigos mencionados, seguindo a ordem lógica ilustrada pela Figura 11. Adicionalmente, inclui-se uma seção de considerações finais (Capítulo 6), em que se discutem as respostas trazidas pela modelagem, suas limitações e sugestões para estudos futuros.

[33] Trata-se do projeto *Next generation of advanced integrated assessment modelling to support climate policy making* (NAVIGATE).

2. Produção de combustíveis marítimos alternativos no Brasil: uma perspectiva de avaliação integrada

Neste capítulo, reproduz-se o manuscrito final submetido à revista *Energy* para publicação do artigo *Production of alternative marine fuels in Brazil: An integrated assessment perspective* (volume nº 219; identificação nº 119444; DOI: 10.1016/j.energy.2020.119444).

PRODUCTION OF ALTERNATIVE MARINE FUELS IN BRAZIL: AN INTEGRATED ASSESSMENT PERSPECTIVE

Eduardo Müller-Casseres, Francielle Carvalho, Tainan Nogueira, Clarissa Fonte, Mariana Império, Matheus Poggio, Huang Ken Wei, Joana Portugal-Pereira, Pedro R. R. Rochedo, Alexandre Szklo, Roberto Schaeffer

Abstract

This study aims to provide an Integrated Assessment Model (IAM) perspective of the production and distribution of alternative marine fuels in Brazilian ports, considering the International Maritime Organization (IMO) emission reduction target for 2050 (IMO2050). Although other mitigation measures are available, it is likely that alternative fuels will be required, implying additional costs and entailing relevant impacts on other energy chains and land use. Hence, the national IAM BLUES model is adapted to represent the relevant part of the international shipping sector. A set of scenarios is developed considering different fuel alternatives, demand assumptions and national mitigation targets. Findings show that taking into account emissions of CO_2 only or of all greenhouse gases (GHGs) within the IMO strategy significantly impacts the optimal technological portfolio. Furthermore, achieving the IMO2050 goal without considering a national decarbonization strategy may result in potential spillovers. The intense use of the energy sector could partially compromise the gains obtained by maritime decarbonization or even surpass it. Therefore, only an integrated mitigation strategy would lead to more effective decarbonization of the entire marine supply.

a. Introduction

The shipping sector is an important contributor to global greenhouse gas (GHG) emissions, accounting for 1.06 GtCO_2/yr (direct emissions), with 70-87%[34] of this amount associated with the international freight transport system [165]. Shipping GHG emissions (almost entirely composed of CO_2) originate from the use of fossil energy. Currently, heavy fuel oil (HFO) and marine gasoil (MGO) are the prevalent fuels in maritime operation, and accounted for approximately 95% of the sector's energy demand in 2018 [165]. In practice, marine fuels are often composed of a blend of these two types of petroleum products in varied proportions [123], [166]. In terms of energy conversion and carbon intensity, HFO and MGO are similar, with nearly equivalent specific consumption and emission factors [167]. As such, in this work, which provides a more aggregate view of the sector, these fuels are treated indistinctly under the designation "bunker".

In 2018, the International Maritime Organization (IMO), the United Nations body responsible for the regulation of international shipping, established a preliminary strategy to reduce the sector's contribution to climate change. This includes a 50% reduction of the total shipping-related GHG emissions by 2050 compared to 2008 (hereafter IMO2050) [110].

To fulfil IMO2050, several mitigation measures can be considered. For example, more efficient vessel design can provide efficiency gains through the use of lightweight materials, air lubrication or new hull shapes and sizes [126], [140]. Operational measures, such as speed and voyage optimization, favored by the digitalization of freight transport, could also play an important role [126], [168]. Other measures, as the use of auxiliary propulsion devices and waste heat recovery, might help to further reduce the energy demanded by ships [126], [169]. Reductions in the demand for shipping, especially in fossil fuel transportation, might also play an important role [66].

[34] A range is presented due to the different possibilities of emissions allocation. International shipping can be defined based on origins and destinations (voyage-based allocation) or on ship types (vessel-based allocation) [165].

Nevertheless, these measures are not sufficient to meet IMO2050. Hence, it is likely that the bulk of the decarbonization of shipping will rely on the adoption of alternative fuels [127], [170]. From a technical perspective, several low-carbon fuels could be considered, such as vegetable oils, synthetic biofuels, bio-LNG, bio-alcohols and electrofuels (e-fuels) [170]. In any case, the use of alternative fuels will imply extra costs and might have relevant impacts on other energy chains and land use. Although some studies have carefully assessed the decarbonization potential of renewable marine fuels [127], [170], [171], an integrated perspective of the different options is lacking.

Therefore, this study aims to provide an Integrated Assessment Model (IAM) perspective of the production and distribution of alternative marine fuels in Brazilian ports up to 2050, considering IMO emission reduction target. IAMs are modelling tools used to develop overall long-term mitigation strategies. They vary in terms of methodology and scope, but in general, it can be said that IAMs combine several strands of knowledge to explore the impacts of human development and societal choices in the natural world. They generally contain a detailed representation of a region's energy, land use, agricultural and climate systems, as well as their interlinkages [50], [172], [173].

The use of an IAM for the analysis to be performed here is an original proposal compared to the earlier mentioned studies. While the latter are based on sectoral models, exploring in detail specific aspects of international maritime transport routes and services, an IAM-based analysis is capable of providing a systemic view of the problem. Actually, one benefit of this approach is to provide better identification of existing and candidate marine fuel production routes.

Sectoral assessments usually do not include multi-product facilities, such as petroleum refineries and biorefineries. As of today, bunker fuels are produced mainly from heavy residues (low-value cuts) of the fractional distillation of oil [123], [174], [175]. This could still be the case for alternative renewable bunkers, which in the future might be co-produced in bio- and e-refineries (or facilitating the co-production of e-fuels and/or electro-based materials). Only technological-detailed and well-adjusted IAMs can test this hypothesis since these models seek to match not only the shipping fuel demand but also the whole energy service demand of a certain country, region or the world [176]–[178]. This also enables a comprehensive assessment of the impacts of the fuel switch on the entire energy system (e.g., modifications in oil refining, increase in the power sector demand due to the production of e-fuels, a shift of fuel oil use from internal combustion to electricity generation).

Moreover, an integrated system assessment allows investigating the implications of fuel switch in shipping on total GHG emissions. The use of IAMs can help identify whether sectoral emission reductions may lead to effective mitigation of climate change or to an increase in overall emissions. In other words, this kind of modeling analysis can reveal potential rebound effects due to increasing pressure on upstream activities. Furthermore, IAM results include information on direct and indirect changes in land use, which have impacts on non-energy GHG emissions, water balance and food production. Finally, in contrast with sectoral analyses, an integrated modelling analysis allows the quantification of the total costs of decarbonization (e.g., energy and land-use systems, including investment and operational costs and logistics), and not only the fuel production and ship acquisition costs.

Brazil was selected as the case study of this work in view of its foreign trade particularities that severely affect the country´s economy. Brazil's foreign trade is characterized by the export of low value-added commodities with a large discrepancy in terms of mass and value [179], [180]. Besides, Brazil's unfavorable geographical position when it comes to international trade entails longer travel times, in addition to higher fuel costs and carbon intensities [181]. On the other hand, the consolidated biofuel market may represent an advantage for the country to kick-off the production of new marine fuels. Finally, the existence of the BLUES model, an internationally recognized Brazilian IAM [182], [183], together with a national political will to address IMO2050 [184], reinforce the motivations of this study.

Following this introduction, an overview of potential alternative fuels for seaborne transport is provided. Subsequently, methods used to integrate the relevant shipping routes and fuel options into the BLUES model are detailed, as well as the design of scenarios. Next, results of the scenario analysis are presented and discussed. Finally, concluding remarks and suggestions for future studies are explored.

b. Alternative fuels for shipping

Figure 1 provides an overview of conventional and potential alternative marine fuels, including fossil and renewable resources. Even though petroleum products are prevalent, natural gas is presently a relevant energy carrier in the shipping industry, having provided around 0.4 EJ to vessels in 2018 [165]. Even since before the set of IMO's targets, liquefied natural gas (LNG) has been gaining space due to the increasingly competitive gas prices [185] and stricter regulations regarding atmospheric pollution [95]. Today, several ships, particularly a number of gas carriers, are equipped with dual-fuel engines, which can run with both bunker and LNG [165]. Despite its limited benefits in terms of climate mitigation, LNG is still seen by part of the industry as a transition fuel for the next decades [170], [186].

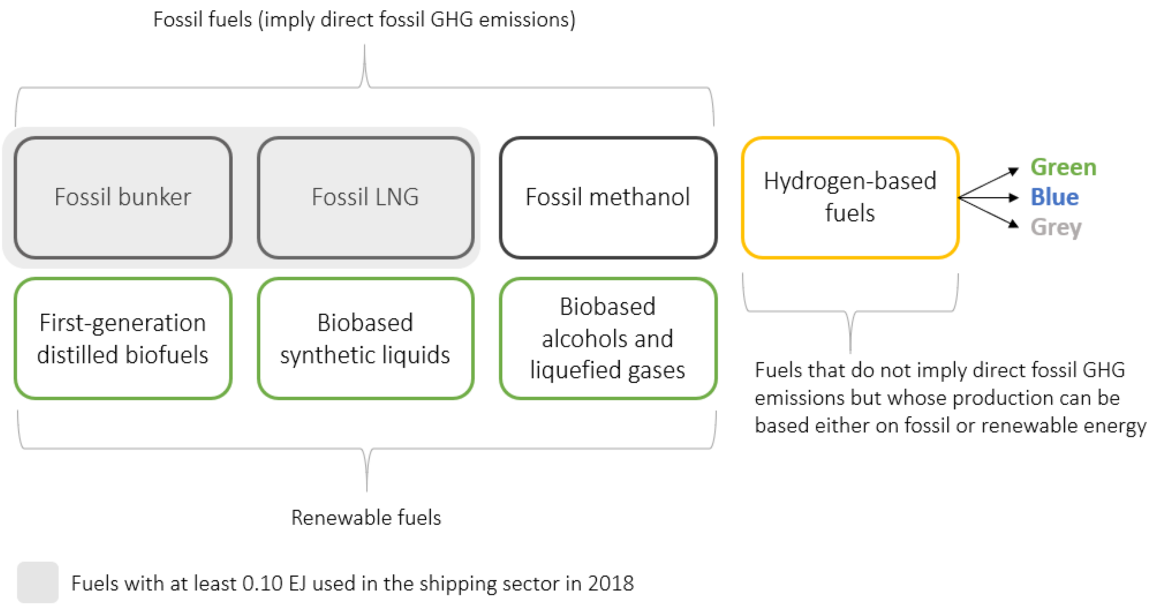

Figure 1: Conventional and alternative marine fuels

In terms of biobased options, fuels can be divided in three groups: first-generation distilled fuels, synthetic liquids and alcohols/liquefied gases. The first group is composed of biofuels obtained through extraction and treatment processes, such as straight vegetable oils (SVO), hydrotreated vegetable oils (HVO), and biodiesel (fatty acid methyl ester – FAME), typically associated with feedstocks like oilseeds and animal fats [187]. The second group includes advanced biofuels produced through thermochemical routes from forest and agro-industrial residues. This includes bio-oils, such as hydrotreated pyrolysis oils (HDPOs) [188] and Fischer-Tropsch (FT) liquids [189]. The FT process outputs multiple hydrocarbon fractions, similar to oil refineries. Most of its products (e.g., biojet, bio-ultra low sulphur diesel and FT-naphtha) have higher market value than fractions suited for use in vessels (FT-diesel and FT-gasoil). Thus, FT-marine fuels can be seen as coproducts. The third group corresponds to biobased gases and alcohols, including liquefied biomethane (bio-LNG), biomethanol (bio-CH_3OH) and bioethanol. Bio-LNG is produced from biogas, which is generated through anaerobic digestion and upgrading [190] Bio-CH_3OH can be produced from biogas or through a thermochemical route similar to the one presented in the second group. Finally, ethanol can be produced from sugar crops or through the enzymatic hydrolysis of lignocellulosic biomass [191].

Alternative energy carriers for shipping can also be based on hydrogen (H2-fuels[35]). This includes not only hydrogen itself (H_2) but also ammonia (NH_3), produced through the Haber-Bosch process, and liquid organic hydrogen carriers (LOHCs) [120], [122], [170]. Hydrogen-based synthetic fuels can also be part of this group. In this case, hydrocarbons or alcohols are obtained through the FT process, similar to the biomass-to-liquids (BtL) route, but combining molecular hydrogen and captured carbon dioxide [121]. As indicated in Figure 1, even though hydrogen-based fuels (H_2-fuels) do never imply direct fossil GHG emissions, they can be fossil-based. In this sense, Figure 2 illustrates the possible H_2-fuels denominations according to the energy source used to produce hydrogen. Green H_2-fuels are defined as those relying on renewable-based processes, such as photovoltaic-powered electrolysis. In contrast, blue and grey H_2-fuels are produced from fossil sources, such as natural gas (through steam methane reforming, SMR). Blue H_2-fuels differ from grey H_2-fuels for including a carbon capture and storage (CCS) plant in their production process.

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[35] In case these energy carriers are produced by storing electrical energy in their chemical structure, they are called e-fuels.

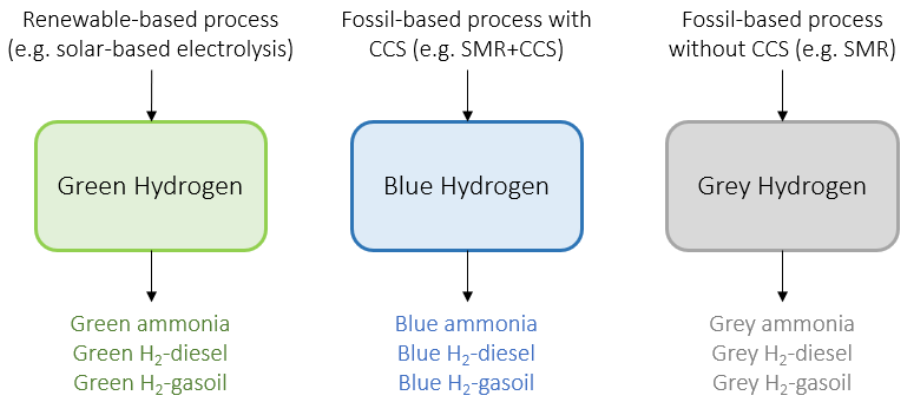

Figure 2: Green, blue, and grey H_2-fuels

c. Methods

Figure 3 provides an overview of the methodology. To conduct the analysis, the Brazilian Land Use and Energy Systems (BLUES) model was applied. As shown in Figure 4, BLUES is a national IAM that represents the Brazilian energy, material, agriculture, and land use energy sectors and takes into account the interactions between these systems [192]. The model is an intertemporal optimization tool comprising the period between 2010 and 2050, used to perform scenario analyses of energy use, GHG emissions, petrochemicals fabrication, agricultural production, and land-use changes in Brazil [46], [193]. The detailed description of BLUES can be found in the common IAM documentation webpage [183].

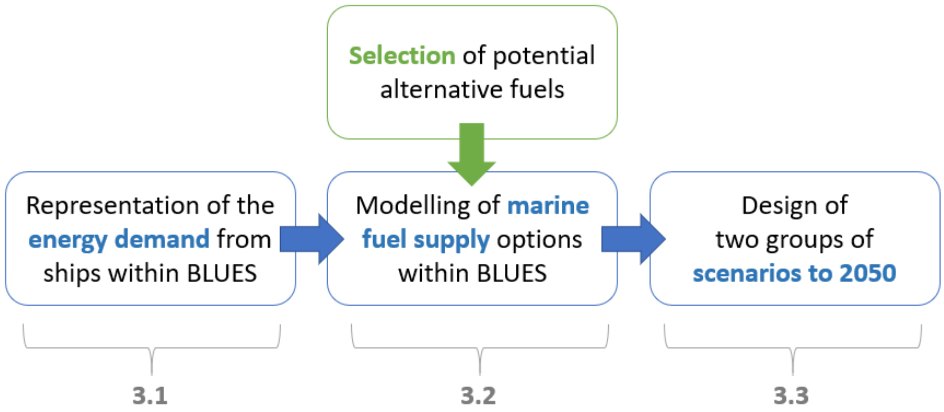

Figure 3: Overview of the methodology

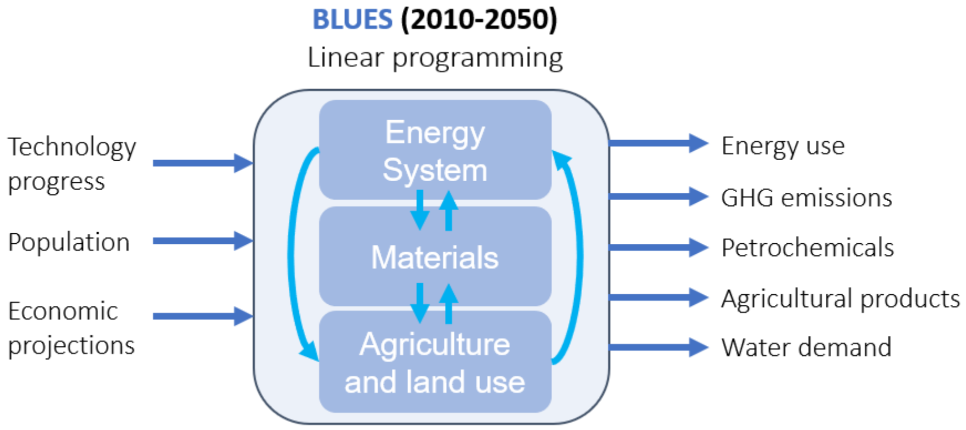

Figure 4: Structure of the BLUES model

Energy demand

Originally, international trade was not represented[36] in BLUES, given that it is a national model. As such, an important part of the methodology here is the incorporation of shipping fuel demand into BLUES (Figure 5).

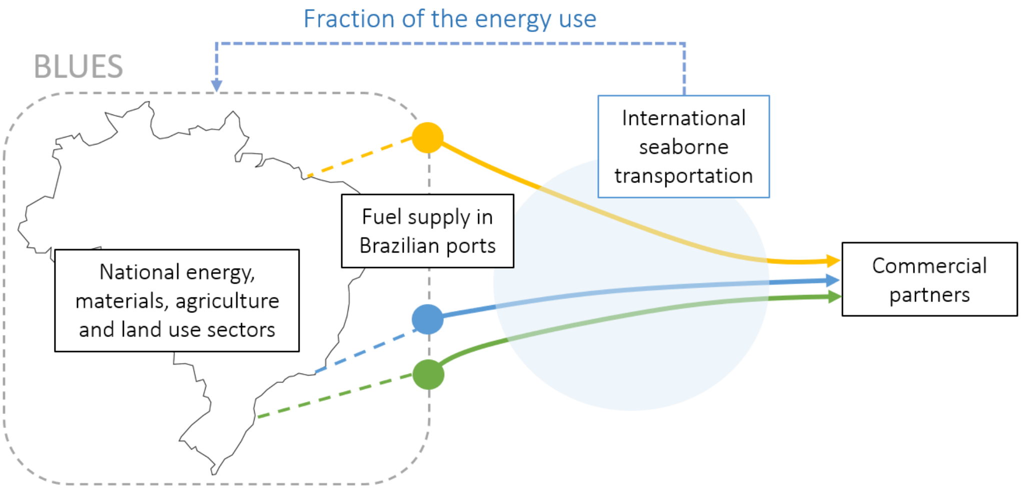

Figure 5: Adaptation of the BLUES model to represent international seaborne trade

[36] The trade itself is represented for several products in BLUES, but the energy demand linked to this trade is not modelled, given that it is not directly associated to the country.

This integration was performed based on the assumption that only a fraction of the energy demanded by Brazil's international trade is provided by national ports. The remaining part is supplied by ports of the commercial partners (i.e., China, Singapore, Europe, etc.) or even along the shipping routes.

In terms of mass, Brazil's exports are way higher than its imports. Hence, while imports are treated as a single category, exports are divided into five categories that represent the country's main export products: iron ore, crude oil, soybean, sugar, and others [179]. Also, iron ore is divided into two categories, reflecting the two different kinds of ships used to transport this commodity [181]. Coastal navigation, which is a small part of fuel demand, is also modelled. Even though coastal navigation is not in the scope of IMO's target, it is assumed that it will follow the trends of long-haul shipping.

Table 1 shows the estimation of the transport work related to Brazilian exports, imports, and coastal navigation [179], [194]. The proportion of the fuel supplied by Brazilian ports is similar for all products[37] (around 31%). Estimates derivate from the comparison of the results of the modelling with historical data for the base year (5.3 million tonnes of bunker in 2018) [195].

Table 1: Estimation of transport work associated with fuel supplied in Brazilian ports in 2018

	Mass traded (Mt)	**Typical distance (nm)**	**Total transport work (Tt-km)**	**Transport work fueled by Brazil (Tt-km)**
Iron ore (Valemax)	195	8,943	2.99	0.93
Iron ore (Capesize)	195	8,943	2.99	0.93
Crude oil	58	7,165	0.71	0.22
Soybeans	84	9,039	0.84	0.26
Sugar	21	8,382	0.25	0.08
Others	153	8,382	1.52	0.48
Imports	151	8,382	3.50	1.09
Coastal navigation	229	780	0.23	0.23

[37] Except for coastal navigation, whose fuel supply is 100% provided by Brazilian ports.

Two demand scenarios are developed based on the literature on global shipping forecasts (Figure 6). The low demand scenario is based on the activity growth reported in DNV's maritime forecast[38] [196], while the high demand scenario is based on the Business as Usual (BAU) scenario of IMO's third GHG study [197]. It is assumed that the exported products do not change over the period of analysis.

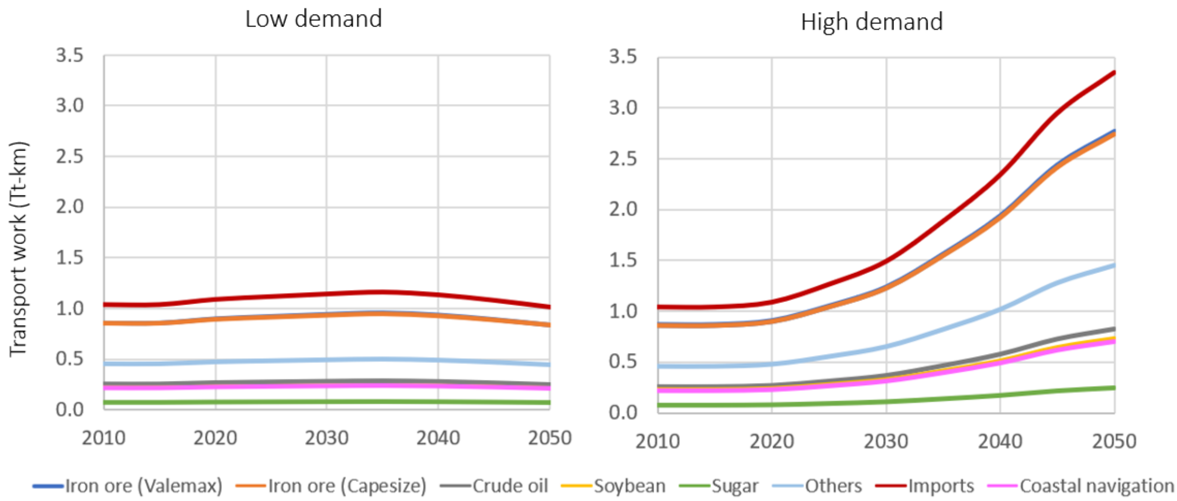

Figure 6: Demand for transport work associated with fuel supplied in Brazilian ports in high and low demand scenarios

The energy associated with Brazilian transport work in each scenario is determined using a simplified energy model and is calibrated with historical data for 2010-2018. The model estimates the demand for main engines (used for propulsion), auxiliary engines (electricity generation), and auxiliary boilers (heat production).

[38] The adopted literature scenarios are based on secondary energy, not transport work (useful energy). In the case of the high demand scenario, which considers the maintenance of efficiencies base year conversion rates, this is not significant. In the case of the scenario with the lowest consumption, however, there is a lag between the profile of the energy curve and that of demand, given the premises related to efficiency. However, for simplicity and data limitation, the final energy is directly used as a proxy for the growth of the projected tonne-kilometers. This implies, in the worst-case scenario, a range of slightly wider demand.

The propulsion energy demand is estimated through simplified hydrodynamic equations [126], [141]. The total hull resistance R_T and the associated brake power P_B are presented in equations 1 and 2, respectively.

$$R_T = \frac{1}{2}\rho C_T S v^2 \quad [1]$$

$$P_B = \frac{(1+m)R_T v}{\eta_T} \quad [2]$$

In equations 1 and 2, ρ is the seawater density, C_T is the total resistance coefficient, S is the wetted surface, m is the sea margin, v is the speed of the ship and η_T is the total propulsion efficiency. These parameters are estimated based on ship sizes and categories. Table 2 shows the vessels considered for each product, as well as their deadweight tonnage.

Auxiliary engines and boilers energy demand estimation follows [197]. It considers typical loads for different vessel categories, sizes and operational modes (at-berth, at-anchorage, maneuvering and at-sea) [198]–[205] (Table 2).

Table 2: Ship types and categories

Product	Ship type	Ship category	Deadweight (dwt)
Iron ore (Valemax)	Bulk carrier	Valemax	400,000
Iron ore (Capesize)	Bulk carrier	Capesize	150,000
Crude oil	Oil tanker	Suezmax	150,000
Soybean	Bulk carrier	Panamax	60,000
Sugar	Bulk carrier	Panamax	60,000
Other	Bulk carrier	Panamax	60,000
Import	Oil tanker	Panamax	60,000
Coastal navigation	Oil tanker	Panamax	75,000

In terms of fuel use, three different powertrains are considered: conventional 2-stroke diesel engines, dual-fuel engines, and solid oxide fuel cells (SOFCs) used in combination with electric motors. Table 3 shows the fuels suited to each one of these configurations. The literature indicates that fuels with lower energy density, such as methanol, LNG, and ammonia, might reduce the space available for cargo. Therefore, a volume loss of approximately 5% is considered for dual-fuel engines and solid oxide fuel cells [119]. Differences in investment costs are also considered [119], [206], [207]. As shown in Table 4, depending on the motorization, significant increases in the total CAPEX are observed, especially for the case of fuel cells. However, some drop-in[39] alternative fuels need only minor changes of the ship and bunkering to be directly used.

Table 3: Technology options regarding the powertrain

Powertrain	**Abbreviation**	**Extra cost (2010 USD/kW)**	**Volume loss (%)**	**Suitable fuels**
Two-stroke diesel engine	2S-D	0	0	Bunker, drop-in fuels
Dual-fuel engine	DF	242	5	LNG, methanol, bunker, drop-in fuels
Solid oxide fuel cell	SOFC	4675	5	Ammonia

[39] Fuels that can be used in marine diesel engines with no or small adaptation.

Table 4: Investment costs for the vessels considered in the modelling

Ship	**Powertrain**	**CAPEX (2010 kUSD)**
Bulk - Valemax	2S-D	81,000
Bulk - Valemax	DF	87,000
Bulk - Valemax	SOFC	198,000
Bulk - Capesize	2S-D	38,000
Bulk - Capesize	DF	42,000
Bulk - Capesize	SOFC	108,000
Bulk - Panamax	2S-D	30,000
Bulk - Panamax	DF	32,000
Bulk - Panamax	SOFC	67,000
Tanker - Suezmax	2S-D	49,000
Tanker - Suezmax	DF	53,000
Tanker - Suezmax	SOFC	119,000

As shown in Table 5, specific fuel consumption (SFC) varies according to the fuel used [119], [197], [208].

Table 5: Main engine specific fuel consumption

Fuel	**SFC (g/kWh)**
Fossil/synthetic bunker	179
SVO	170
HVO	190
LNG	150
Methanol	381
Ammonia	319

Efficiency gains are also modelled, since this is expected to be a major aspect contributing to the reduction of the energy demand from international shipping. Consistently with the projections of the literature [126], [209] and with the Energy Efficiency Design Index [104], when compared to 2010, new vessels are taken to be 20% more efficient in 2030 and 30% in 2050.

Fuel supply

As explained in section b, several alternative fuels can be considered for shipping. In this study, the most promising alternatives from each group are selected for integrated modelling. The fuel alternatives are summarized in Figure 7.

In the first generation biofuels group, SVO and HVO stand out as the most promising alternatives, with mature production technologies, good applicability and reasonable costs [114]. Usually, these fuels are associated with sustainability concerns on land-use change [210]–[212]. This is addressed in this study since integrated modelling is performed in an energy-land-use system model.

Regarding thermochemical routes, biobased FT-liquids are selected for the analysis, given their high mitigation potential, good applicability and especially its economies of scope. This includes FT-diesel and FT-gasoil, potential coproducts of higher market value fractions that can be used in different proportions to formulate FT-bunkers.

From the third group, which corresponds to biobased gases and alcohols, biomethanol is selected rather than LNG. Despite its drop-in characteristic relatively to fossil LNG, bio-LNG faces technical challenges, such as feedstock heterogeneity, geographical dispersion, and the need for cryogenic storage. Biomethanol would benefit from the existing infrastructure of fossil methanol and, despite not being a drop-in fuel, it has good applicability to the global fleet, once its use requires minor modifications on existing marine dual-fuel engines [213].

Finally, regarding hydrogen-based fuels, ammonia and synthetic hydrocarbons are selected rather than pure hydrogen. In spite of their direct emission reduction potential, both hydrogen and ammonia have very low applicability to the existing fleet, requiring preferably electrochemical-based motorization, which is not a mature technology yet [69], [119]. On the other hand, ammonia has better energy density and is more easily stored when compared to hydrogen, which can be an advantage [120]. Amongst the H_2-

based hydrocarbons, H_2-diesel and H_2-gasoil are a natural option since they are fully compatible with existing marine engines. It is worth noting that the model is free to choose between grey, blue, and green H_2-fuels according to its optimization strategy.

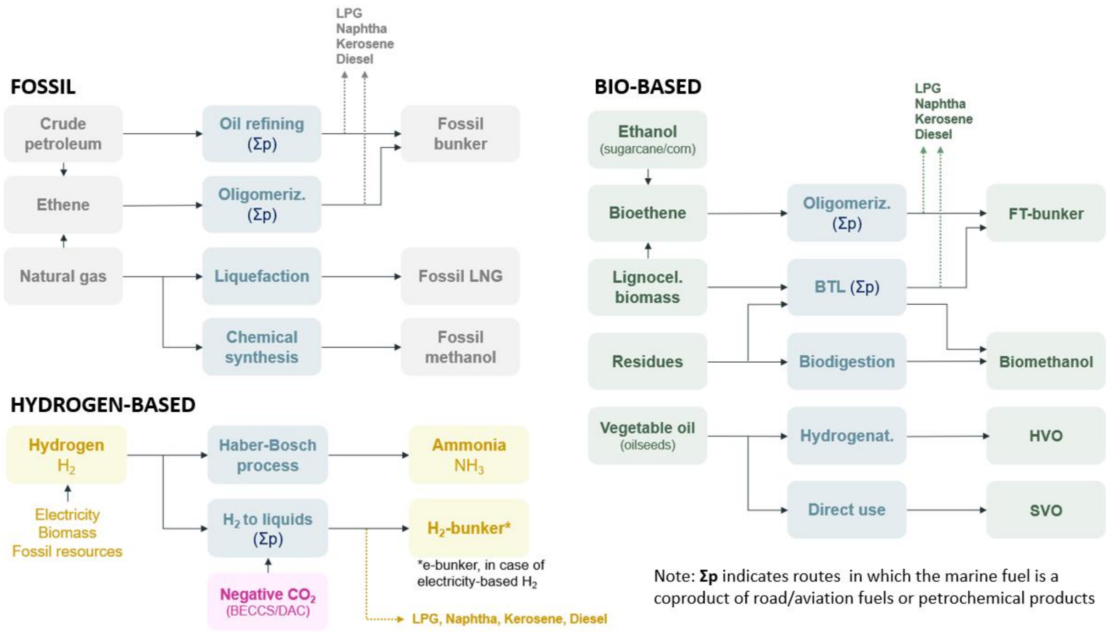

Figure 7: Marine fuel options represented in BLUES

Design of scenarios

With the alternative fuels for shipping represented within BLUES, eight scenarios are developed combining different assumptions. These scenarios are divided into two groups: portfolio and individual fuel scenarios. The idea is to explore a set of possible pathways in terms of freight demand and decarbonization scenarios of the Brazilian maritime transport sector. By exploring these scenarios, this study shows how an integrated assessment can indicate technological choices, and trade-offs, between emissions in ships and emissions in the upstream energy and land-use sectors. Clearly, various scenarios could also be explored, but for the sake of simplicity, this study aims at highlighting the relevance of using IAMs for studying the IMO target by deepening a set of threshold scenarios.

Portfolio scenarios (group 1) present no restrictions on fuel choice. Therefore, based on costs and carbon intensities, the model finds the least-cost combination of fuels. The portfolio scenarios premises are presented in Table 6.

Table 6: Scenarios' design (group 1, portfolio)

Scenario	Carbon metric	IMO2050	National target	Fuel restrictions
Baseline	-	No	No	None
IMO CO_2	CO_2	Yes	No	None
IMO GHG	CO_2eq	Yes	No	None
Brazil B2C	CO_2eq	Yes	Yes	None

The ***Baseline*** scenario represents a current policy view, admitting that announced mid-term policies are adopted and implemented. In ***IMO CO₂*** scenarios, the model is forced to halve the CO_2 emissions associated with the Brazilian foreign trade in 2050, consistently with the IMO2050 target. ***IMO GHG*** scenarios are similar to the latter but use CO_2eq instead of only CO_2 as a carbon metric. The idea is to capture the effect of all GHG emissions and not only carbon dioxide. Finally, ***Brazil B2C*** scenarios include emissions restriction not only to maritime transport but also to the whole Brazilian agriculture, land-use, and energy systems. As in [46], the Brazilian budget is provided by a global model (Computable Framework for Energy and the Environment - COFFEE). This model, also an IAM, has Brazil as one of its 18 regions. Considering a global budget compatible with warming well below 2°C, COFFEE outputs emissions trajectories for all the modelled regions, including Brazil. This value is then used as an input in ***Brazil B2C*** scenarios.

Individual fuel scenarios (group 2) are those in which only one fuel (or group of fuels) is selected as a mitigation alternative. The idea behind these scenarios is to analyze the impacts of choosing a single technological option to decarbonize the maritime sector. The individual fuel scenarios are presented in Table 7. Again, each scenario follows two trends over the evaluated period: low and high demands for maritime transportation.

*In **IMO drop-in*** scenarios, in addition to bunker, the model can choose any fuel that is a drop-in or nearly drop-in alternative. This includes SVO[40], HVO, and synthetic residual fuels coming from the Fischer-Tropsch process (FT-gasoil, in the case of a bio-based fuel or H_2-gasoil, in the case of a hydrogen-based fuel).

In **IMO *H_2-bunker*** scenarios, the model is restricted to fossil and hydrogen-based bunker (H_2-bunker). H_2-bunker is formed by the blend of H_2-diesel and H_2-gasoil, produced from hydrogen and carbon dioxide through the FT process. Carbon dioxide can only come from bioenergy with carbon capture (BECC) or direct air capture (DAC).

In ***IMO CH_3OH*** scenarios, in addition to fossil bunker, the model can use methanol (from fossil sources) or biomethanol (produced from anaerobic digestion or biomass gasification).

Finally, in ***IMO NH_3*** scenarios, the model is restricted to ammonia and fossil bunker. There is no restriction on the type of hydrogen used to produce ammonia and thus, the model can choose between fossil- and renewable-based hydrogen.

Table 7: Scenarios' design (group 2, individual fuels)

Scenario	Carbon metric	IMO2050	National target	Fuel restrictions
IMO drop-in	CO_2eq	Yes	No	Only drop-in[1]
IMO H_2-bunker	CO_2eq	Yes	No	Only H_2-bunker[2]
IMO CH_3OH	CO_2eq	Yes	No	Only methanol[3]
IMO NH_3	CO_2eq	Yes	No	Only ammonia[4]

[1]Drop-in fuels: SVO, HVO, FT-gasoil (residual fuel from FT-synthesis), or H_2-gasoil.

[2]Blend of H_2-diesel and H_2-gasoil.

[3]Fossil methanol and biomethanol.

[4]Fossil-based and renewable-based ammonia.

[40] SVO is considered as a nearly drop-in alternative, given concerns regarding its viscosity and oxidative and thermal stability [392].

In terms of energy demand, each scenario follows two trends for maritime transportation activity: low and high demand.

d. Results

Portfolio scenarios

Figure 8 shows fuel consumption for group 1 scenarios. In the absence of a national climate target, results indicate that LNG, SVO, and HVO are the preferable fuels to decarbonize maritime emissions (***IMO CO_2*** scenarios). In these scenarios, LNG figures as the least-cost choice, reducing CO_2 emissions compared to conventional fossil bunker, but still responsible for part of the emissions. On the other hand, an extra effort is needed to achieve IMO2050 and, therefore, carbon-neutral fuels play an important role. Hence, SVO (from soybeans) arises as a choice in the ***IMO CO_2 (Low)***[41] scenario, followed by HVO in the ***IMO CO_2 (High)*** scenario, replacing all traditional bunker in 2050 in the latter.

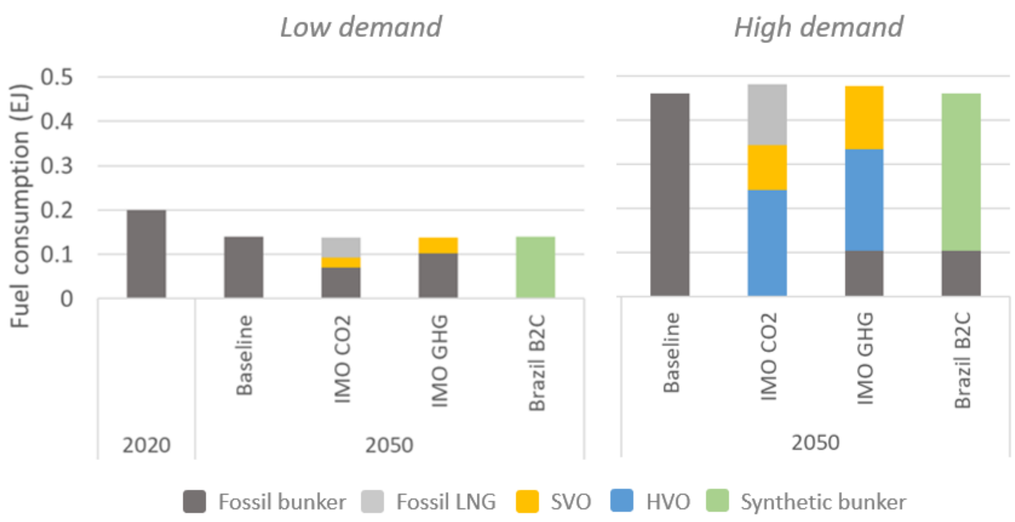

Figure 8: Fuels consumption in low and high demand portfolio scenarios

When restricting all GHG emissions (***IMO GHG*** scenarios), CH_4 emissions from LNG are taken into account and the fuel is replaced by fossil bunker and SVO. The latter is

[41] In this section, we use "*High*" or "*Low*" between parenthesis to differentiate high demand and low demand scenarios.

produced from soybeans, doubling soybean oil production in ***IMO CO_2 (High)*** and ***IMO GHG (High)*** scenarios in 2050, compared to the ***Baseline (High)*** scenario.

Despite the area expansion required for crops in these scenarios (around 9 Mha in each one), deforestation would not increase under a purely technical-economic evaluation. In Brazil, deforestation is not proportional to agricultural production, but rather mostly related to land grabbing [46], [214]–[218]. For SVO production, degraded pasture areas can be converted into crop areas, with no pure technical reasons to increase deforestation rates.

The inclusion of a carbon budget for Brazil´s national GHG emissions on top of IMO2050 (***Brazil B2C*** scenarios) shows a synergy between the whole country and international shipping decarbonization efforts. In a well-below 2^{o}C world, advanced biofuels are produced in Brazil to replace part of the fossil kerosene and diesel. These technological routes are also able to supply heavy hydrocarbon fractions as a coproduct, which could be used as synthetic bio-based bunker fuels (biobunkers). In this sense, it can be stated that the decarbonization of the maritime freight transport needed to meet IMO requirements would be included in a deep mitigation pathway in Brazil compatible with a well-below 2^{o}C world.

The cumulative land-use change from 2020 to 2050 is presented in Figure 9. Results show a small increase in crop area to produce soybeans for SVO and HVO in ***IMO CO_2 (High)*** and ***IMO GHG (High)*** scenarios. In a well-below 2^{o}C world (***Brazil B2C*** scenarios), land use largely contributes to mitigation in Brazil through reforestation and pasture recovery, resulting in a significant land-use change in a horizon up to 2050.

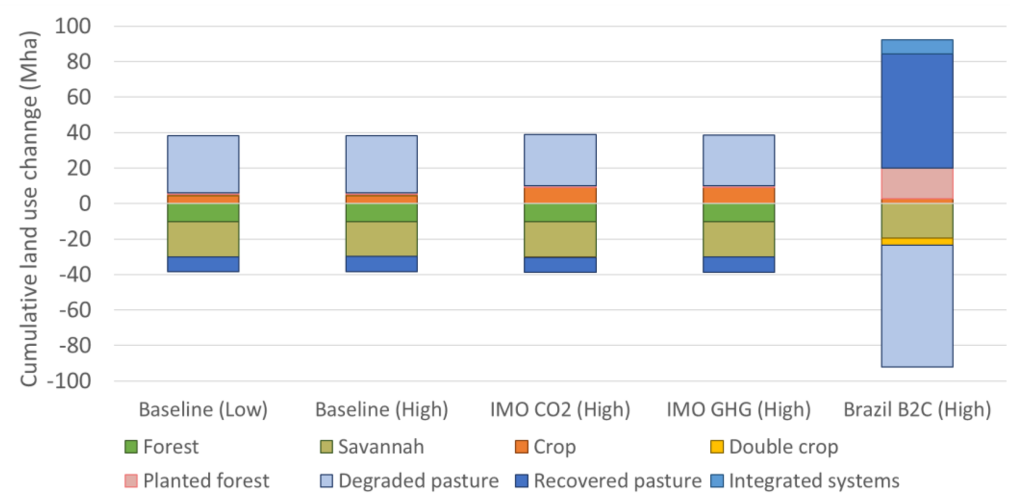

Figure 9: Cumulative land-use change between 2020 and 2050

Individual fuel scenarios

Figure 10 shows the results of group 2 scenarios, in which only one fuel category competes with fossil bunker, meaning that Brazil chooses a single technology or group of technologies to achieve IMO2050.

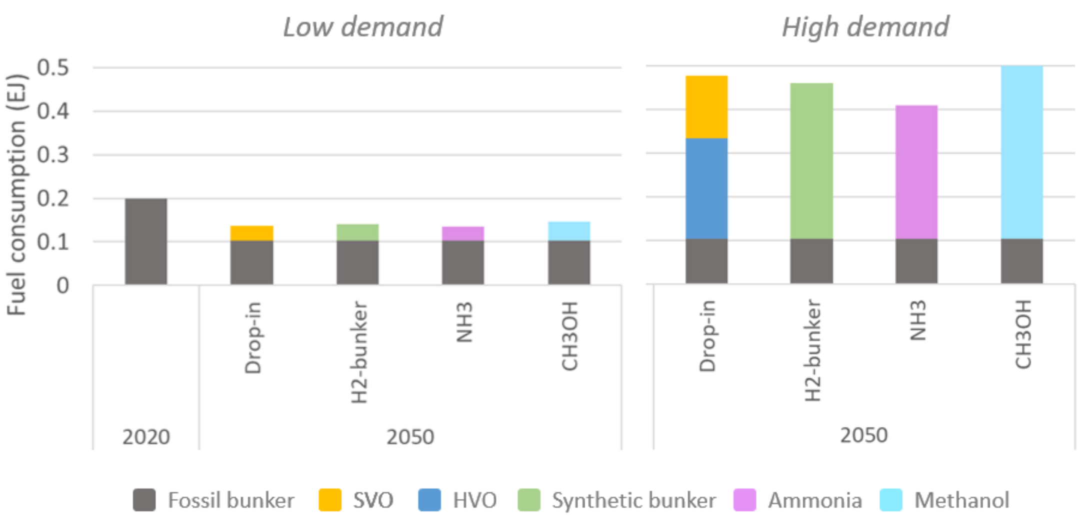

Figure 10: Fuels consumption in low and high demand individual scenarios

In ***IMO drop-in*** scenarios, the same result as ***IMO GHG*** is reached since the use of drop-in fuels represents the least-cost option. Due to its lower costs, SVO is again the preferred alternative, followed by HVO.

In ***IMO H_2-bunker*** scenarios, the synthetic fuel is produced from both fossil-based hydrogen – from hydrogen production units (HPUs) in oil refineries –, due to its lower cost, and renewable hydrogen. HPU capacities must increase 20 times between 2020 to 2050 to produce the required amounts of hydrogen, which is unlikely to occur. Also, a large quantity of CO_2 is required for the FT process, which is supplied by carbon capture coming from different types of bioenergy plants (ethanol, FT-diesel, and bio-based hydrogen production).

For this reason, ethanol production increases around 30% in the ***IMO H_2-bunker (High)*** scenario compared to the ***Baseline (High)*** scenario. Part of this surplus is used to produce advanced kerosene through ethanol dehydration and subsequent ethene oligomerization.

A similar effect is observed in ***IMO NH_3*** scenarios, with ammonia being produced entirely from fossil-based hydrogen due to its lower production cost. In the ***IMO NH_3 (High)*** scenario, a 12-time increase is observed in HPU capacity until 2050. With respect to the fleet, in the ***IMO NH_3 (Low)*** scenario, 127 ammonia-based vessels would be required up to 2050, whilst in the ***IMO NH_3 (High)*** scenario this quantity would be 1,077, which represents an 8.5-time increase. As fossil-based ammonia does not produce direct emissions in ships, no incentive to produce clean hydrogen is observed.

In contrast, in ***IMO CH_3OH*** scenarios, in which the use of fossil methanol would imply direct CO_2 emissions in ships, only biomethanol is used.

Emissions spill over and cost increase

Figure 11 presents, for the high demand scenarios, a relation between the national emissions and the mitigation (CO_2eq abated) on maritime transportation associated with Brazilian foreign trade, attained as a result of IMO2050. It states that the decarbonization of the navigation sector implies a spill over on Brazilian emissions due to an increase in energy sector activities.

Figure 11 shows, for some of the individual pathway scenarios, that the spill over exceeds the mitigation achieved for seaborne transport; thus, representing an increase in total emissions. Even in ***IMO CO_2***, ***IMO GHG***, and ***IMO CH_3OH*** high demand scenarios, around half of the emissions avoided by switching to low-carbon maritime fuels would be additionally emitted by the Brazilian energy system, partially compromising the gains obtained by maritime decarbonization efforts.

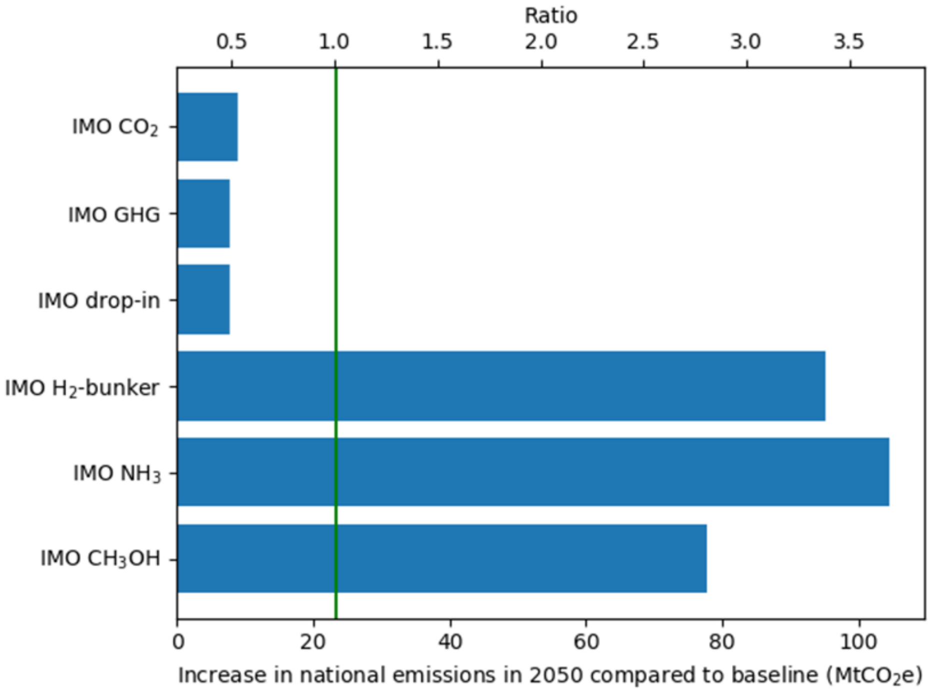

Figure 11: Increase in national emissions in different high demand scenarios. The green line represents the level at which an increase in national emissions equal to decrease observed in the maritime emissions. In Brazil B2C (High) scenario, there is significant reduction in national emissions that can not be associated with IMO's target. As such, this scenario is not presented in the figure.

Regarding costs (Table 8), the objective function of the model accounts for all the expenses of the energy system and land use, including investment and operational costs, as well as the costs associated with energy demand (e.g., new final energy consumption devices). Therefore, it reflects the cost increment of the energy systems to produce the fuels needed to achieve IMO2050 targets, as well as the costs for new vessel acquisition. For instance, it includes the cost of HPU expansion in oil refineries and in cropland technologies for enhancing soybean production for SVO and HVO. This clearly shows the relevance of using IAMs to assess the IMO target.

Table 8: Relative cost increase in high and low demand scenarios

	Relative cost increase[1,4]	
	Low demand	**High demand**
IMO CO_2	1.0[2]	1.0[3]
IMO GHG	1.6	1.1
IMO drop-in	1.6	1.1
IMO H_2-bunker	4.9	2.4
IMO NH_3	7.1	3.0
IMO CH_3OH	12.5	5.9

[1]Cost increment due to the whole energy and land use system, including investment and operational costs, demand, transformation, logistics, vessel acquisition, and others.

[2]Cumulative cost increase: 91 MUSD

[3]Cumulative cost increase: 1,900 MUSD

[4]*Brazil B2C* scenarios' cost represents the system's decarbonization to attain global climate targets and not only IMO2050. In this scenario, biobunker is a residue of synthetic biofuels routes already used to comply with a well-below 2°C world, focusing on diesel, jet fuel, and naphtha. As such, marine residual fuels have a null shadow price. As transportation costs to reach Brazilian ports are small compared to the full cost cycle, they can be neglected. Therefore, *Brazil B2C* scenarios can be seen as a non-regret policy to IMO's target.

The individual pathways scenarios required a large expansion of the fuels supply chain capacities. As aforementioned, HPU capacity would need to increase 20 times in the ***IMO H_2-bunker (High)*** scenario and approximately 950 extra ammonia-based vessels would be required in the ***IMO NH_3 (High)*** scenario, compared to the ***IMO NH_3 (Low)*** scenario. On the other hand, low demand scenarios do not strongly stress the energy and land-use systems. They offer plausible solutions, respecting reasonable industrial developments that could be a feasible pathway for the future.

e. Discussion

In case large amounts of low-carbon fuels are required to achieve IMO2050, relevant impacts could be observed on a national level, especially if it focuses on direct emissions, disregarding second-order effects. From a strictly technical point of view, our results indicate that Brazil can follow any low-carbon fuel strategy. However, second-order effects associated with the different scenarios, as well as their cost-effectiveness, vary widely.

In the case of group 1 (portfolio scenarios), a clear distinction is observed between scenarios assuming the coexistence of the IMO2050 strategy and a national climate target and scenarios in which IMO2050 is the only climate target. In the latter, LNG, SVO and HVO have to be produced exclusively because of shipping, while in the presence of a national climate target, ships are fueled by bio-based bunker, generated as a coproduct of higher value synthetic hydrocarbons.

As expected, results from individual fuel scenarios are less cost-effective, as the optimization was forced to focus on technologies such as fuel cell-based ships, biodigestion and hydrogen production units. In the case of scenarios based on hydrogen-derived fuels, unrealistic increases in HPU capacities and fleet expansion were observed.

Furthermore, all individual fuel scenarios implied significant spill over effects, with GHG emissions reductions from shipping being way lower than the corresponding increase in national emissions. This is well illustrated by the results of the ***IMO NH_3 (High)*** scenario, in which the use of ammonia causes an increase of approximately 105 $MtCO_2e$ in national emissions in 2050 compared to the baseline, whereas navigation's emissions reduction would achieve around 28 $MtCO_2e$. This effect is partially due to the fact that, regardless of its origin, ammonia is a carbon free fuel in terms of direct emissions. As such, and given the lower cost of the fossil production route, IMO2050 is met at the expense of a higher carbon intensity in the supply chain.

The carbon leakage observed in this modelling exercise draws our attention to the need for a certification of alternative fuels. So far, IMO2050 refers exclusively to direct emissions [110]. Therefore, if ammonia or even hydrogen emerges as a marine fuel in the next decades, it is likely that increases in national emissions will take place all over the world. Nevertheless, this can be avoided through rigorous control of the origin of the fuel, including the possibility of producing blue ammonia.

Although the results of this study do not point to a similar effect for the case of methanol, there is a similar risk regarding this fuel. Unlike fossil-based ammonia, methanol obtained from natural gas, oil or coal is by definition a fossil resource. As such, its combustion is seen by the model as a source of extra direct GHG emissions. This is why the use of the fuel is very limited in ***IMO CH_3OH*** scenarios, dominated by biomethanol. This distinction prevents high spill over effects and, in methanol scenarios, the reduction in shipping emissions is indeed higher than the increase in national emissions. However, considering that biomethanol is chemically identical to fossil methanol, it can be said that, in the absence of adequate control of the supply chain, the shipping sector is exposed to the same risk described for the case of ammonia.

For biofuels, results indicate that it is technically and economically feasible to produce bio-based bunker fuels in Brazil without deforestation, but this does not guarantee that there will be no deforestation in the country. In this sense, the production of biofuels should be certified to avoid land speculation [216], [217]. Also, the model indicates the possibility of co-producing biomass-based marine fuels with higher value-added products, such as diesel, naphtha and biomaterials.

f. Final remarks

The set of IMO2050 has brought the climate mitigation discussion into the global maritime transportation sector. Achieving this goal can be challenging depending on the technological evolution of ships, and specially on the development of the demand for shipping, which is a function of the trade of products like coal, oil, grains, iron ore, chemicals and containerized cargo. With the expectation that the maritime activity will remain approximately constant over the next 30 years, constructive and operational efficiency gains in ships might promote most of the abatement of emissions required to comply with IMO2050 strategy. On the other hand, a future increase in maritime activity, which is consistent with the recent historic trend, will make IMO2050 strategy much harder to attain. In this case, low-carbon fuels might make a significant contribution, given that the impact of energy efficiency on emissions reduction is limited.

Brazil has some advantages to kick off the production of low-emissions alternative fuels for the maritime sector considering its experience in producing and implementing alternative transportation fuels. From an IAM point of view, the optimal portfolio of alternative fuels can vary depending on demand assumptions and mitigation targets. LNG, for example, stands out as a promising alternative in case only CO_2 emissions are accounted for within IMO goals, while it is replaced by SVO and HVO, when considering total GHG emissions.

Scenarios with a national decarbonization effort (***Brazil B2C***) show that drop-in renewable bunker fuels, produced mostly from technologies coupled with CCS, represent the most of fuel consumption and synthetic bunker is coproduced with higher value-added products, such as synthetic diesel and naphtha. These results highlight the synergies between both efforts, indicating that the achievement of IMO goals would be implicit in a national decarbonization strategy.

While it is possible to attain IMO2050 in Brazil with plants dedicated to the production of maritime fuels, achieving IMO2050 goal from a direct emission perspective may result in potential spill overs due to the intense use of the energy sector. In short, only an integrated national mitigation strategy could lead to effective decarbonization of the entire Brazilian marine fuel supply.

3. Há sinergias na descarbonização da aviação e do transporte marítimo? Uma perspectiva integrada para o caso do Brasil

Neste capítulo, reproduz-se o manuscrito final submetido à revista *iScience* para publicação do artigo *Are there synergies in the decarbonization of aviation and shipping? An integrated perspective for the case of Brazil* (volume nº 25; fascículo nº 10; DOI: 10.1016/j.isci.2022.105248).

ARE THERE SYNERGIES IN THE DECARBONIZATION OF AVIATION AND SHIPPING? AN INTEGRATED PERSPECTIVE FOR THE CASE OF BRAZIL

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Summary

Aviation and shipping account for 22% of total transport-related CO_2 emissions. Low-carbon fuels (such as biofuels and e-fuels) are the most promising alternatives to deeply decarbonize air and maritime transport. A number of technological routes focused on the production of renewable jet fuel can coproduce marine fuels, emulating the economies of scope of crude oil refineries. This work aims to investigate possible synergies in the decarbonization of aviation and shipping in Brazil, selected as an interesting case study. An Integrated Assessment Model (IAM) of national scope is used to explore different combinations of sectoral and national climate targets. This IAM represents not only the energy supply and transport systems, but also the agricultural and land use systems. In the absence of a deep mitigation policy for Brazil, results indicate synergies related to oilseed- and lignocellulosic-based biofuels production routes. Imposing a strict carbon budget to the Brazilian economy compatible with a world well below 2ºC, the portfolio of aviation and shipping fuels changes significantly with the need for carbon dioxide removal strategies based on bioenergy. In such a scenario, synergies between the two sectors still exist, but most renewable marine energy supply is a by-product of synthetic diesel produced for road transport, revealing a synergy different from the one originally investigated by this work.

a. Introduction

The Glasgow Climate Pact reached at COP26 strengthened climate mitigation ambition, recognizing that the impacts of climate change will be much lower with a temperature anomaly of 1.5°C compared with 2.0°C [219]. The transport sector is a major CO_2 emissions source, accounting for some 8.5 $GtCO_2$ in 2019 (i.e., around 25% of the total energy-related CO_2 emissions that year) [220], [221]. Moreover, the demand for transport will likely increase in the coming decades. Without mitigation measures, this will imply higher annual CO_2 emissions from this sector [55], [66], [222], [223]. Most transport-related CO_2 emissions come from light (45%) and heavy (30%) road vehicles. Aviation and shipping come next, with 11% each. Rail, pipeline and non-specified modes represent only 3% of transport emissions [224] (Figure 1).

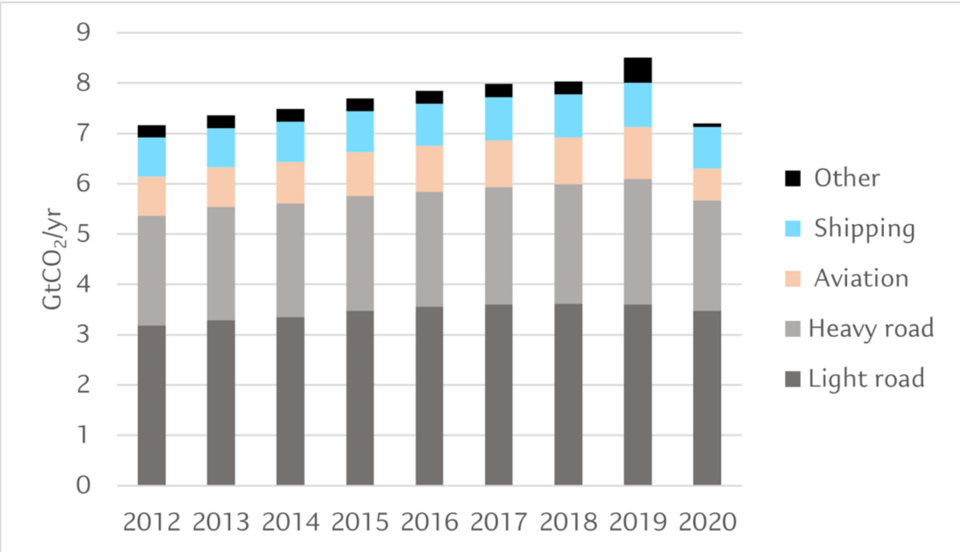

Figure 1: Global CO_2 emissions from the transport sector between 2012 and 2020 [97], [224]

With the rise of electric vehicles (EVs), electrification is increasingly regarded as key to decarbonize passenger road transport (EVs could strongly reduce the carbon intensity of the transport sector - however, without proper power supply decarbonization, transport electrification could increase overall energy emissions) [225]. Furthermore, EVs could become an important option for road freight, mainly in short-haul routes [39], [162], [225]–[230]. In the case of air and maritime transport, the full electrification of powertrains is unlikely to be the most competitive option due to energy density issues (see Figure 2). The low energy density of batteries (even the most advanced ones) implies either an enormous range reduction or an unrealistic extra weight onboard [64], [162].

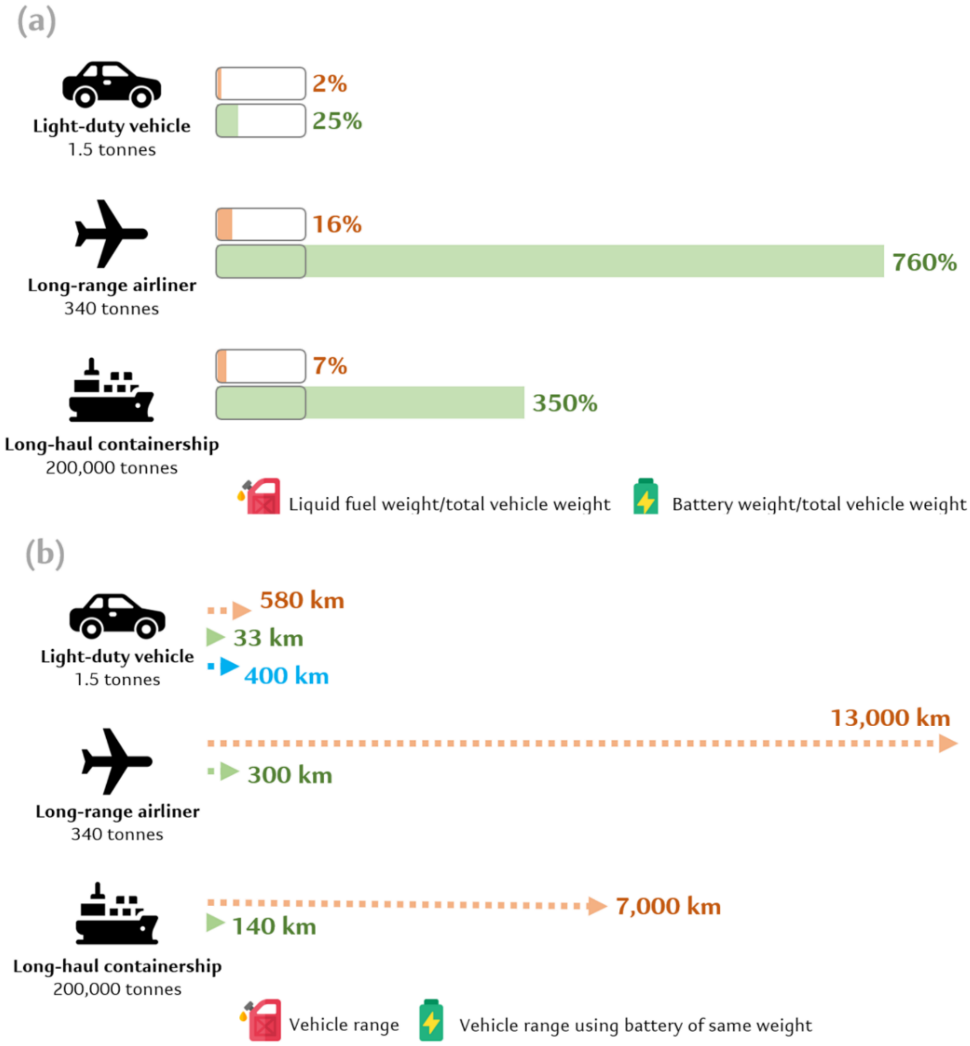

Figure 2: Energy density—liquid hydrocarbons versus batteries (A) Red: ratio between full-tank fuel weight and total ICE-based vehicle weight. Green: ratio between battery weight and total electric vehicle weight considering an amount of batteries equivalent to the energy stored in the fuel tank of an ICE-based vehicle. (B) Red: ICE-based vehicle range. Green: electric vehicle range considering an amount of batteries equivalent to the mass contained in the fuel tank of an ICE-based vehicle. The blue arrow represents the range of a typical electric car (Chevrolet Bolt). Pure electric cars make up the low energy density of batteries by adding a large battery while making the rest of the car as light as possible. Still, they tend to be heavier than ICE vehicles. Source: Own elaboration, based on [65].

As such, aviation and shipping are part of the hard-to-abate sectors, defined as sectors associated with energy services/industrial processes that are particularly difficult to provide without adding CO_2 to the atmosphere [53], [66], [162], [231]–[233]. Still, rapidly reducing CO_2 emissions from aircrafts and ships is essential to keep the 1.5°C warming limit within reach. In the Working Group III Contribution to the Sixth Assessment Report (AR6) of the IPCC, scenario categories are defined by their likelihood of exceeding global warming levels. From the eight existing categories, C1 (limit global warming to 1.5°C with no or low overshoot) and C2 (return to 1.5°C after a high overshoot) represent the lowest warming scenarios [21]. In scenarios falling into the lowest global warming categories (C1 and C2), aviation emissions typically equal 0.3-1.0 $GtCO_2$/yr in 2050 (compared to 1.0 $GtCO_2$ in 2019) [36], [224]. For the same warming categories, shipping emissions decline to 0.3-0.7 $GtCO_2$/yr in 2050 (from 1.0 $GtCO_2$/yr in 2018) [55], [234].

Both the International Civil Aviation Organization (ICAO) and the International Air Transport Association (IATA) have goals and measures focused on achieving carbon neutrality (including out-of-sector options) by 2050, including a 50% reduction in annual aviation emissions by 2050 compared to 2005 (hereinafter IATA2050) [235]–[239]. Similarly, the shipping sector has recently started to incorporate the climate dimension into its long-term planning. In 2018, the International Maritime Organization (IMO) set a preliminary strategy to reduce shipping-related GHG emissions, which includes a 50% cutback in total emissions by 2050 compared to 2008 (hereinafter 2050) [234], [240].

If applied strictly to sectoral direct emissions, both IATA2050 (which means 0.35 $GtCO_2$/yr in 2050) and IMO2050 (which means 0.50 $GtCO_2$/yr in 2050) can be seen as in line with global scenarios that limit global warming to 1.5°C (C1) or return to 1.5°C after a significant overshoot (C2). This is especially true if the 50% cutback targets are complemented with upfront emission reductions [21], [36], [55]. In this context, low-carbon fuels (i.e., fuels having renewable resources as their main feedstock – e.g., biofuels and e-fuels) are front runners in the mitigation strategies of both sectors since the energy efficiency mitigation potential is intrinsically limited (strictly speaking, in addition to renewable-based fuels, low-carbon fuels could include energy carriers produced from fossil resources with carbon capture or even nuclear energy. For simplicity, low-carbon fuels and renewable fuels are treated as synonyms over the text. They include conventional/advanced biofuels and renewable hydrogen-based fuels) [68]. This limitation refers to the whole set of potential mitigation measures that can help lower aviation and shipping energy intensities, including constructive and operational measures (e.g., improvements in hull and aircraft design, wind assistance, slow steaming, weather routing etc.) [126]. Depending on the perspective, all of these can be considered energy efficiency measures (contrary to fuel switch). Moreover, the annual global demand for international transport is expected to increase significantly over the next decades [162], [234], [241].

In oil refineries, aviation fuels have strict specifications in terms of chemical properties while marine fuels (bunkers) require high energy density at low costs (to deal with the type of energy service required by shipping – long-haul transport, usually of lower value-added goods). Thus, aviation fuels often make up the margin of oil refineries (as "premium" fuels), whereas bunkers are normally produced from residual fractions, seeking to meet the compromise between quality and price [125]. Similarly, several technological routes focused on the production of renewable aviation fuels coproduce fractions suited to the formulation of renewable marine fuels. As such, the economies of scope observed today in oil refineries could also be present in low-carbon energy systems. In this case, renewable-based bunker would be a by-product of renewable-based kerosene. This would represent a synergy between the sectors, making the mitigation of aviation and shipping more efficient, potentially minimizing impacts on land use change [118].

This study aims to evaluate this theoretical synergy for a practical case study in Brazil, given its relevant foreign trade specificities. The country's economy is highly dependent on the exports of low value-added products (implying high energy consumption per unit of exported value) [180] and its maritime trade routes typically involve distances longer than 8,000 nautical miles. The country is therefore exposed to significant risks in terms of freight costs. Furthermore, the Brazilian aviation market is the seventh largest in the world [242]. Another reason that justifies the choice of Brazil is its leading role in bioenergy production and use [243].

As detailed over the course of the paper, BLUES is an Integrated Assessment Model (IAM) representing not only the aviation and shipping sectors, but the whole energy, agriculture and land-use systems of Brazil [46], [183]. BLUES simultaneously represents the food and energy supply-demand balances, therefore taking aspects such as food security into account. IAMs have been broadly used to explore the consequences of various long-term climate change mitigation strategies. They contain a detailed representation of the world's energy, land use, agricultural and climate systems, as well as their inter-linkages [27], [40], [244], [245]. In this work, an integrated assessment perspective is used to analyse the possible developments of the aviation and shipping sectors under specific climate targets, with a special focus on the upstream connections between these two sectors. In short, the objective of this scientific investigation can be summarized in the following manner: "Several renewable fuel production routes can output both aviation and maritime fuels. Given that aviation fuels typically have higher value-added, is it possible that the decarbonization of the Brazilian jet fuel market engenders a low-cost renewable energy surplus capable of meeting a significant share of the country's maritime fuel demand, thereby lowering the mitigation effort of the shipping sector?"

The novelty of this study can be summarized in the following points:

- Analysis of the role of aviation and shipping in deep mitigation scenarios using a national IAM.
- Assessment of the decarbonization of the two sectors beyond the sectoral perspective, considering the interlinkages between energy, agriculture, and land use.
- Modelling and optimization of marine and aviation renewable fuel production routes with high detail, including economies of scale and scope.
- Pioneer reflection on the possibility of a combined decarbonization supply strategy for the aviation and shipping sectors in Brazil.

Despite the focus on the linkage aviation-shipping, another notable synergy indicated by this work involves the road transport sector. Just as kerosene, the production of fossil or renewable diesel has heavy fractions as a by-product. As such, in deep mitigation scenarios, for which the BLUES model indicates bio-based diesel (such as the one produced from biomass gasification and FT synthesis) as the optimal alternative to decarbonize the large Brazilian diesel market, significant amounts of biobunker are coproduced.

b. Coproduction of renewable aviation and marine fuels

Figure 3 summarizes the main technologies capable of producing renewable-based aviation fuels, with marine fuels as by-products. As shown in Table 1, four technologies are assessed: synthetic kerosene from hydrotreated esters and fatty acids (biokerosene, HEFA/HVO), synthetic kerosene from the oligomerization of alcohols (biokerosene, AtJ), synthetic kerosene from lignocellulosic biomass (biokerosene, BtL) and synthetic kerosene from electrolytic hydrogen (e-kerosene). All of these fuels are fully drop-in alternatives, both in case of aviation and shipping.

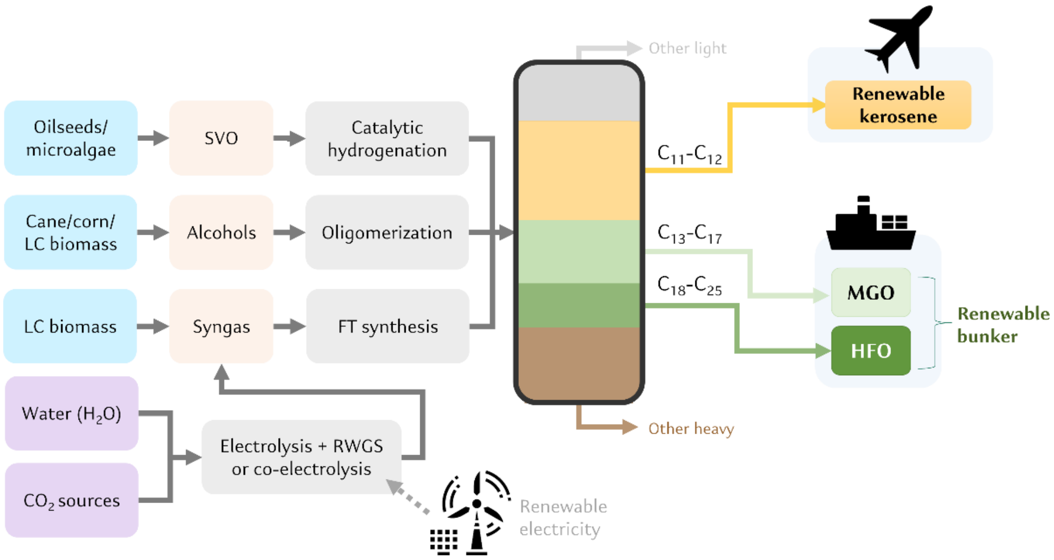

Figure 3: Main renewable aviation and marine fuels coproduction technologies. Blue boxes indicate bio-based feedstock. Violet boxes indicate feedstock associated with hydrogen/electricity-based processes. Proportions presented in the figure are illustrative and can vary widely both across and inside the different production processes. Note: MGO, Marine Gas Oil; HFO, Heavy Fuel Oil; SVO, Straight Vegetable Oil

Table 1: Renewable drop-in aviation and marine fuels

Aviation fuel	ASTM name[4]	Marine fuel[6]	Short process description
Biokerosene, HEFA/HVO[1]	HEFA-SPK	Biobunker, HEFA/HVO	Hydroprocessing of fatty acids and esters
Biokerosene, AtJ[2]	ATJ-SPK	Biobunker, AtJ	Oligomerization + hydrogenation of alcohols
Biokerosene, BtL[3]	FT-SPK	Biobunker, BtL	Biomass gasification + FT synthesis
e-kerosene	FT-SPK[5]	e-bunker	Electrolysis/co-electrolysis + FT synthesis

[1]HEFA = Hydroprocessed Ester and Fatty Acids, HVO = Hydrotreated Vegetable Oil

[2]AtJ = Alcohol-to-Jet

[3]BtL = Biomass-to-Liquids

[4]ASTM = American Society for Testing and Materials. Taking into consideration that the same aircraft can be fuelled in different countries, international specifications have been adopted for jet fuels. The standard regulating the technical certification of SAF is ASTM D7566. Upon release from blending the fuel is certified to ASTM D1655 and from this point is regarded as conventional Jet A or Jet A1 kerosene [246].

[5]According to ASTM, FT-SPK is defined as a bio-based fuel. However, considering that the Fischer-Tropsch synthesis can also be used in electricity-based pathways to produce synthetic kerosene, we assume that the name FT-SPK is also applicable to this case.

[6]In this column, we use the term “bunker” in a broad sense, including both light and heavy gasoil.

The HEFA/HVO, AtJ and BtL routes are certified biokerosene production routes, approved for blends up to 50% with conventional jet fuel [63]. However, among all certified technologies, only HEFA/HVO has reached the commercialization status (TRL 9), as shown in Table 2. Currently, ten HEFA/HVO plants are in operation and produce 5 billion litres of fuel (mostly renewable diesel) annually [247]. In their turn, BtL and AtJ reached TRL 7, which means that processes have been demonstrated in an operational environment. Contrastingly, e-kerosene is still in validation stages (TRL 5) [248].

Table 2: Technology Readiness Level (TRL) of low-carbon fuel production pathways

TRL	Production Route	Companies
Basic principles reported (1)	-	-
Concept formulated (2)	-	-
Proof of concept (3)	-	-
Preliminary evaluation (4)	-	-
Process validation (5)	e-kerosene	Carbon Engineering, Norsk e-fuel, Zenid
Full-scale technical evaluation (6)	-	-
Fuel approval (7)	BtL, AtJ	Byogy, Comsyn, LanzaTech, Red Rock Biofuels, Total, Velocys
Commercialization validated (8)	-	-
Production capability established (9)	HVO/HEFA	Eni, Honeywell, Omega Green, Neste Oil

In terms of costs, all pathways register values above current jet fuel prices. As illustrated by Figure 4, the average price of fossil kerosene was around 15 USD/GJ in 2018, while the production costs of low-carbon fuels vary between 18 and 510 USD/GJ, according to the literature [118], [249]–[254]. Among biofuels, price levels are approximately within the same ranges. The AtJ route registers both the lowest (18 USD/GJ) and the highest (93 USD/GJ) levelized costs, which is explained by feedstock cost variation and intermediate alcohol production technology. For e-kerosene, LCOF is almost 10 times higher than the average cost of biokerosene, and at least 15 times higher than the price of conventional jet fuel. This is mainly due to high costs associated with low-maturity level technologies which are needed in the production pathway of this kind of fuel, such as carbon capture. Generally, low-carbon fuel costs are highly dependent on feedstock, inputs, and technology specificities.

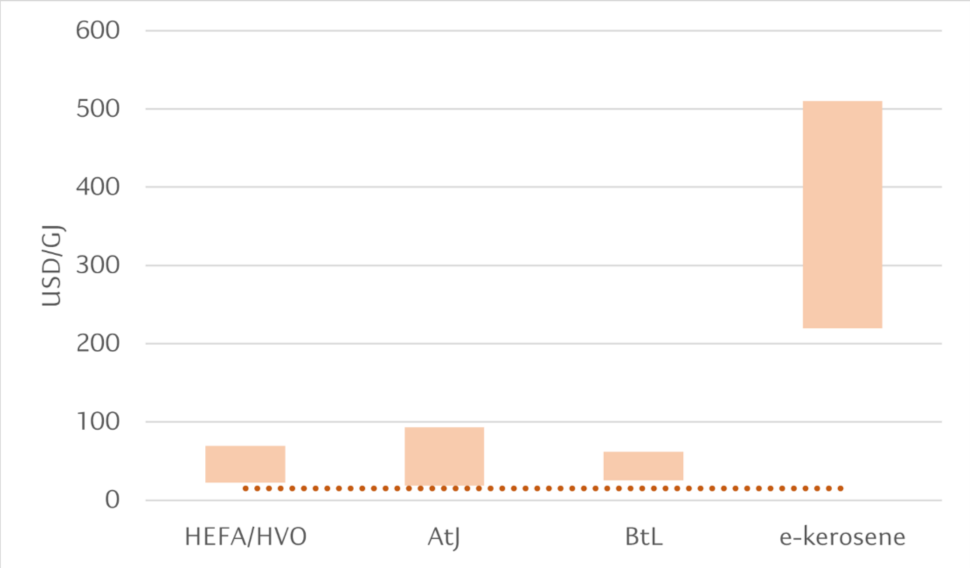

Figure 4: Levelized Cost Of Fuel (LCOF) for low-carbon jet fuel production technologies [118], [249]–[253]. *The dashed line represents the average price of conventional jet fuel in 2018 (15 USD/GJ)* [255]

Additionally, the use of biomass to obtain renewable fuels can also occur through the coprocessing of biomass-derived oils in existing oil refineries. This solution uses infrastructure and labour which are already available and, thus, can be readily applied without significant additional investments. Although refining units capable of processing biomass-derived oils are not usually focused on the production of jet fuel, this strategy is also assessed by this work because these units produce heavy oil fractions suitable to shipping [256]. The most common biomass-derived oils proposed for coprocessing include Straight Vegetable Oils (SVOs) and Pyrolysis Oil (POs, also known as bio-oils [257]). While SVOs are suitable for coprocessing in Fluid Catalytic Cracking (FCC) and Hydrotreatment (HDT) units, POs can be fed mainly to FCC units [258], although some studies also tested its processing in thermal cracking and de-asphalting units [259]. In all cases, the products obtained in the end of the refining process contain a bio-carbon content. SVO coprocessing shows higher maturity level when compared to PO coprocessing. Many refineries, including some from companies such as BP, Repsol and Shell, already operate this kind of process [260]. Usually, low investment costs are required due to the application of existing infrastructure. O&M costs are mainly influenced by biomass acquisition costs. In the case of hydrotreatment operations, O&M

costs tend to be higher due to high steam reformed or electrolysed hydrogen consumption and, in some cases, by the need for more expensive catalysts [257], [261].

c. The BLUES model

The analysis conducted in this study uses the BLUES model, an IAM of national scope. BLUES is a partial equilibrium, intertemporal and least-cost optimization tool representing the Brazilian energy, agriculture, land-use, and materials sectors, along with their multiple inter-linkages (Figure 5). With inputs related to population growth, macroeconomic assumptions and technology progress, the model seeks to find the minimum cost solution for the expansion and development of the represented sectors, outputting variables such as energy use, GHG emissions, agricultural production, water use and atmospheric pollution. This modelling framework is particularly suited to long-term analyses of the energy and land-use systems under specific conditions through the development of scenarios. The detailed description of the BLUES model can be found in the Integrated Assessment Modelling Consortium (IAMC) documentation webpage [183], [262].

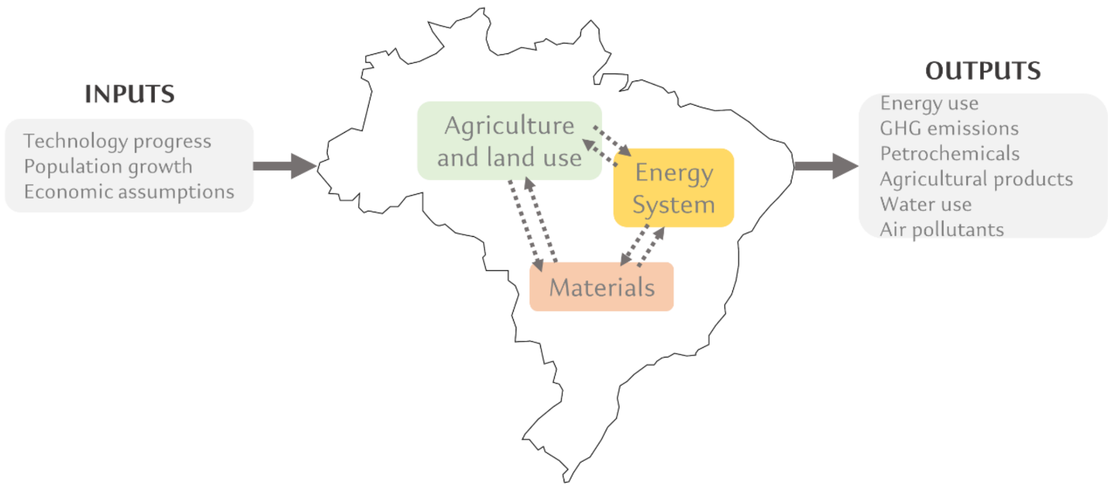

Figure 5: Basic structure of the BLUES model

It is worth noting that the BLUES model depicts the whole energy and land systems, including food chains, from primary resources to the final consumption. Historical capacities, investment and operational costs, efficiency/yield coefficients and energy inputs are attributed to all activities/technologies. Furthermore, CO_2 emission factors are attributed to every energy source. These emission factors derive from the carbon content of each fuel and from the IPCC TFI tier 1/2/3 methodological framework [263]. Since the BLUES model follows an integrated approach, overall CO_2 emissions include all steps of supply chains.

Over the past five years, the BLUES model has been extensively used in studies related to climate mitigation. For example, [46] analysed the impact of the weakening of deforestation governance on the mitigation effort needed in other sectors of the Brazilian economy. Besides, [264] developed an integrated analysis of the role of bio-based petrochemicals in deep mitigation scenarios. Also, [265] explored the possible developments of the Brazilian marine energy supply and their potential impacts on the national energy and land-use system. As a last and more recent example, [266] used eleven well-established IAMs of national scope (including BLUES) to list out good practice policies that may allow bridging the emissions gap in key countries. The representation of energy alternatives for aviation and shipping in BLUES is summarized in Figure 6.

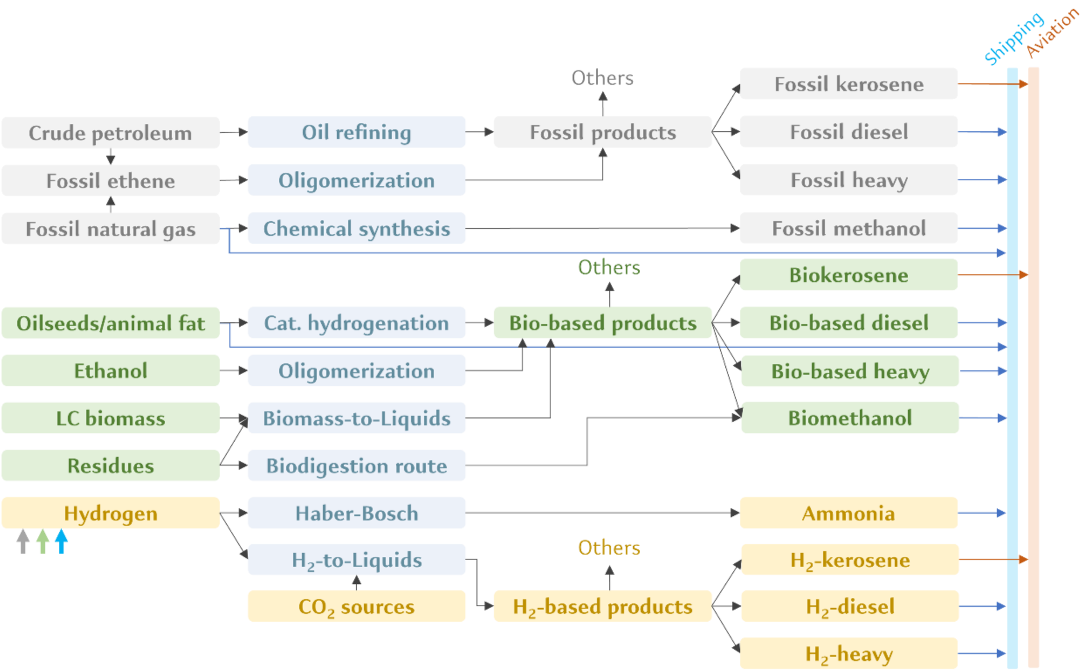

Figure 6: Aviation and shipping fuel options represented in the BLUES model

d. Scenario design

Several scenarios could be explored considering the possible combinations of aviation and shipping sectoral mitigation targets and national mitigation goals. For simplicity, this study focuses on four main scenarios (Table 3).

Table 3: Design of scenarios

Scenario	**IATA2050**	**IMO2050**	**National climate policy**
IATA/ICAO	Yes	No	None
IMO	No	Yes	None
IATA/ICAO IMO	Yes	Yes	None
B2C	Yes	Yes	Yes

The ***IATA/ICAO scenario*** represents a current policies view of the Brazilian energy system combined with IATA and ICAO mitigation pledges (particularly with IATA2050). Similarly, the ***IMO scenario*** reflects Brazilian current policies combined with IMO mitigation pledged by 2050. The ***IATA/ICAO IMO scenario*** is a merger of the first two (i.e., it addresses simultaneously the mitigation strategies in aviation and shipping sectors). Finally, the ***B2C scenario*** includes emissions restrictions not only to aviation and shipping, but also to the whole Brazilian agriculture, energy and land-use systems aligned with the Paris Agreement goals. This deep mitigation scenario is based on the results of the COFFEE model [42], an IAM of global scope that includes Brazil as one of its 18 regions. In this specific run, the global carbon budget inputted to COFFEE was 600 $GtCO_2$ [20] implying a carbon budget of 15.4 $GtCO_2$ for Brazil over the period 2010-2050.

Additionally, three sensitivity scenarios are explored, as shown in Table 4. The ***Small BtL scenarios*** are variations of the ***IATA/ICAO IMO*** and ***B2C scenarios*** that have different cost assumptions for the BtL technology. Climate mitigation scenarios from the BLUES model typically show a large increase in BtL technologies between 2020 and 2050 [46], [265], [267]. This is partly due to cost assumptions for these technologies (e.g., the standard plant capacity in the model is 1.6 ML/day, with considerable gains of scale). ***Small BtL scenarios*** seek to reflect a future energy system in which the development of BtL technologies is slower, relying mostly on small pioneer plants, with higher costs [268], [269]. As such, in these scenarios, the standard plant capacity is 0.13 ML/day. ***Small BtL*** scenarios also reflect the uncertainty associated with Carbon Capture and Storage (CCS). The potential combination with CCS is one of the key advantages of BtL routes, but optimistic cost assumptions can overlook the low technological maturity of both processes. Although the Brazilian CCS potential is impressive, there are significant technological, economic, and regulatory barriers that may limit carbon capture expansion. For example, the development of a CO_2 transportation network is a major challenge [270].

Finally, the ***IATA/ICAO IMO (Kerosene exports) scenario*** is a sensitivity case with changes in the demand for renewable kerosene. In view of the high potential for bioenergy production in Brazil, some global mitigation scenarios see the country as an important biofuel exporter in the coming decades [243]. Therefore, the ***IATA/ICAO IMO (Kerosene exports) scenario*** represents a view of the Brazilian energy system in which, in addition to the domestic jet fuel demand, the country would supply renewable kerosene to the international market. For the sake of simplicity, the export volume is taken to be equal to total domestic consumption (which should be a reasonable order of magnitude).

Table 4: Sensitivity scenarios

Scenario	**Difference compared to base scenarios**
IATA/ICAO IMO (Small BtL)	Smaller BtL plants
IATA/ICAO IMO (Kerosene exports)	Higher kerosene demand
B2C (Small BtL)	Smaller BtL plants

e. Results

Fuel consumption

The two panels in Figure 7 show the yearly consumption of aviation and marine fuels in 2050 for the main scenarios. In 2050, the demand for jet fuel is around 230 PJ (compared to 95 PJ in 2020), while marine fuel consumption is approximately 460 PJ (compared to 200 PJ in 2020). This represents increases of 140% and 130%, respectively, over a 30-year period.

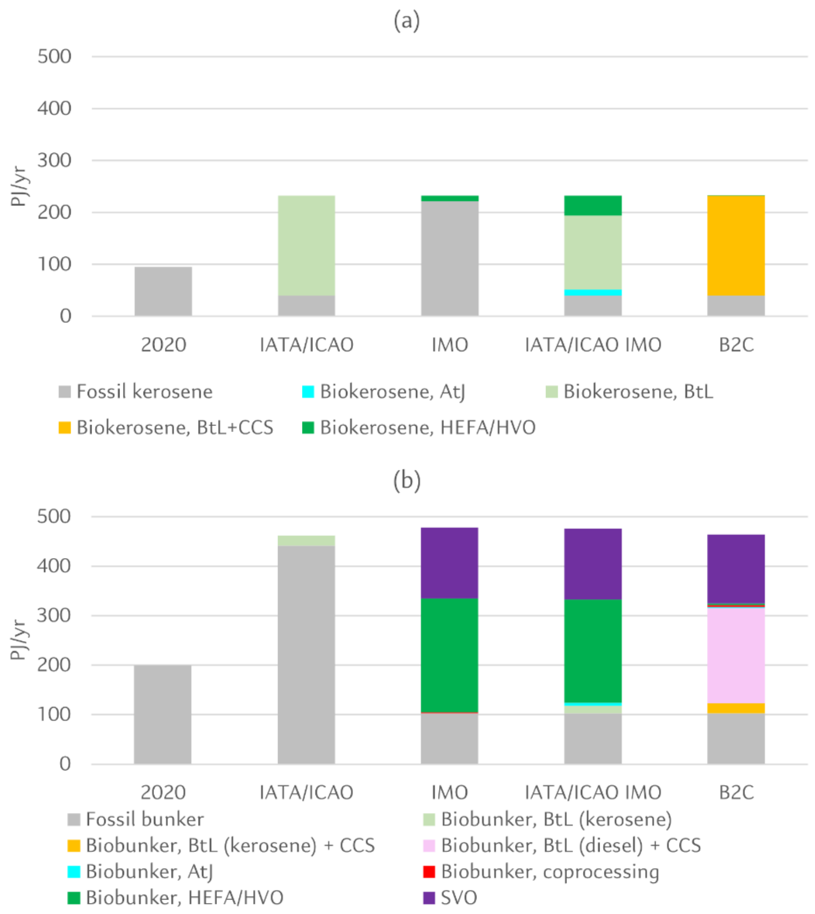

Figure 7: Fuel consumption in 2050 across main scenarios. (A) Aviation fuels (B) Marine fuels

In the ***IATA/ICAO scenario***, with the aviation supply restricted to a small amount of fossil fuel, most of the energy (84%) comes from biokerosene from the BtL route. Contrastingly, in the absence of climate policy the shipping energy mix continues to be dominated by fossil bunker. A tiny fraction (4%) of shipping fuels comes from BtL-kerosene plants as by-products.

The opposite situation is observed in the ***IMO scenario***. While the aviation sector remains almost 100% fossil (with some biokerosene coproduced in HEFA/HVO plants), the shipping energy mix shifts from fossil to bio-based fuels to meet the required emission reduction. SVO and HVO (which are based on the same feedstock) stand out as the main options. Together, these fuels account for 81% of the marine energy supply in 2050.

The results of the ***IATA/ICAO IMO scenario*** combine the fuel mixes of the two individual scenarios. By imposing the targets from IATA and IMO in the model, findings show that the aviation sector relies mostly on BtL-kerosene (although the AtJ route starts to appear), while the shipping sector still relies on SVO and HVO (with some participation of AtJ- and BtL-biobunker coproduced in kerosene plants).

In the ***B2C scenario***, the existence of a climate policy for the whole Brazilian economy significantly impacts the aviation and marine fuel supplies. In the jet fuel market, regular BtL plants are entirely replaced by plants equipped with carbon capture and storage (CCS), which provide negative emissions. In the shipping energy mix, SVO continues to be an important fuel (30% of the total supply), but HVO is replaced by biobunker coming mostly from BtL-road diesel plants (42% of the total supply). Biobunker from BtL- and AtJ-kerosene plants account for a residual share, as well as biobunker from coprocessing. Interestingly, an ambitious target to Brazil automatically implies the low-carbon fuel shares required by IATA and IMO.

As shown in Figure 8, with more pessimistic assumptions for the BtL technology (***IATA/ICAO IMO scenario (Small BtL) scenario***), results change significantly compared to the ***IATA/ICAO IMO scenario***. Most of the BtL-kerosene is replaced by AtJ-kerosene, which accounts for 50% of the total supply in 2050. Moreover, a small share (6%) of the demand is met by biokerosene from coprocessing in oil refineries. In this scenario, 13% of the marine fuel supply is based on coproducts of AtJ-kerosene.

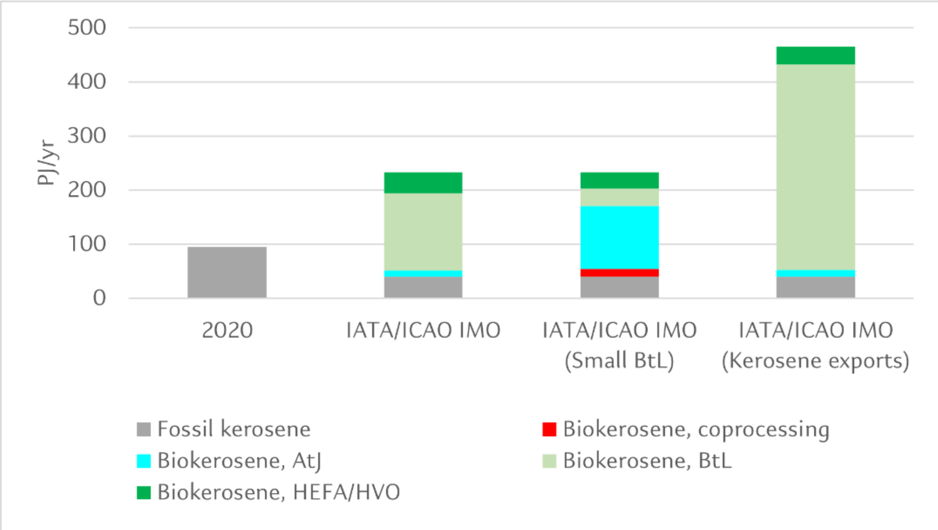

Figure 8: Aviation fuels consumption in 2050 – IATA/ICAO IMO sensitivity scenarios

When accounting for a higher renewable jet demand (460 PJ) due to the international market (***IATA/ICAO IMO scenario (Kerosene exports) scenario***), the expansion of the biokerosene supply continues to be based on the BtL technology. In this scenario, 83% of the jet fuel demand is met by BtL-biokerosene. There is also a moderate impact on the marine fuel market, with a larger share of biobunker (9%) coproduced in BtL-kerosene plants.

As shown in Figure 9, in the ***B2C (Small BtL) scenario***, results do not change significantly compared to the base scenario. In view of the need for negative emissions due to the carbon budget of 24 $GtCO_2$, the BtL technology continues to be widely deployed. The reduction in the share of BtL-kerosene is only 7% (compensated by an increase of AtJ-kerosene).

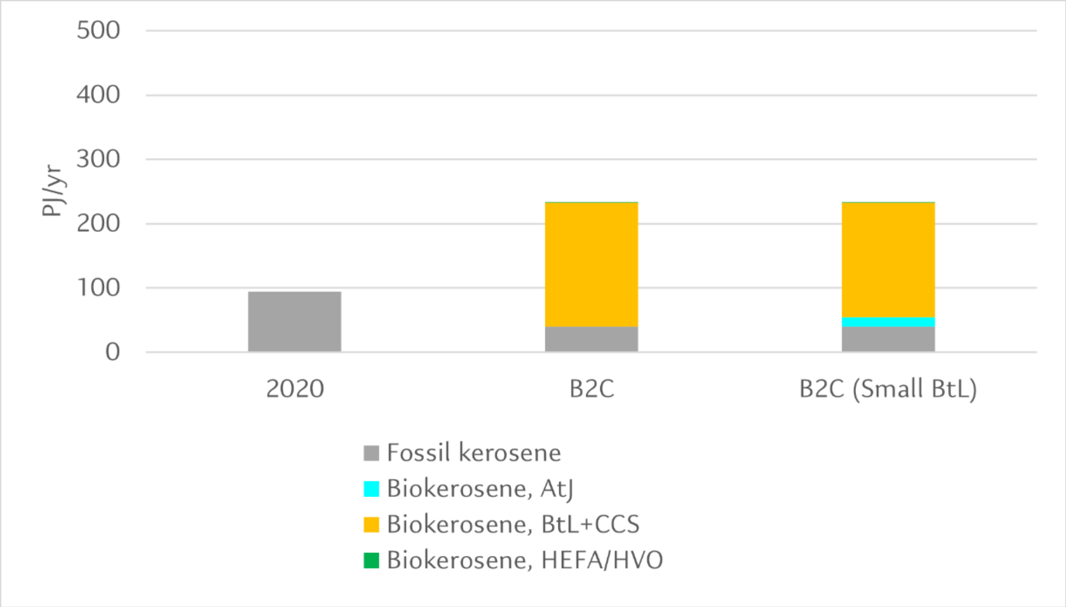

Figure 9: Aviation fuels consumption in 2050 – B2C scenarios

CO_2 emissions

Figure 10 shows the annual CO_2 emissions from Brazil in current policies and B2C scenarios from 2020 to 2050. In the absence of national climate policies, emissions continue to grow over the period, reaching 1.0 $GtCO_2$/yr in 2050. Contrastingly, in mitigation scenarios, emissions fall from 0.74 to 0.53 $GtCO_2$/yr in 2030. Between 2030 and 2050, with the rise of emission reduction technologies and the large-scale deployment of Bioenergy with Carbon Capture and Storage (BECCS), there is a steep reduction in the country's emissions, reaching -0.55 $GtCO_2$/yr in 2050. The CO_2 emission pathway of B2C scenarios is in line with other mitigation scenarios from the literature. For instance, global IAMs typically show annual emissions in Brazil between -2.3 and 0.8 $GtCO_2$/yr by 2050 [271]. Specifically, studies focusing on the decarbonization of the country have been showing emissions around 0.40 $GtCO_2$/yr in 2030 and -0.50 $GtCO_2$/yr in 2050 [272], which is very close to the B2C pathway.

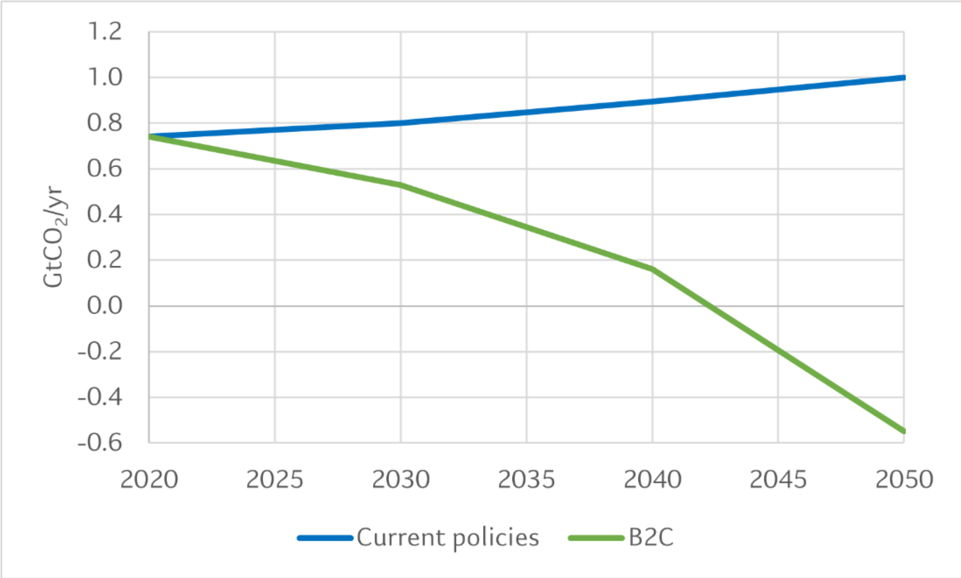

Figure 10: Annual CO_2 emissions in Brazil across scenarios. The "Current Policies" line represent the IATA/ICAO, IMO, and IATA/ICAO IMO scenarios, as well as their sensitivity cases

Land-use change

Figure 11 shows the cumulative change in land use in Brazil for the period 2020-2050. Results show that, without national mitigation measures, there is a strong expansion of pastures for livestock (24 to 27 Mha), which engenders native forest (10 Mha) and savanna (15 Mha) losses. The effect of large-scale use of oilseeds on land use is also evident: in scenarios that include the IMO target, with heavy reliance on oilseed derived fuels, the growth of the area devoted to agricultural crops is far higher to that observed in the IATA scenario. This also means that the compliance with the IMO target must be associated with the control of land use change impacts.

When the national climate policy is considered (***B2C scenario***), the dynamics of land-use change is completely different. Although there is forest loss (0.1 Mha), when considering the planted area over the period (16 Mha), there is a net increase in forest cover between 2020 and 2050, as well as in carbon retention. In the case of savanna areas, there is a significant loss (19 Mha), but this change does not occur in Permanent Preservation Areas. Furthermore, most of the land use change observed in climate policy scenarios is related to the recovery of degraded pastures (64 Mha). Finally, there is an important role for integrated systems (such as crop-livestock-forest integration, in line with studies from the Brazilian Public Agricultural Research Corporation [273], [274]).

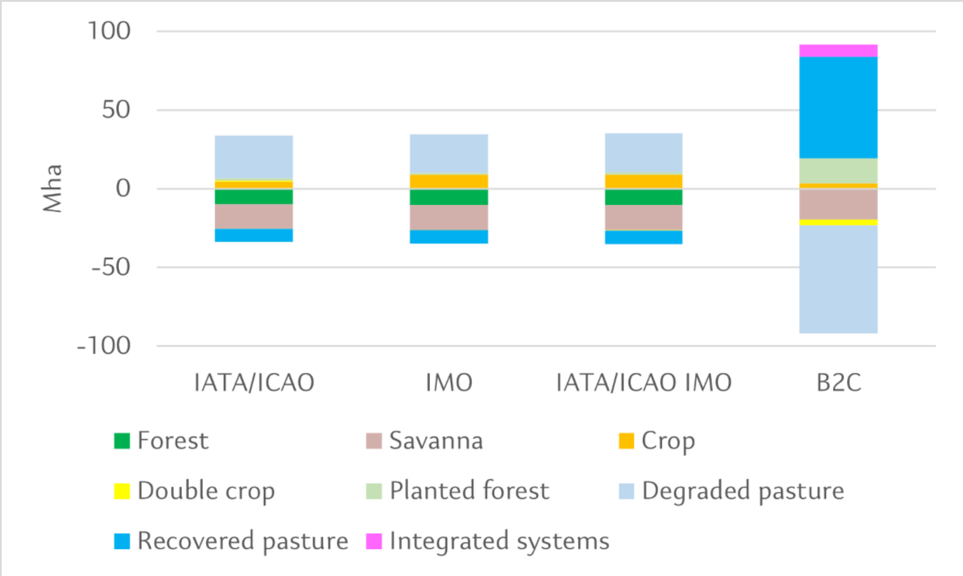

Figure 11: Cumulative changes in land use between 2020 and 2050

f. Discussion

Clearly, considering the projected increase in demand and the limits of energy efficiency gains over the next decades, the replacement of most fossil fuels by renewable fuels in the aviation and shipping sectors will be essential to meet their sectoral emissions targets in 2050. However, the portfolio of renewable fuels to be used can vary significantly.

For aviation, in the absence of a national climate policy, the production of BtL-kerosene without CCS is the preferred route across scenarios. Even with higher demand, BtL-kerosene represents more than 80% of the jet fuel supply in 2050. When accounting for uncertainties related to the development of the BtL technology, the AtJ route increases its share and has an important role to play. When decarbonization goes hand in hand with a low-carbon pathway in Brazil, the BtL technology becomes dominant again, but this time associated with CCS.

The decarbonization of shipping follows a different path. Oilseed-based fuel routes, which account for most of the energy supply in 2050 in all scenarios without a national climate policy, are more cost-competitive than BtL routes. Due to its low cost, SVO is the first option when it comes to renewable fuels for shipping. However, quality issues limit the demand for SVO, creating a need for higher-quality fuels. This demand is met by HVO, which represents most of the energy supply in these scenarios. In the context of a low-carbon future in Brazil (***B2C scenario***), the renewable marine fuel supply changes significantly. Although SVO continues to be important, a large share of the energy demand is met by biobunker coming as a by-product of BtL-diesel plants with CCS. As such, in these scenarios, there is a remarkable synergy between the decarbonization of shipping, not with aviation, but with the road transport sector. As pointed out in the methods sections, the demand for shipping follows a conservative projection, with significant increase in 30 years. With a lower demand, the synergy with the road transport sector could be even larger. In such a scenario, biobunker from BtL would possibly meet a very high share of the sector's energy demand.

The transportation sector portrayed by the B2C scenario can be summarized as follows: in the passenger road transport, electrification is significant, but ethanol keeps its role as a relevant renewable energy carrier. Furthermore, part of the automotive gasoline is replaced by its bio-based equivalent, produced in FT-liquids plants. However, the most important product of these facilities is FT-diesel, outputted in large quantities to fuel Brazil's road-dependent freight system. Using BECCS, the production of green diesel becomes the most important source of negative emissions in the country. Finally, FT-liquids also become the dominant solution in aviation (with dedicated biokerosene plants) and shipping (through biobunker as a by-product). Vegetable oils play a complementary role in the marine fuel supply.

As it became clear, our results indicate some synergies in the decarbonization of the aviation and shipping sectors in Brazil, with the replacement of fossil fuels taking place through different energy chains for each sector (Figure 12). The first one is the coproduction of kerosene in HVO-diesel plants: across scenarios, between 4% and 12% of the jet fuel demand is met by this by-product. In the other way around, the production of BtL-kerosene always happens together with the production of BtL-bunker. As such, across scenarios, between 3% and 9% of the shipping energy supply corresponds to BtL-bunker associated with biokerosene.

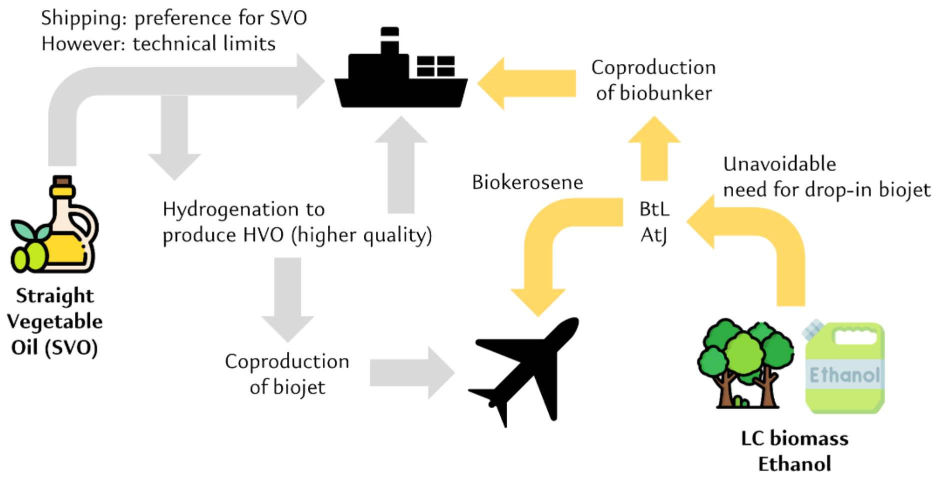

Figure 12: Synergies in the production of renewable fuels for aviation and shipping

The absence of a full-scale synergy is strongly associated with the different scales of the two sectors in Brazil. While the aviation fuel demand is close to 95 PJ in 2020, the bunker market is twice as much, accounting for around 200 PJ. Considering the biorefinery yields presented in the introduction and the fact that kerosene has higher added value compared to bunker (being therefore the main product of production plants), it can be inferred that higher levels of synergy might be observed if the marine fuel market is smaller than the aviation market (and therefore more suitable to be supplied by a by-product of biokerosene plants). Interestingly, as show in Figure 13, the relation between the aviation and fuel markets in Brazil is approximately 0.48, whereas this is around 1.5 worldwide. This indicates a much larger potential for synergies globally.

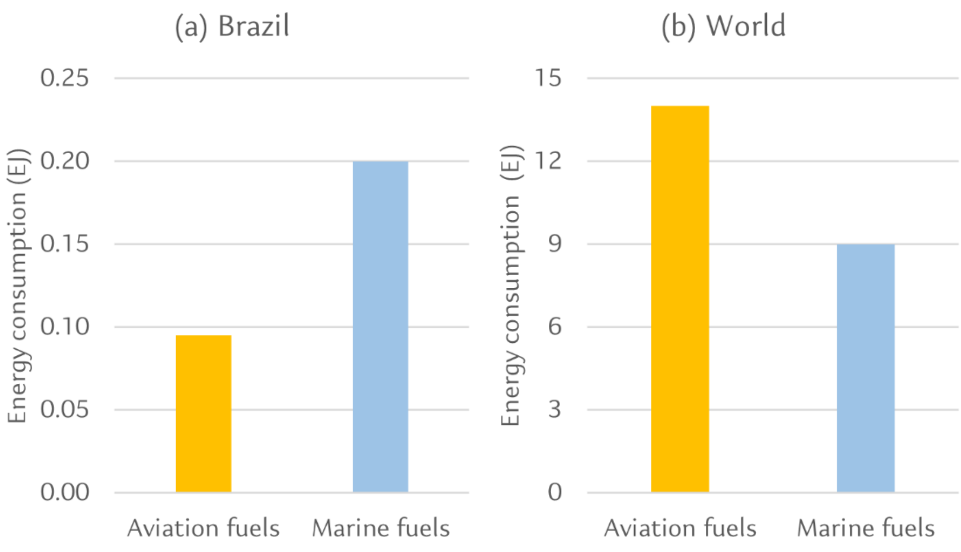

Figure 13: Aviation and marine fuels consumption in 2018: (A) Brazil; (B) World. Data source: [62], [275]

g. Limitations of study

This study sought to assess the potential synergies in the decarbonization of aviation and shipping, two major hard-to-abate sectors. To that end, the specific case of Brazil was examined, considering GHG abatement targets proportionally compatible with the international mitigation goals in both sectors. Given the existence of fuel routes that coproduce renewable kerosene and maritime bunker fuels, the specific aim was to answer the question stated in the title of the article benefitting from an integrated perspective provided by the Brazilian Land Use and Energy System (BLUES) integrated assessment model.

Four scenarios were developed to compare the impacts of decarbonizing aviation, shipping, and the Brazilian economy individually or in a joint way. Results varied widely, with sectoral decarbonization targets having little impact beyond their own scope. Moreover, when considered together, the aviation and shipping targets showed limited synergies mostly associated with the BtL and HEFA/HVO routes (and to a lesser extent with the oligomerization route). Finally, in the deep decarbonization scenario (Brazil compatible with a world well-below 2^{o}C), the need for CCS engendered a significant synergy between shipping and road transport (and, on a much smaller scale, between aviation and shipping). In short, for all cases, the total annual potential exceeds by far the current demand of both sectors [269].

Several aspects not widely discussed in this work can be explored in future studies. For example, potential synergies between the decarbonization of aviation and shipping could be analysed on a world scale. Furthermore, other potential biomass feedstocks from wastes such as Used Cooking Oils (UCOs) and wet-waste derived Volatile Fatty Acids (VFA), currently not represented in the BLUES model, could be assessed [276], [277]. Under a methodological perspective, studies questioning the perfect foresight approach used in this article might also add value to the literature. Recursive dynamic optimization, for instance, can provide "myopic" runs to see if more readily available technological options would be favoured in terms of market share. Besides, it is important to highlight that this work treated aviation and shipping demand as exogenous, possibly overlooking demand-side mitigation measures (e.g., sustainable lifestyle changes), which can be critical for passenger aviation. In the case of shipping, there can be impacts related not only to avoided fossil fuel trade but also to structural changes in global supply chains due to the energy transition. Future works could focus on a detailed representation of maritime cargoes (e.g., iron ore, copper, and capital goods) and their linkages with the energy sector.

h. Method details

Energy demand

To project the demand for aviation, income-demand elasticities are calculated for Brazil using linear regression on a natural logarithmic model. The gross domestic product (GDP) was assumed as a proxy of income. Demand for aviation is disaggregated in passenger and freight, measured in revenue passenger kilometres (RPK) and revenue tonne-kilometres (RTK), respectively. Historical demand is established based on data from the Brazilian National Civil Aviation Agency [278]. GDP data is obtained from the Institute for Applied Economic Research [279] and the Brazilian Micro and Small Business Support Service [280]. It is worth noting that aviation demand is completely exogenous, following a Business-As-Usual (BAU) scenario with rapid post-Covid recovery. As such, demand-side mitigation measures are not assessed in this study, and the projection used can be seen as a conservative one.

The demand for shipping follows a previous study [265], having as a core assumption that Brazil's main export products will not change over the period of analysis. This simplified approach assumes that the ratio mass exported/mass imported remains constant between 2010 and 2050, with the share between export products also fixed. It is a high demand scenario based on a BAU transport work projection [197]. As in the case of aviation, this methodology is not capable of capturing changes in the dynamics of demand (e.g., avoided fossil fuel trade or increases in bioenergy exports). For its substantial growth in 30 years, it can be seen as a conservative projection. Marine fuel demand is determined using a simplified energy model and calibrated with historical data for 2010 and 2018 [281].

Demand for aviation

To project the mobility demand for aviation in Brazil, income-demand elasticities are calculated using linear regression on a natural logarithmic model. The gross domestic product (GDP) was assumed as a proxy of income. Demand for aviation is disaggregated in passenger and freight, measured in revenue passenger kilometres (RPK) and revenue tonne-kilometres (RTK), respectively. Historical demand is established based on data from the Brazilian National Civil Aviation Agency [278]. GDP data is obtained from the Institute for Applied Economic Research [279] and the Brazilian Micro and Small Business Support Service [280]. The analysis was disaggregated between passenger and freight demand, for the domestic and international market, and regionalized for Brazil territory. Strong linear relations were found between the demand and GDP, with high statistical relevance. R-squared values found range from 0.89 to 0.98 for passenger, domestic demand; 0.83 to 0.92 for passenger, international demand; 0.77 for freight, both international and domestic market, showing overall good response assertiveness. Freight modelling only showed satisfactory results at national level; thus, it was not disaggregated into regions as passenger did. All p-values found for the elasticities were much less than 0.05%, revealing statistical relevance for the estimators in the model.

Covid-19 impacts were quantified as modifiers of demand growth, considering GDP shrinkage, calculating activity reduction due to pandemic in 2020 and 2021 relative to 2019 data. During the elaboration of this model, only the first half of 2021 data was available, thus it was extrapolated for whole year. A rapidly, 2-year recovery scenario is assumed, meaning that modifiers actively reduce the demand further than the GDP reduction only for the years of 2020 and 2021.

Equation 1 presents the elasticity-based projection. Using the elasticities calculated from historical data, base data and future GDP projections, future demand is calculated. Base year is 2010 with time step of 5 years.

$$D(t) = D(t-1) * \left(e * \frac{GDP(t) - GDP(t-1)}{GDP(t-1)} * MOD + 1\right) \qquad [1]$$

In which:

D(t) = future demand, in RPK or RTK

D(t-1) = past demand, in RPK or RTK

e = demand-income elasticities, for passenger or freight aviation demand, for domestic or international markets, for each Brazilian region (only for passenger demand)

GDP(t) = future GDP

GDP(t-1) = past GDP

MOD = Covid-19 demand growth modifiers, for passenger or freight aviation demand, for domestic or international markets, for each Brazilian region (only for passenger demand), in percentage

Demand for shipping

This part of the STAR methods section is based on [265]. International shipping was originally not represented in BLUES, given that it is a national model. As such, an important part of the methodology here is the incorporation of the shipping fuel demand into BLUES. This was performed based on the assumption that only a fraction of the fuel required by Brazil's international trade is provided by national ports. The remaining part is supplied by ports of the commercial partners or along the shipping routes.

Brazil's exports are way higher than its imports on a mass basis. Hence, while imports are treated as a single category, exports are divided into five categories that represent the country's main export products: iron ore, crude oil, soybean, sugar, and others [179]. Furthermore, iron ore is divided into two categories, reflecting the two different kinds of vessels used to transport it [181]. Coastal navigation is also modelled. Even though coastal navigation is not in the scope of IMO's target, it is assumed that it will follow the trends of long-haul shipping.

Table 5 shows the estimation of the transport work related to Brazilian exports, imports, and coastal navigation [179], [194]. The proportion of the fuel supplied by Brazilian ports is similar for all products (around 31%). Estimates derivate from the comparison of the results of the modelling with historical data for the base year (5.3 million tonnes of bunker in 2018) [195].

Table 5: Estimation of transport work associated with fuel supplied in Brazilian ports in 2018

	Mass traded (Mt)	Typical distance (nm)	Total transport work (Tt-km)	Transport work fueled by Brazil (Tt-km)
Iron ore (Valemax)	195	8,943	2.99	0.93
Iron ore (Capesize)	195	8,943	2.99	0.93
Crude oil	58	7,165	0.71	0.22
Soybeans	84	9,039	0.84	0.26
Sugar	21	8,382	0.25	0.08
Others	153	8,382	1.52	0.48
Imports	151	8,382	3.50	1.09
Coastal navigation	229	780	0.23	0.23

Two demand scenarios are developed based on the literature on global shipping forecasts. The low demand scenario is based on the activity growth reported in DNV's maritime forecast [196], while the high demand scenario is based on the Business as Usual (BAU) scenario of IMO's third GHG study [197]. It is assumed that the exported products do not change over the period of analysis. The adopted literature scenarios are based on secondary energy, not transport work (useful energy). In the case of the high demand scenario, which considers the maintenance of efficiencies base year conversion rates, this is not significant. In the case of the scenario with the lowest consumption, however, there is a lag between the profile of the energy curve and that of demand, given the premises related to efficiency. However, for simplicity and data limitation, the final energy is directly used as a proxy for the growth of the projected tonne-kilometers. This implies, in the worst-case scenario, a range of slightly wider demand.

The energy associated with Brazilian transport work in each scenario is determined using a simplified energy model and is calibrated with historical data for 2010-2018. The model estimates the demand for main engines (used for propulsion), auxiliary engines (electricity generation), and auxiliary boilers (heat production).

The propulsion energy demand is estimated through simplified hydrodynamic equations [126], [141]. The total hull resistance R_T and the associated brake power P_B are presented in equations 1 and 2, respectively.

$$R_T = \frac{1}{2}\rho C_T S v^2 \qquad [2]$$

$$P_B = \frac{(1+m)R_T v}{\eta_T} \qquad [3]$$

In equations 2 and 3, ρ is the seawater density, C_T is the total resistance coefficient, S is the wetted surface, m is the sea margin, v is the speed of the ship and η_T is the total propulsion efficiency. These parameters are estimated based on ship sizes and categories. Table above shows the vessels considered for each product, as well as their deadweight tonnage.

Auxiliary engines and boilers energy demand estimation follows [197]. It considers typical loads for different vessel categories, sizes and operational modes (at-berth, at-anchorage, maneuvering and at-sea) [198]–[205] (see below table).

Table 6: Ship types and categories

Product	Ship type	Ship category	Deadweight (dwt)
Iron ore (Valemax)	Bulk carrier	Valemax	400,000
Iron ore (Capesize)	Bulk carrier	Capesize	150,000
Crude oil	Oil tanker	Suezmax	150,000
Soybean	Bulk carrier	Panamax	60,000
Sugar	Bulk carrier	Panamax	60,000
Other	Bulk carrier	Panamax	60,000
Import	Oil tanker	Panamax	60,000
Coastal navigation	Oil tanker	Panamax	75,000

In terms of fuel use, three different powertrains are considered: conventional 2-stroke diesel engines, dual-fuel engines, and solid oxide fuel cells (SOFCs) used in combination with electric motors. Table 7 shows the fuels suited to each one of these configurations. The literature indicates that fuels with lower energy density, such as methanol, LNG, and ammonia, might reduce the space available for cargo. Therefore, a volume loss of approximately 5% is considered for dual-fuel engines and solid oxide fuel cells [119]. Differences in investment costs are also considered [119], [206], [207].

Table 7: Technology options regarding the powertrain

Powertrain	**Abbreviation**	**Extra cost (2010 USD/kW)**	**Volume loss (%)**	**Suitable fuels**
Two-stroke diesel engine	2S-D	0	0	Bunker, drop-in fuels
Dual-fuel engine	DF	242	5	LNG, methanol, bunker, drop-in fuels
Solid oxide fuel cell	SOFC	4675	5	Ammonia

As shown in Table 8, depending on the motorization, significant increases in the total CAPEX are observed, especially for the case of fuel cells. However, some drop-in alternative fuels need only minor changes of the ship and bunkering to be directly used.

Table 8: Investment costs for the vessels considered in the modelling

Ship	**Powertrain**	**CAPEX (2010 kUSD)**
Bulk - Valemax	2S-D	81,000
Bulk - Valemax	DF	87,000
Bulk - Valemax	SOFC	198,000
Bulk - Capesize	2S-D	38,000
Bulk - Capesize	DF	42,000
Bulk - Capesize	SOFC	108,000
Bulk - Panamax	2S-D	30,000
Bulk - Panamax	DF	32,000
Bulk - Panamax	SOFC	67,000
Tanker - Suezmax	2S-D	49,000
Tanker - Suezmax	DF	53,000
Tanker - Suezmax	SOFC	119,000

As shown in Table 9, specific fuel consumption (SFC) varies according to the fuel used [119], [197], [208].

Table 9: Main engine specific fuel consumption

Fuel	**SFC (g/kWh)**
Fossil/synthetic bunker	179
SVO	170
HVO	190
LNG	150
Methanol	381
Ammonia	319

Efficiency gains are also modelled, since this is expected to be a major aspect contributing to the reduction of the energy demand from international shipping. Consistently with the projections of the literature [126], [209] and with the Energy Efficiency Design Index [104], when compared to 2010, new vessels are taken to be 20% more efficient in 2030 and 30% in 2050.

Fuel potential and production routes

The techno-economic potential of SVO, HVO and FT-liquids is based on the values found by [269].

For shipping, the fuel conversion options represented in the model are greatly based on a previous work that summarized pros and cons of different marine fuels [68]. While shipping fuel options are relatively diverse, the aviation sector is restricted to conventional kerosene and fully drop-in alternatives (therefore, options such as natural gas and hydrogen are not allowed to be used by aircrafts). This methodological choice is due to the low technological feasibility of using fuels other than kerosene in commercial aviation (at least during the next few decades) [248]. Although there are some initiatives that aim at using hydrogen and LNG as aviation fuels [282]–[284], energy density concerns make their large-scale deployment unlikely [64]. For example, in light of the

International Energy Agency's deep mitigation scenario, by 2050 the global aviation fuel market would likely be dominated by (both bio- and hydrogen-based) synthetic fuels [162].

Similarly to [265], the modelling of shipping fuels includes several fossil-, bio- and hydrogen-based options. Among the fossil alternatives, there are conventional marine fuels (diesel and heavy fuel oil), but also methanol and LNG. For biofuels, the production routes are approximately the same as the ones used to make kerosene (as explained, this is the main motivation of this work). However, in the case of shipping, the direct use of SVO and the production of biomethanol are also modelled. In terms of hydrogen-based alternatives, the use of ammonia as a marine fuel is also represented.

In addition to dedicated aviation and marine fuels production routes, the coprocessing of SVOs and POs in petroleum refineries is also included in the BLUES model. Coprocessing yields are obtained using the Carbon And Energy Strategy Analysis for Refineries (CAESAR) model, an auxiliary model that performs detailed simulation of oil refineries [285]. The calculation performed by CAESAR assumes reduced crude oil input in refineries (that is, in the atmospheric distillation column) due to the presence of bioliquids in specific units (FCC and/or HDT), outputting thereby new yields used as inputs to the BLUES model.

4. Impacto de futuros globais do comércio sobre o desafio de descarbonizar o setor marítimo internacional

Neste capítulo, reproduz-se o manuscrito final submetido à revista *Energy* para publicação do artigo *Global futures of trade impacting the challenge to decarbonize the international shipping sector* (volume nº 237; identificação nº 121547; DOI: 10.1016/j.energy.2021.121547).

GLOBAL FUTURES OF TRADE IMPACTING THE CHALLENGE TO DECARBONIZE THE INTERNATIONAL SHIPPING SECTOR

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Abstract

International shipping accounts for around 2% of global CO_2 emissions. The International Maritime Organization (IMO) has set the ambition to halve shipping GHG emissions by 2050 to help mitigate climate change. As shipping connects countries and sectors, its future development is highly dependent on regional and sectoral trends. So far, the literature on the decarbonization of shipping has focused on sectoral analyses while integrated assessment models (IAMs) have paid little attention to this matter. In this study, the IMAGE model is used to assess different futures of energy, agricultural and industry impacting the effort required to meet IMO's target for 2050. To that end, long-term seaborne trade projections are created from outputs of the IMAGE model. The results show that varying pathways of socio-economic development strongly affect the size of the sector. The mass shipped globally ranges from 17 to 35 Gt/yr in 2050. This corresponds to an energy demand between 9 and 25 EJ in the same year, which would require significant amounts of low-carbon fuels. Interestingly, in a climate policy scenario, the avoided trade of fossil energy, although partially compensated by an increase of biofuel trade, lowers the international shipping mitigation effort.

a. Introduction

The shipping sector is an important contributor to global greenhouse gas (GHG) emissions, accounting for approximately 1.06 GtCO_2/yr (direct emissions), most of which (0.74 GtCO_2/yr) is associated with international[42] freight transport [165], [286] (this represents around 11% of total transport emissions [287]). Shipping emissions are expected to further grow in the future, in light of historic trends (from roughly 0.6 Gt/yr in 1950 to 11 Gt/yr in 2018) [79], [288]).

In 2018, the International Maritime Organization (IMO), the United Nations body responsible for environmental regulation of international shipping, established a preliminary strategy to reduce shipping-related GHG emissions. This strategy aims to achieve a pathway of GHG emissions consistent with the Paris Agreement temperature goals. This has been translated into the objective of limiting total emissions from international shipping in 2050 to 50% of the emission amount in 2008 [110]. While many mitigation scenarios aligned with the Paris Agreement often have similar reduction rates, other studies have recently questioned whether a 50% reduction is enough (among others because remaining emissions need to be compensated with negative emissions) [66], [99], [289]. Here, we focus on the IMO target. Considering this goal, hereinafter referred to as IMO2050, international shipping GHG emissions should be less than 0.40 GtCO_2eq/yr in 2050.

Over the past decade, the IMO has adopted measures to reduce shipping GHG emissions. Among these measures, the Energy Efficiency Design Index (EEDI) policy is the most important example. Despite its name, the EEDI policy is a carbon intensity policy. It establishes CO_2 emissions newbuilding standards (gCO_2/t-nm) for ships built after 2012, making it mandatory to increase the efficiency of new vessels [105]. Also, more recently,

[42] The fraction of shipping emissions that falls into the category "international shipping" can be defined according to two different approaches, voyage- and vessel-based allocation. While the first defines international emissions as those which occur on a voyage between different countries, the latter defines international emissions according to ship types. The amount presented in the text derives from a voyage-based perspective [165].

the IMO has introduced the Energy Efficiency Existing Ship Index (EEXI) [108]. On the operational side, the IMO has implemented the Ship Energy Efficiency Management Plan (SEEMP) policy. The SEEMP is an operational measure that seeks to help improve the energy efficiency of a ship in a cost-effective manner. It provides a practical approach for ship operators to monitor the fleet efficiency using the Energy Efficiency Operational Indicator (EEOI) [165]. In 2021, a rating scheme based on a mandatory Carbon Intensity Indicator (CII) was approved to strengthen SEEMP [290].

Besides, the establishment of IMO2050 has motivated several studies to analyze the opportunities to decarbonize the maritime sector more deeply. They show that there are many options to reduce the carbon intensity of shipping through new operational improvements, more efficient design and the use of alternative energy sources [69], [126], [127], [170], [171], [186]. Also, some long-term sectoral scenarios have been developed. These show that under the assumption of no new policies, total 2050 emissions from international shipping could range between 1.0 and 1.8 $GtCO_2$/yr. At the same time, mitigation scenarios relying mostly on low-carbon fuels indicate that it is possible to achieve the IMO target, with emissions around 0.6 $GtCO_2$/yr in 2040 and 0.4 $GtCO_2$/yr in 2050 [70], [170], [287]. A few scenarios from DNV GL indicate even the possibility of a full decarbonization of the sector by 2040, far beyond the IMO level of ambition [170].

The sectoral models used to develop these scenarios typically treat shipping demand as an exogenous variable. They, therefore, do not necessarily capture important connections to other aspects of the global economy. This is relevant as the shipping sector basically connects product flows across sectors and between regions and is therefore subject to regional and sectoral developments, impacted also by policy changes. Moreover, technological improvements and switching to alternative marine fuels will go hand in hand with similar developments occurring in other energy-using sectors. Therefore, to better understand the feasibility of the IMO2050 target, it is essential to analyze cross sectoral feedbacks and interactions to assess how the demand for shipping can evolve over time.

To that end, Integrated Assessment Models (IAMs) could be a useful tool. IAMs have extensively been used to explore the consequences of different long-term climate change mitigation strategies. They often contain a detailed representation of the world's energy, land use, agricultural and climate systems, as well as the different inter-linkages, cross-sector, cross-regions and over time [27], [40], [50], [291]. Nevertheless, the long-term scenarios developed so far by IAMs pay relatively little attention to emissions from international transport – and often describe these emissions by means of a rather aggregated relationship with income. In most cases, IAMs use exogenous drivers to project the demand for shipping [70] and there is no differentiation of ship types, efficiency standards and motorization technologies. One exception to this is a recent work that used a national IAM to assess the impacts of achieving IMO2050 on the Brazilian energy and land use systems [265]. In the present study, which has global scope, by developing a shipping model within the integrated assessment model IMAGE [292], we use the IAMs unique opportunity to understand and project the demand for international shipping activity in the context of a wider description of the economy. We use this to explore the robustness of meeting the IMO2050 target under the uncertainty of global sectoral developments impacting the international shipping sector.

This article is organized in the following manner. After this introduction, an overview of the shipping sector is provided. Then, a brief description of the IMAGE model is presented. Subsequently, the methodology used to project trade and energy demand from an IAM perspective is detailed and the corresponding results are presented. Finally, concluding remarks and suggestions for future studies are explored.

b. International shipping and IMO2050

Figure 1 shows the evolution of global seaborne trade between 1970 and 2019. The total mass loaded in merchant ships grew from 2.6 Gt/yr in 1970 to 11.1 Gt/yr in 2019, with an average rate of increase equal to 34% per decade. Fifty years ago, maritime trade consisted mostly (55%) of crude oil and petroleum products (in the figure referred to as liquid bulk). With the rise of the container-shipping industry and the increase in trade of dry bulk commodities, the liquid bulk share gradually declined over this period. At present, approximately 29% of the mass loaded yearly on ships corresponds to oil and products, while another 29% refers to major bulk shipping (mainly coal, grains and iron ore). Other dry cargoes, including containers, account for the majority of seaborne trade (42%) [288]. It is important to highlight the specificity of container shipping, which accounts for most of the growth of the sector over the last four decades. While liquid and dry bulk trade operate at lower speeds (12-15 knots), containerships have higher nominal speeds (20-25 knots), which implies a completely different consumption dynamic. The mitigation potential associated with slow steaming, for example, is much higher in the case of the container network [131], [293].

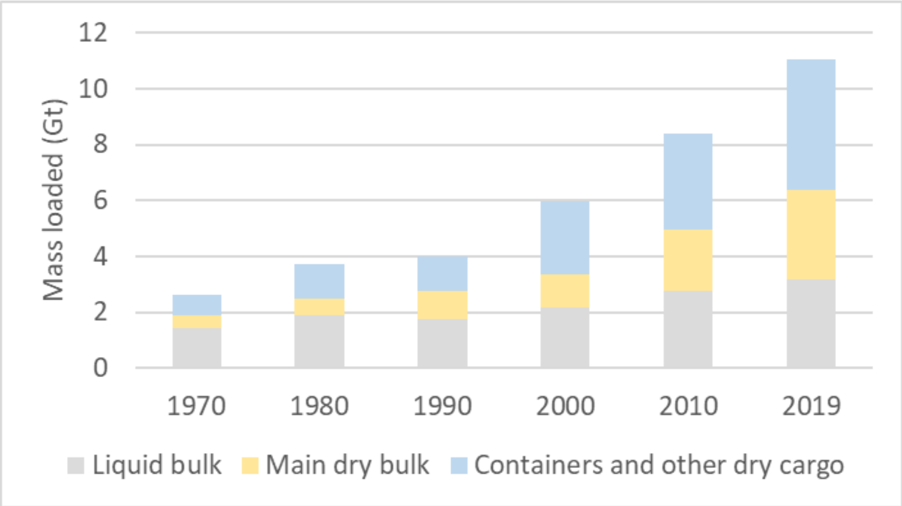

Figure 1: Global seaborne trade activity between 1970 and 2019. Data: [288]

Also in terms of average haul, seaborne trade has changed significantly over the past decades (Figure 2). Until the mid-1970s, the typical distance traveled by merchant ships has grown robustly, exceeding 5000 miles around 1977, as a result of Middle East's increasing share in crude oil supply. Later, during the 1980s, the rise of new oil producing regions (e.g., North Sea and Mexico) caused a reduction in the seaborne average haul, which reached the level of 3700 nautical miles. Afterwards, the typical travelling distance started to rise again, led by products such as iron ore and petroleum products. In the 21st century, despite short-term fluctuations, the average haul remained approximately constant around 4900 miles. The current trend is still upwards, but intra-regional trading blocs are becoming more cemented [79], [294].

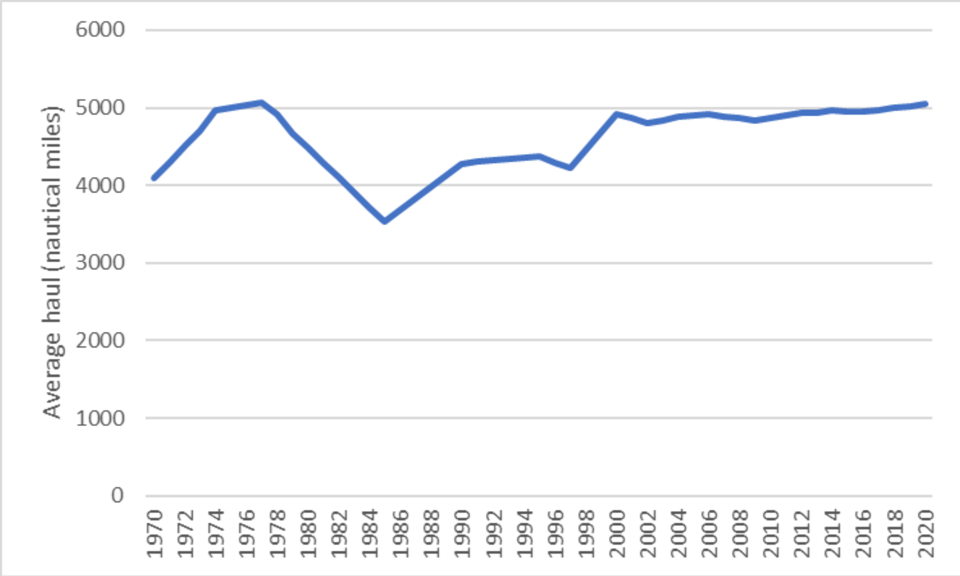

Figure 2: Estimated average haul of world seaborne trade between 1970 and 2020. Data: [87], [288], [294]

As in other transport sectors, carbon dioxide (CO_2) emissions from shipping originate from the combustion of fossil fuels. Specifically in the case of ships, they are burned to produce mechanical energy for propulsion, but also heat and electricity for use onboard the ship. Until the first half of the 20th century, coal was shipping's prevalent energy source but, since then it was completely replaced by oil products [123]. In 2018, heavy fuel oil (HFO) and marine gasoil (MGO), or more generally, bunker[43], accounted for 95% of the sector's energy demand [165]. The other 5% refers to liquefied natural gas (LNG), a newer marine fuel used mostly in a number of gas carriers. However, the entry into force of stricter air pollution regulations and the decrease in costs of using natural gas as a marine fuel are expected to increase LNG's participation also in other types of ship.

Figure 3 shows total GHG emissions from shipping between 2012 and 2018, almost completely composed of CO_2 emissions[44]. In recent years, the proportion between

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[43] Actually, marine fuels are usually formed by a blend of HFO and MGO in varied proportions. Considering the similarity of these fuels regarding their energy conversion and carbon intensities, in this work, they are treated indistinctly under the designation "bunker".

[44] Methane and fluorinated gases make up the rest of greenhouse gas emissions from shipping.

international shipping CO_2 emissions and total shipping CO_2 emissions has been around 75%. Figure 3 also shows that there has been a relative stabilization of emissions over the 2010s, despite the increase in activity [165]. This is due to lower speeds practiced as a way to absorb idle capacity since the 2008 crisis [132], [295], but also to relevant efficiency gains derived from the implementation of energy efficiency measures, such as the EEDI [104], [105]. In 2020 specifically, there may have been an even more significant reduction in shipping emissions due to the global COVID-19 crisis [288]. However, in the long run, with the possible saturation of efficiency gains and the continued increase in international trade, emissions are expected to resume a growth trend [165], [287]. Currently, international shipping emissions are approximately 300 $MtCO_2$/yr above the 2050 target. As discussed, this gap tends to become larger if activity increases. Therefore, it is likely that the decarbonization of shipping will require the use of significant amounts of low-carbon fuels.

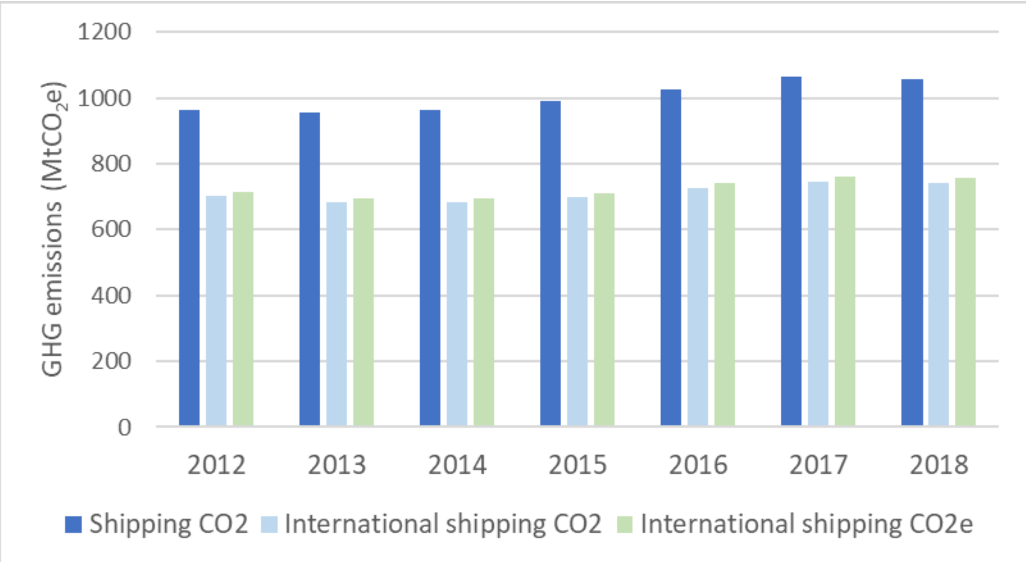

Figure 3: Greenhouse gas emissions from international shipping between 2012 and 2018. Data: [62]

c. Methods

In this section, the methods used to analyze the decarbonization of international shipping under the point of view of an IAM are explained. Figure 4 provides an overview of the methodological procedure adopted in this work. In six different scenarios, bilateral mass-based trade matrices were created for 19 international shipping products from outputs of the IMAGE model, considering the timeframe 2000-2100. Then, the total energy demand associated with this seaborne trade was estimated using a simplified power model. Finally, for all six scenarios, the amount of low-carbon fuels required to meet IMO2050 was determined based on the total energy demand and the GHG emission limit set by IMO's target.

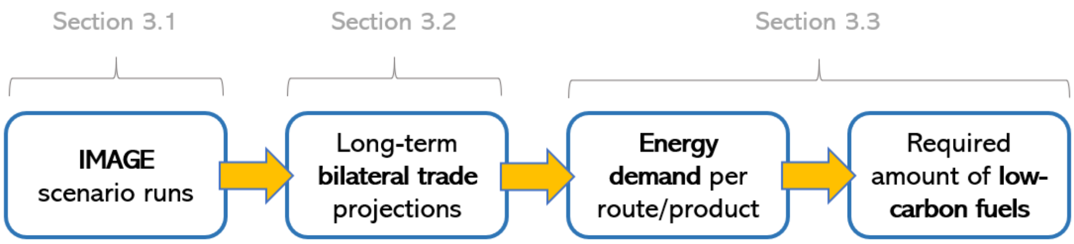

Figure 4: Overview of the methodology

The IMAGE model and the SSP narratives

The Integrated Model to Assess the Global Environment (IMAGE model) is a global IAM developed by the Netherlands Environmental Assessment Agency (PBL). It is a model framework that simulates the interactions between human societies, the biosphere, and the atmosphere to assess issues such as climate change, biodiversity, and human well-being. Detailed technical information can be found on the IMAGE 3.0 Documentation webpage [296].

The IMAGE framework has been used extensively to assess global environmental challenges, most prominently climate change, land-use change, water scarcity and nutrient cycles. The complexity of these challenges, with often a global, long-term, cross-sectoral character call for a broad modelling scope. The IMAGE framework therefore includes a detailed representation of energy system dynamics, including energy producing sectors and their interactions with energy demanding sectors such as steel and cement production, freight and passenger transport, and residential and service sector buildings. The framework includes an economic model to project agricultural product demand and a detailed gridded assessment of land availability depending on land use and land cover. Compared to other IAMs the framework has less detail on economics, but as a partial equilibrium simulation model a relatively comprehensive representation of sectors, regions, and physical flows. This is of great importance for the proposed dynamic modelling of international shipping demand [292].

As discussed, energy, agricultural and industrial products form a large part of the products shipped by maritime transport. In IMAGE, projected trade of energy and agricultural products depends on detailed resource supply and demand dynamics, including spatial resource availability, extraction costs, technology development, yield improvements, developing consumption patterns. The trade of materials, minerals, chemicals are not explicitly modelled in IMAGE, but their production and demand is. Here we briefly discuss the projected trade of the energy and agricultural products, and the projected production and demand of the remaining products, which form the starting point of international shipping demand projections [296].

In IMAGE, fossil fuel resource availability is modelled through long-term supply cost-curves that describe different resource categories associated with increasing cost levels. The cheapest deposits are assumed to be exploited first. Conversion losses in for example refining and liquefactions and technology development are projected to decrease over time but also respond to price signals. These developments combined with the resource depletion determine the final fossil fuel production costs. In the fuel trade model, each region can import fuel from other regions depending on the relative production costs and the transportation costs, which depends on the distance between regions. The distribution of imported fuel from supplying regions is based on a multinomial logit equation, where the cheapest supplying region has the largest share. To account for trade barriers due to political or geographical constraints an additional "cost" factor is added, determined by calibration. To simulate cartel behavior, regions that can supply at costs that are significantly lower than the production costs of the importing regions (the assumed threshold is 60%), are assumed to supply at only slightly below production costs. The trade of biofuels has a similar structure as fossil fuel trade. However, there are a few important differences. First of all, the availability of biofuels depends on the land availability for commercial energy crops, with as important criteria that bioenergy crops can only be cultivated on either abandoned agricultural land or on natural grass land. Labor, land rent and capital costs are input in to the primary bioenergy production costs, and crop yield is calculated on the basis of the IMAGE crop model with 0.5 x 0.5 degree grid detail. The model distinguishes between two biofuel types, namely solid biofuels, used by the industry and power sector, and liquid biofuels which is mainly used by the transport sector.

The agricultural economy is simulated within the IMAGE framework by the MAGNET model [297], which is based on the standard GTAP model, with a multi-regional, computable general equilibrium structure. Compared to GTAP, the model has a more detailed representation of land-use, household consumption, livestock, food, feed, energy crop production and emission reduction from deforestation components. The traded agricultural products are differentiated according to the country of origin, and as such not identical but imperfect substitutes following the Armington assumption [298]. The availability and suitability of land depends on information coming from the IMAGE land model, resulting in a dynamic land-supply function. The total land supply, similar to the case of biofuels, is calculated on a 5x5 arcminutes grid, and depends on the available land, and crop productivity related also to soil and climatic conditions and yields. The crop and pasture yields can change as a result of technological change, intensification, climate change, changes in agricultural area.

The demand and production of cement, steel and chemicals are explicitly modelled in IMAGE. The demand for steel and cement are described as function of per capita economic activity, based on historic production and trade data between 1970-2012. A material production model then simulates how to fulfill this demand, based on trade, production stock turnover, material recycling and competing steel and cement production technologies. The calculated technology mix, depending also technology development and energy prices, determine the total energy demand originating from the steel and cement sector [299].

The shared socioeconomic pathways (SSPs) are scenarios of global socio-economic development in the 21st century developed by the climate change research community to serve as a common reference in the long-term analysis of climate impacts, vulnerabilities, adaptation and mitigation[45] [172], [173], [300], [301]. This framework describes five internally consistent qualitative pathways of future changes in demographics, human development, economy, lifestyle, government and institutions, innovation and natural resources through consistent storylines. They have been frequently used as to assess the uncertainty in baseline development. The different pathways, varying in their perspective on economic growth, population growth, globalization, technology development (see table below) clearly also have an impact on projected trade of products. In this paper, these storylines are used to assess the uncertainty in demand for products traded through international shipping and how this impacts mitigation efforts. Table 1 concisely describes the narratives behind the five SSPs. In the supplementary material, Table 1 summarizes key aspects of the five SSPs [37], [38], [300]–[306].

[45] IMAGE is one of the marker models that was used to formulate the SSP scenarios as one of the marker models. The same scenario formulation, which describes demographic, technology, lifestyle, economic changes that follow the different SSP narratives, is used in this study [37].

Table 1: The Shared Socioeconomic Pathways

SSP	**Narrative**
SSP1	The SSP1 narrative is characterized by a fast and sustainable development firmly based on global cooperation. This storyline includes high investments in health and education across countries and an increasing preference for green technologies [39].
SSP2	In the SSP2 narrative, a sort of midpoint between the other four SSPs, the efforts to foment global cooperation and achieve development and environmental goals are present but advance more slowly than in SSP1. Socioeconomic indicators progress compatibly with historic trends and there are no major technological disruptions [40].
SSP3	The SSP3 storyline is marked by an increasingly fragmented world. Competition, regional conflicts and security concerns make national governments focus on domestic issues. There is a narrower view of social development, highly dependent on local factors of production. Investments in health and education decline and inequality worsens [38].
SSP4	The worsening of socioeconomic disparities and the escalation of social stratification are the hallmark of this narrative. In the SSP4 world, the gap between increasingly rich, well-educated and globally connected humans and low-income, poorly educated people becomes wide open. Such disparities also grow between countries – an accelerated technological development observed in specific regions coexists with labor-intensive, low-tech economies across the globe [303].
SSP5	The SSP5 world is characterized by a high degree of social, technological and human development favored by international cooperation and a strong global market. Contrary to SSP1, the push for development is coupled with a preference for fossil fuels and the adoption of resource intensive lifestyles across the world. Investments in health, education and environmental management are high [304].

International trade

As discussed, the majority of international trade takes place by sea. In this subsection, we discuss the methodological procedure adopted to project the total international trade over the century and to distinguish between seaborne and non-seaborne trade flows.

The analysis of international trade was done separately for 19 products or groups of products: 1) coal; 2) oil and oil products; 3) natural gas; 4) liquid biofuels; 5) solid biofuels; 6) chemicals; 7) iron ore; 8) steel products; 9) cement; 10) bauxite; 11) phosphate rock; 12) wheat; 13) maize; 14) rice; 15) soybeans; 16) vegetables and fruits; 17) other agricultural; 18) containers; 19) vehicles. For each one of these categories, mass-based trade matrices were created for the period 2000-2100 using relevant outputs from the IMAGE model and historical data. The dimension of these trade matrices (27 x 27) follows the geographical breakdown of the IMAGE model, which considers 26 actual world regions and one extra region. The assumptions adopted for each product/group of product are explained in Table 2 in the supplementary material.

Even though the seaborne mode is prevalent in international trade [307], road, rail, airlines and pipelines are also used to transport traded goods. As such, the results obtained using the methods explained include a few interregional flows that do not use maritime transportation, especially when it comes to adjacent regions. Some notable examples are the oil and/or gas flows such as Russia-China [308], Russia-Europe [309], Canada-USA [310], and Rest of South America-Brazil [311]. In some cases, e.g., between the different European regions (11-14), this is valid for all products. As such, prior to the calculation of the demand for maritime transport work, these trade flows were excluded from the original matrices.

As discussed, the IMAGE framework includes several baseline and mitigation scenarios. In this work, considering the objective to capture the impact of the uncertainty of the global socioeconomic development on the international shipping sector, we worked with the five SSP baselines. Furthermore, in order to analyze the effects of a climate policy on the demand for shipping, a mitigation scenario was included in the study. Table 2 summarizes the characteristics of the six scenarios.

Table 2: Analyzed scenarios

Scenario	Short description	Climate policy
SSP1	SSP1 baseline: low population, high economic and technology development (preference for green technologies)	None
SSP2	SSP2 baseline: medium assumptions	
SSP3	SSP3 baseline: high population, low economic and technology development	
SSP4	SSP4 baseline: medium population, unequal economic and technology development	
SSP5	SSP5 baseline: low population, high economic and technology development (preference for fossil technologies)	
SSP2-mit	SSP2 mitigation scenario (standard)	Climate policy compatible with a world well-below 2ºC

Energy and emissions modelling

To model the energy demand associated with trade, a simplified energy model was used. First, to determine the transport work per product and route, representative ports were assigned to the IMAGE regions and thereby distance matrices were created. Then, ship categories were assigned to the different routes and the roundtrip energy demand was calculated, considering main engines, auxiliary engines, and boilers. Finally, the total energy demand was estimated based on the required number of roundtrips.

The seaborne transport work (*mass traded x distance*) was estimated based on the distances between representative ports, defined as ports of major regional importance. In the present context, they were considered to concentrate the imports and exports of a certain region. The travelling distances were calculated with the help of an online tool [194]. For most cases, the minimal distance between ports was used. However, chokepoints and typical ship sizes were also considered (for example, the Middle East-North Europe VLCC crude oil route goes around the Cape of Good Hope instead of going through the Suez Canal). The base distance matrix was defined considering representative oil terminals. For all other products, incremental changes were made in the base matrix to better represent trade specificities. Some of these changes are illustrated in Figure 5. In the supplementary material, the representative ports are listed in Table 3.

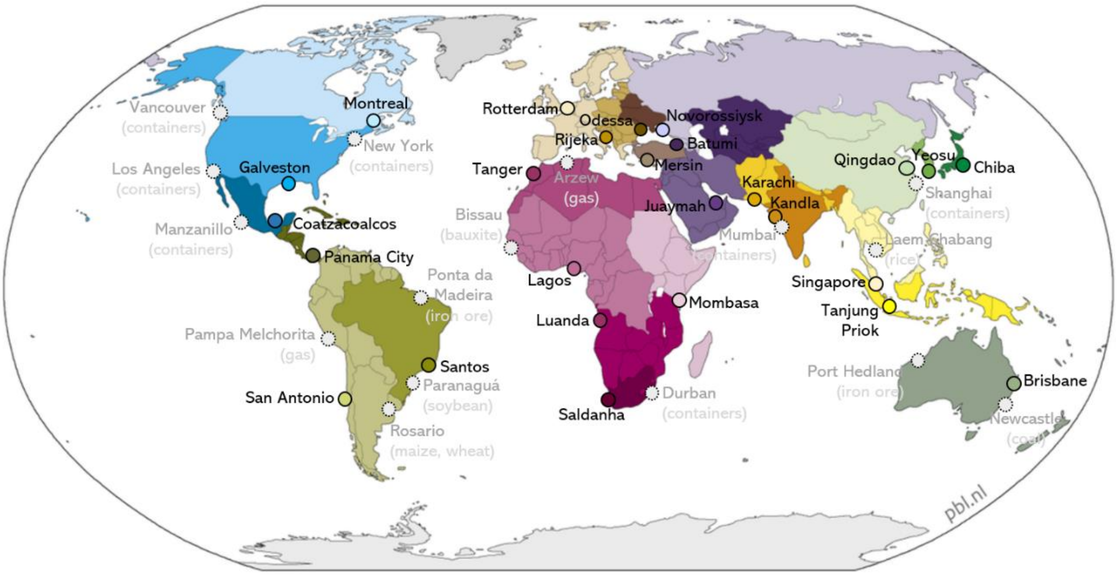

Figure 5: Representative ports selected for the 26 regions inherited from the IMAGE model. Names in black represent the base representative ports (selected originally for crude oil). Names in grey are examples of changes in the base list to better represent other products

For the energy modelling, different vessel types and sizes were considered. In the supplementary material, a table summarizing the ship classes used for each product is provided. In some cases, the vessel class considered for a certain product does not match exactly the actual existing ships. This is the case for general cargo ships, which are approximated as small bulk carriers. The roundtrip energy consumption is calculated using a simplified energy model that estimates the demand for mechanical energy (propulsion – main engine), electricity (auxiliary engine) and heat (auxiliary boilers[46]). The propulsion energy demand is calculated through hydrodynamic equations [126], [141]. The hull resistance R_T and the associated brake power P_B are presented in equations 1 and 2, respectively.

[46] The boiler is required in the case of viscous fuels, such as bunker, but not in the case of gaseous fuels and methanol.

$$R_T = \frac{1}{2}\rho C_T S v^2 \quad [1]$$

$$P_B = \frac{(1+m)R_T v}{\eta_T} \quad [2]$$

In equations 1 and 2, ρ is the seawater density, C_T is the total resistance coefficient, S is the wetted surface, m is the sea margin, v is the speed of the ship and η_T is the total propulsion efficiency. These parameters are estimated based on ship sizes and categories. The estimation of auxiliary engines and boilers energy demand follows [197]. It considers typical loads for different operational modes (at-berth, at-anchorage, maneuvering and at-sea) [198]–[205]. The route's yearly final energy demand is determined by multiplying the roundtrip demand by the total number of trips, given by equation 3.

$$n = \frac{M}{lf * dwcc} \quad [3]$$

In equation 3, n is the number of trips, M is the total mass traded, lf is the load factor and $dwcc$ is the deadweight cargo capacity. For the energy calculation, laden and ballast voyage load factors were distinguished (ballast deadweight was taken to be 30% of the total deadweight as an approximation). For the conversion from final to fuel energy demand, an average specific fuel consumption (SFC) of 7.3 MJ/kWh is adopted [119], [197], [208]. This SFC, equivalent to an efficiency of 49%, is consistent with the conversion of almost all fossil and renewable marine fuels[47]. The results are calibrated

[47] In terms of energy, the conversion efficiency is approximately the same for the different fuels in the case of internal combustion engines. For HFO and MGO, for example, it is around 7.2 MJ/kWh. For LNG and SVO, it is around 7.3 MJ/kWh. For methanol and FT-bunker, it is around 7.5 MJ/kWh. However, the

according to the data on fuel consumption from the Fourth IMO GHG Study [165], using the period 2012-2018 as a reference. To model efficiency gains, two scenarios are considered, one more conservative and another assuming higher gains. These high gains do not necessarily come from efficiency stricto sensu, but eventually from other high-impact mitigation measures such as the deployment of auxiliary propulsion devices and slow steaming. Table 3 describes the two efficiency scenarios.

Table 3: Efficiency scenarios

Efficiency scenario	**Description**	**Efficiency gains relatively to 2000**	
		2050	**2100**
Incremental gains	More efficient hull design, energy efficiency policy	30%	35%
High gains	Auxiliary propulsion devices, slow steaming	40%	50%

d. Results

International trade scenarios

Figure 6 shows the evolution of global seaborne trade in the six scenarios. In all scenarios, there is an increase in the total exchange of goods between countries over the century. However, how fast global trade increases depends on the SSP. In SSP2, for example, global trade grows from around 11 Gt/yr in 2020 to 22 Gt/yr in 2050 and 33 Gt/yr in 2100. In SSP5, with a highly connected and competitive global market, the rise is much larger, reaching 35 Gt/year in 2050 and 53 Gt/yr in 2100. In the case of SSP1, until mid-century, the trajectory is similar to the one observed in SSP2. From that point on, the increasingly strong preference for local resources and technologies causes a stabilization of trade around 20 Gt/yr. The slow development and regional isolation observed in SSP3

efficiency can be significantly higher in the case of an electrochemical conversion. For ammonia in a fuel cell system, for instance, it is around 6.0 MJ/kWh (or 60%).

entail a relatively low global trade, especially until 2050 (18 Gt/yr). Nevertheless, in the second half of the century, with very high world population and low technological efficiency, the increase in trade goes on, reaching 27 Gt/yr. The development of global trade in SSP4 is somehow an intermediate stage between SSP1 and SSP3. In the SSP2 mitigation scenario, international trade follows a trend similar to that of its baseline. However, over the three decades between 2020 and 2050, a gap is created between these two scenarios. This is mainly due to an avoided trade of fossil fuels in SSP2-mitigation.

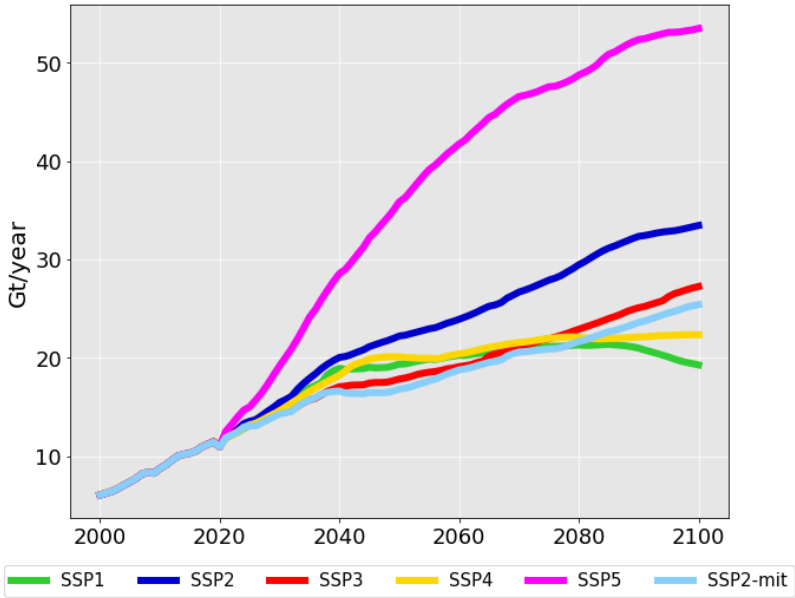

Figure 6: Global seaborne trade in the six scenarios

Table 4 shows the average cargo travelling distance in the six scenarios in 2050. The average haul varies between slightly below 5,000 (SSP2-mit scenario) and slightly above 5,300 (SSP5 scenario) nautical miles, illustrating different trade network patterns according to the SSPs. While in SSP5 there is a strong signal towards a single global market, in SSP3, regional exchanges dominate. In the case of SSP2-mit, the low average haul is explained by the avoided trade of oil, a product that typically involves long-distance shipping.

Table 4: Average haul in the six scenarios

Scenario	Average haul in 2050 (nm)
SSP1	5040
SSP2	5289
SSP3	4981
SSP4	5243
SSP5	5305
SSP2-mit	4964

Figure 7 and Figure 8 show the results breakdown by group of product and world regions. The variation in projected trade across the scenarios is significant for all products, but most pronounced for the trade of energy products. The results for specific products are discussed next.

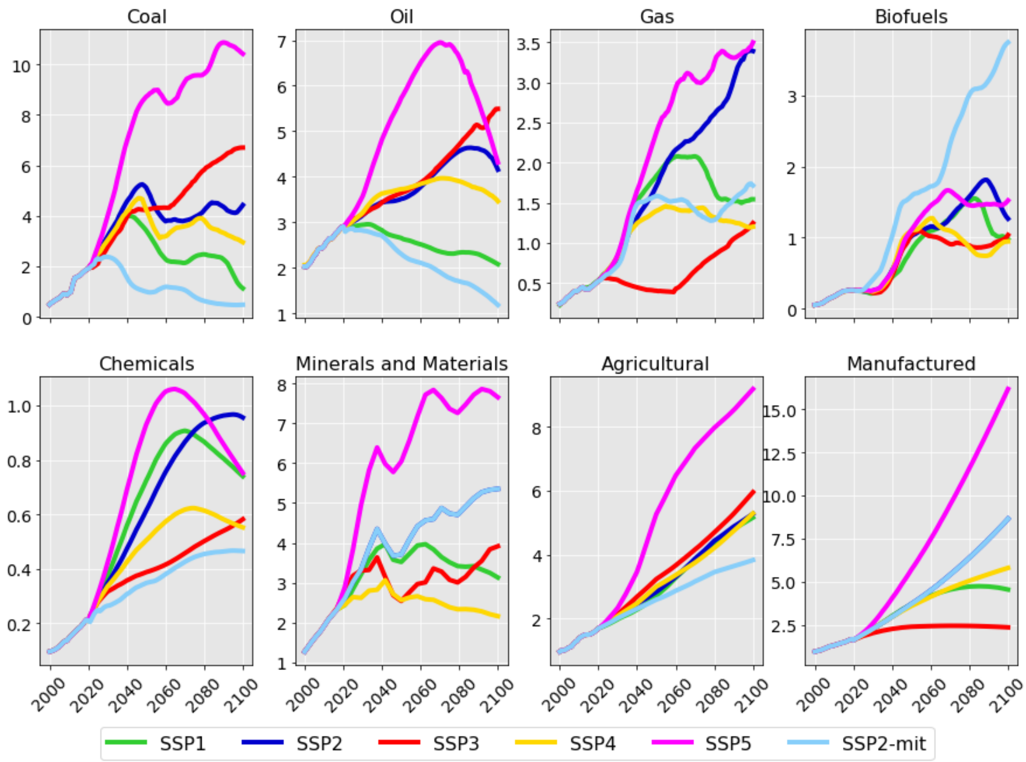

Figure 7: Global seaborne trade in the six scenarios breakdown by group of products. Unit: Gt/yr

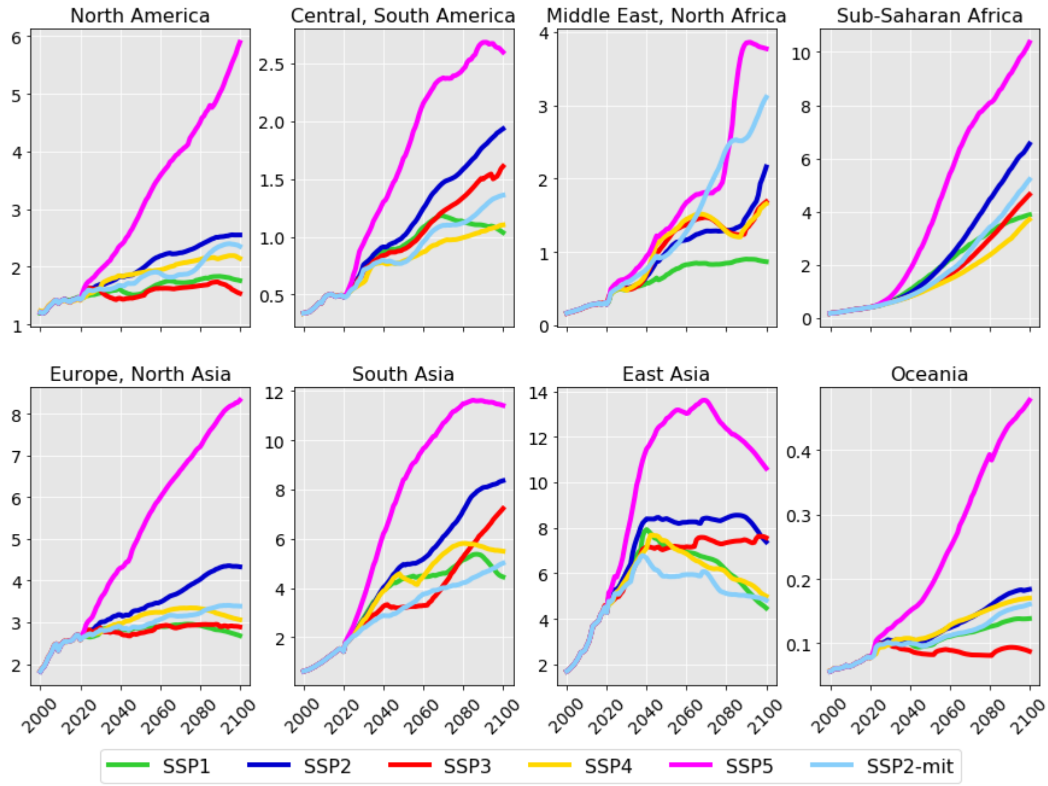

Figure 8: Global seaborne trade in the six scenarios breakdown by group of products. Unit: Gt/yr

In most SSPs, given the low cost of coal-based electricity, in the absence of a climate policy, the use of coal continues to increase, especially in India and China. As such, in almost all baseline scenarios, the trade of coal grows significantly between 2020 and 2040, peaking around 2045. The height of this peak varies widely across the SSPs. In SSP2, it is equal to 5.7 Gt/yr, with a stabilization at approximately 4.0 Gt/yr (twice as much as 2020) in the second half of the century. In SSP5, a world that indiscriminately uses fossil resources, this peak equates 10.5 Gt/yr. Furthermore, after a slight decline between 2050 and 2060, the fossil-based economic development of regions like Western and Eastern Africa causes a new rise in the trade of coal (equal to 12.3 Gt/yr in 2100). Contrastingly, in SSP1, the peak takes place way sooner and at a much lower level (4.2 Gt/yr in 2040). Then, it declines consistently over the century, reaching 1.8 Gt/year in 2100. In SSP3, no peak is observed and the trade of coal increases significantly after 2050, reaching 6.5 Gt/yr in 2100. In the mitigation scenario, electricity supply shifts gradually towards renewable-based facilities. As a result, the trade of coal declines over the century, reaching 1.0 Gt/yr in 2050 and 0.5 Gt/yr in 2100.

The trade of petroleum and products, mostly driven by the demand of the transport sector, vary broadly across the six scenarios. In the SSP2 baseline, even though the amount imported by OECD countries declines, the total trade of oil increases steadily until 2080, reaching 4.5 Gt/yr. This is mainly due to the imports of regions like Africa, India, Indonesia and South America, where the electrification of the transport sector happens slowly, in contrast with OECD countries. In SSP1, the trend of electrification is stronger all over the world. As such, the use of petroleum products is moderate even in these regions, enabling a significant reduction of the global oil trade (2.6 Gt/yr in 2050, 2.0 Gt/yr in 2100). In SSP5, the fossil-powered development of the whole world relies heavily on the global petroleum market. Thus, a steep increase is observed in the trade of oil over the century, reaching 7.0 Gt/yr around 2075. However, after that, the continuing electrification of the transport sector slightly reduces the oil trade. In SSP3, in spite of slow development and low international cooperation levels, the energy demand is high, and there is a preference for fossil resources. Therefore, even though the global oil market is weakened, accounting for a smaller fraction of the oil consumption, in absolute terms, the trajectory followed by the oil trade is similar to SSP2 but reaching a highest point in the last decades of the century (5.9 Gt/yr in 2100). In the presence of a climate policy, the electrification of the passenger transport progresses at a stronger pace. Furthermore, biofuels are increasingly used in freight road transport and aviation. This brings about a consistent decline of oil trade, reaching 2.2 Gt/yr in 2050 and 1.2 Gt/yr in 2100.

The global natural gas market follows very different trends in the six studied scenarios. In SSP2, for instance, as the cleanest fossil fuel, natural gas assumes a prominent role, compatible with a middle of the road narrative. As such, the trade of gas increases robustly over the 21st century, growing from 0.6 Gt/yr in 2020 to 1.6 Gt/yr in 2050 and 3.3 Gt/yr in 2100. Most of the gas is imported by Asian countries, but also by Africa and Europe. In SSP5, a very similar trend is observed. Contrary to what is perceived for the other fossil fuels, the gap between SSP2 and SSP5 is not wide. With the fossil-fueled development prioritizing coal and oil, these energy sources supply a high fraction of the world's energy demand, leaving less room for gas. In the SSP1 baseline, the trade of natural gas is especially important in the first half of the century (1.7 Gt/yr by 2050), serving as a transition fuel. In the long term, the fuel gradually loses ground to greener technologies (e.g., wind, solar and biomass in power systems). In the end of the century, gas trade equals 1.5 Gt/yr. A different trend is observed for the SSP3 baseline. In a world where global markets are weakened, the trade of natural gas, whose transportation is more costly than coal and oil, is severely affected. Global gas exchanges decrease from 0.6 Gt/yr in 2020 to 0.4 Gt/yr in 2060. In the second half of the century, the trade of gas increases, reaching 1.3 Gt/yr in 2100. In the mitigation scenario, the role of natural gas is similar to the one described for SSP1. Thanks to its lower emission factor, gas is used a transition fuel for heat and electricity generation. However, carbon-free technologies are stronger in this scenario than in SSP1 and, therefore, less gas is used and traded.

The biofuel trade follows similar pathways in all baseline scenarios, especially until 2050, when it reaches approximately 1.0 Gt/yr. In SSP1, SSP2 and SSP5 the increasing yields push the trade further, showing that there is still room for the market to grow. In the climate mitigation scenario, the demand for low-carbon fuels ramps up the trade of biofuels quickly, reaching 1.6 Gt/yr in 2050, and 3.9 Gt/yr in 2100. This is largely driven from the demand for BECCS to provide Carbon Dioxide Removal (CDR).

In the first half of the century international trade of chemicals grows rapidly as many regions increase the demand of plastics and fertilizers. As most scenarios show a declining global population after mid-century, combined with structural changes requiring fewer chemicals (i.e., reduced fertilizer demand in SSP1), there is a large drop in the trade of chemicals post 2050. In the mitigation scenario, changes in consumer behaviour and the increased cost of petrochemicals reduces this demand and trade.

Total agricultural trade follows similar trends in most of the scenarios analyzed, with an increase from 1.8 Gt/yr in 2020 to around 2.5 Gt/yr in 2050 and 5 Gt/yr in 2100. However, the drivers of this trade differ across scenarios. SSP1 and SSP3, for example, follow a very similar trajectory. However, while for the latter the increase in trade is mostly associated with a huge growth of the global population, in the case of SSP1, whose world population is much lower, this increase is related to the abolishment of tariffs and exports subsidies (i.e., the ratio between agricultural trade and agricultural production is much higher). In SSP5, with high demands from the food system (caused, for instance, by the rise of meat-rich diets), the trade of agricultural products grows faster, reaching 5 Gt/yr in 2050 and 9 Gt/yr in 2100. Contrastingly, the mitigation scenario is marked by a lower agricultural trade, especially after 2050 (4 Gt/yr in 2100).

The trade of minerals and materials varies substantially across the scenarios. Both SSP2 and SSP2-mitigation project an increase in the trade of these products, especially iron ore. In these scenarios, the trade grows from around 2.5 Gt/yr in 2020 to 4.0 Gt/yr in 2050 and 5.2 Gt/yr in 2100. On the other hand, the SSP1 baseline, which is characterized by a less material-intensive industry, has a lower trade, especially in the second half of the century. The lower limit corresponds to SSP4 - in a world where inequalities persist and worsen, poor countries dot not develop their infrastructure and industry and this severely impacts the trade of steel and iron ore.

Total agricultural trade follows similar trends in most of the scenarios analyzed, with an increase from 1.8 Gt/yr in 2020 to around 2.5 Gt/yr in 2050 and 5 Gt/yr in 2100. However, the drivers of this trade differ across scenarios. SSP1 and SSP3, for example, follow a very similar trajectory. However, while for the latter the increase in trade is mostly associated with a huge growth of the global population, in the case of SSP1, whose world population is much lower, this increase is related to the abolishment of tariffs and exports subsidies (i.e., the ratio between agricultural trade and agricultural production is much higher). In SSP5, with high demands from the food system (caused, for instance, by the rise of meat-rich diets), the trade of agricultural products grows faster, reaching 5 Gt/yr in 2050 and 9 Gt/yr in 2100. Contrastingly, the mitigation scenario is marked by a lower agricultural trade, especially after 2050 (4 Gt/yr in 2100).

In view of the higher consumption of goods and services, in addition to a crescent population, the trade of manufactured products surpasses today’s level (1.9 Gt/year) in all scenarios. In SSP2, for example, it reaches 3.0 Gt/year in 2050 and 6.2 Gt/year in 2100. In SSP5, with a much higher private consumption due, for example, to the dissemination of materialism and status consumption, the trade of manufactured goods is extremely high (7 Gt/yr in 2050, 16 Gt/yr in 2100). The exception is SSP3, in which a fragmented world and slow economic development contribute to weaken the global trade. In this scenario, trade stabilizes around 2.5 Gt/yr from 2030.

Figure 9 shows, for the six scenarios, the CO_2 emissions associated with international shipping in the case of a completely fossil-fueled fleet. On the right side of the figure, the BAU/no ambition emission estimates for 2050 from DNV GL and IMO are also shown [165], [170]. The presented emissions ranges are estimated based on the two vessel efficiency storylines while the percentage indicates the proportion of total global CO_2 emissions coming from international shipping. For most scenarios, international shipping emissions lie between 1.0 and 1.7 $GtCO_2$/yr in 2050 (in line with IMO and DNV GL). The exception is SSP5, in which emissions reach the level of 2.0-2.5 $GtCO_2$/yr in 2050 when considering 100% fossil-based energy. For baseline scenarios, the CO_2 emission share of the sector lies between 2 and 4% in 2050. For the mitigation scenario, the proportion of shipping is way higher (13%), since global CO_2 emissions are at a much lower level due to mitigation in other sectors. In 2100, the proportion is negative (-18%) because, with large-scale deployment of carbon dioxide removal (CDR), global net CO_2 emissions go negative.

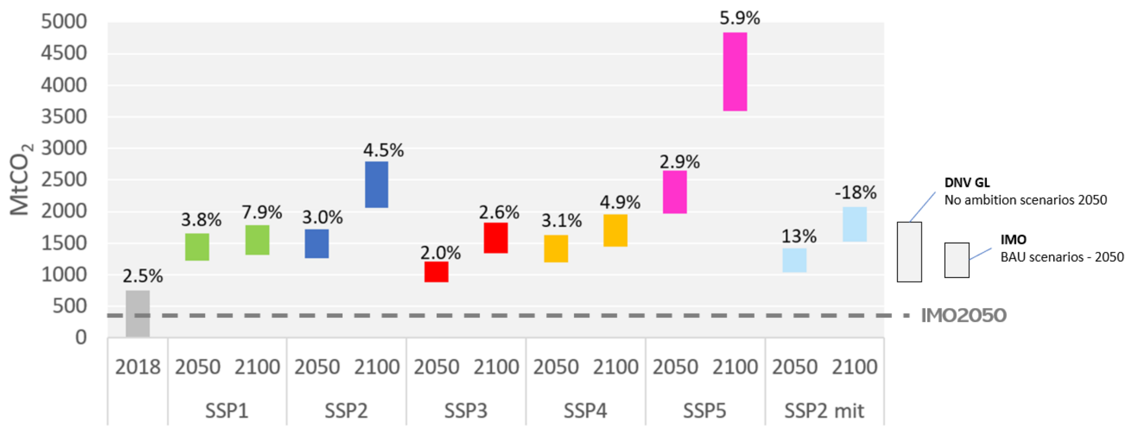

Figure 9: CO_2 emissions with a fossil-fueled fleet. The percentage above each bar indicates the ratio between international shipping and total CO_2 emissions

Figure 10 shows, for both efficiency storylines, the amount of low-carbon fuels required to meet the IMO2050 target per scenario. In both cases, taking the absolute goal for 2050 into account, the fossil energy is limited to approximately 6 EJ/yr. As such, considering incremental gains, the total energy demand from international shipping varies from 12 to 25 EJ/yr, implying a demand for renewable fuels between 6 and 17 EJ/yr in 2050. With high efficiency, the range for total energy is 9-17 EJ/yr, with a demand for renewable energy between 3 and 11 EJ/yr. For the sake of comparison, the world yearly biofuel production in 2018 was around 3 EJ [312].

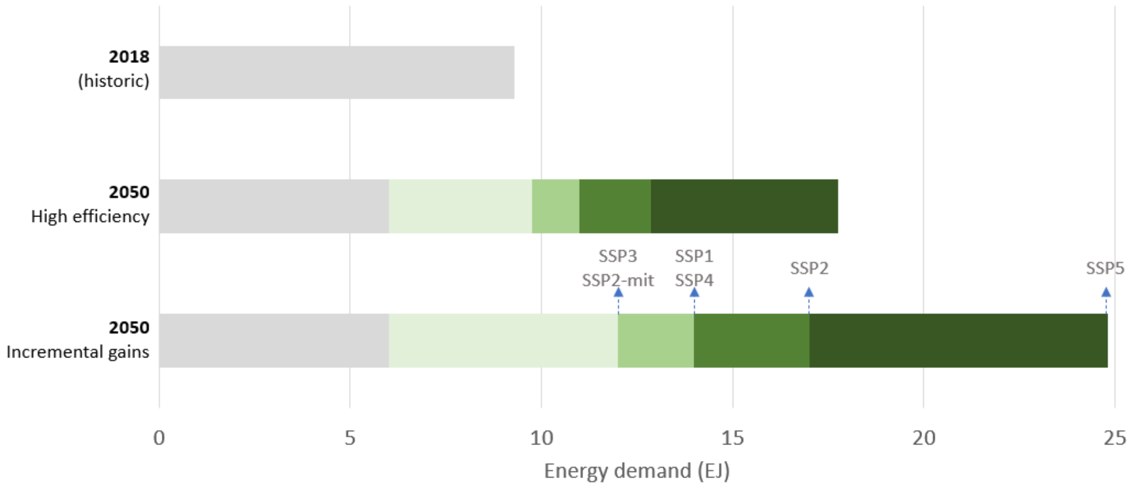

Figure 10: Required renewable energy demand to meet the IMO2050 target

To that end, several low-carbon fuels could be used. Concerning biofuels, the options can be divided in three groups [265]. The first group is composed of first-generation distilled biofuels, for instance straight vegetable oils (SVO), hydrotreated vegetable oils (HVO), and biodiesel, usually produced from animal fats and oilseeds [187]. The second group comprises advanced biofuels obtained through thermochemical processes, e.g. bio-oils, such as hydrotreated pyrolysis oils (HDPOs) [188] and Fischer-Tropsch (FT) synthetic liquids [189]. Advanced biofuels conversion facilities frequently output various hydrocarbon cuts, similarly to oil refineries. For example, biojet and FT-naphtha have higher market value than the coproduced fractions suited for marine use. As such, advanced biofuels for shipping can be regarded as byproducts, which could be a major advantage in terms of cost. The third group corresponds to biogases and bio-alcohols suited to the increasingly common dual-fuel marine engines. Examples are liquefied biomethane (bio-LNG) and biomethanol. Low-carbon energy carriers for shipping can also be produced from hydrogen (H_2-fuels) [265]. This includes not only hydrogen for direct use but additionally ammonia (NH_3) and synthetic fuels. Although H_2-fuels do not imply direct fossil GHG emissions, they can be fossil-based. Therefore, for H_2-fuels to be considered low-carbon, they must be either renewable-based (green H_2-fuels) or fossil-based with CCS (blue H_2-fuels). In any case, all low-carbon fuels face technical-economic obstacles (e.g., competition for land, water stress, production technology readiness, applicability to the existing fleet, safety concerns, energy density, deployment of CCS) and scaling up their production and use to the required levels of 3-17 EJ might be a challenge.

Discussion and conclusions

The aim of this work was twofold. The first objective was to develop a methodological framework for the coupling of an IAM with a detailed model of international shipping in order to capture the impacts of different integrated scenarios on the demand for seaborne trade over the 21st century. The second objective was to use this integration to project the energy demand from shipping in the six scenarios studied, ultimately to better understand how different global trade futures impact the effort required, in terms also of the amount of renewable fuels needed, to meet the IMO2050 target.

The development of the shipping model followed a demand-driven approach based on socioeconomic and technological outputs of the IMAGE model. Starting from these variables, and considering the 26 IMAGE regions, yearly mass-based trade matrices were generated for each product. Thereby, it was possible to obtain long-term projections of global trade according to six scenarios, namely the five SSP baselines and one climate policy scenario.

International seaborne trade follows very different trends in the six scenarios studied (17-35 Gt/yr in 2050 and 19-53 Gt/yr in 2100 compared to 11 Gt/yr in 2020). The results are a function of the preference for certain energy carriers and of economic development in general, but they also depend heavily on consumption patterns and global cooperation levels. For instance, one could expect, given the low techno-economic efficiency and high population observed in SSP3, that this scenario would imply a high demand for shipping. Instead, during most of the century, SSP3 represents the lower end of the baseline trade projections in this study. This is due to a weakening of global cooperation, which causes each region to focus on its own mineral, agricultural and energy resources, following a logic of regional rivalry. Contrastingly, for all products, the upper end of global trade is defined by the SSP5 baseline, whose storyline includes fast development, high consumption, and a strong globalization. In this sense, SSP5 behaves as an outlier compared to the rest of scenarios. The remaining baselines lie somehow in-between, always closer to the lower end. In the middle of the road baseline, global trade doubles in 2050 and triples in 2100.

As countries' economies mature and develop into more service-oriented ones, the seaborne trade-intensity of imports and exports are likely to change into the future, which may have implications in the context of the different global scenarios we explore in this study. However, over the 2050 time horizon of our analysis, China is very likely to remain the main producer of energy converters associated low-carbon energy futures (solar PVs, electric batteries, electric vehicles etc.), and as such it will very likely remain the main processor of ores (and as such the main importer of mineral commodities), even as it moves to a more service-oriented economy. Consequently, up to 2050 the Chinese economy will continue dominate global seaborne trade (resource intensive imports and manufactured intense exports), which does not challenge the robustness of our results. However, future studies must further investigate the impact of industrialization on the profile and main routes of seaborne trade into the future.

Climate policy results in a lower demand for international shipping due to reduced fossil energy trade. In the presence of a climate policy compatible with a world well-below 2^{o}C (SSP2-mitigation), an avoided demand of coal, oil, gas and chemicals reduces the international maritime activity by around 20% in 2050 and 25% in 2100. The drastic increase in the trade of biofuels does not compensate the reduction seen in the other energy sectors. As such, it can be said that the results indicate an interesting positive feedback effect of the energy supply transition on the shipping sector. At the same time, the shipping model used in this study does not capture potential activity growths due to increased trade of products associated with the renewable energy supply chain, such as materials for batteries, solar panels, electric motors and even hydrogen. It is also worth noting that the IMAGE model is not able to see important details of the petroleum industry, such as different crude oil streams and refinery schemes. In this sense, our results for the mitigation scenario might underestimate a technological inflexibility that could keep the trade of oil and products at a fixed bottom level.

In a more conservative efficiency scenario, the total energy demand from international shipping lies in the range 12-25 EJ in 2050 and 18-46 EJ in 2100. With

higher efficiency gains, the demand lies in the range 9-17 EJ in 2050 and 13-32 EJ in 2100. The conservative scenario reflects a business-as-usual storyline for efficiency improvements, with incremental gains. The high efficiency scenario reflects a more disruptive development of the mitigation measures, for example with the use of auxiliary propulsion devices and the existence of speed limits.

With a fossil-fueled fleet, international shipping emissions lie between 0.8 and 2.6 $GtCO_2$/yr in 2050, with most scenarios (SSP1, SSP2, SSP2-mit and SSP4) in agreement with the literature. Existing scenarios that depict a fossil-fueled fleet project international shipping emissions between 1.0 and 1.8 $GtCO_2$/yr in 2050. This means that the central projections well align with the literature but that some scenarios go beyond the literature range, i.e., the low economic growth (SSP3) scenarios with high vessel efficiency (0.8 GtCO2/yr), and high growth SSP5 scenarios (2.0-2.6 GtCO2/yr). Given the focus of these storylines, the broader emissions range is a coherent result.

Renewable fuels need to make up the bulk of shipping's energy supply in 2050 (3-17 EJ) if the IMO2050 target is to be met. With fossils restricted to ca. 6 EJ in all scenarios, the fulfillment of IMO2050 would require a steep increase in the global renewable fuel production. To that end, several low-carbon fuels can be considered. They can be more or less interesting depending on factors such as their applicability, cost and sustainability but, in any case, the scaling-up of their production to the levels indicated by our calculation represents a major challenge.

It is worth noting that this work was based on an ex-post analysis. The trade projections developed are based on scenario outputs of the IMAGE model. As such, the modelling is to a certain extent static and does not take into account year-by-year feedbacks. In future works, the authors intend to fully integrate the shipping module used here into the IMAGE model. Thereby, it will be possible to represent specific alternative marine fuels that will be part of the overall optimization. Furthermore, it must be stressed that although IMAGE contains relatively high sectoral and regional detail, as a partial equilibrium simulation model it represents less macro-economic detail. Input-output tables and also the global trade analysis project (GTAP) contain detailed trade flows and computable general equilibrium (CGE) consistent economic feedbacks but less suitable to represent the future changes and storylines as we have examined in this paper.

5. O transporte marítimo internacional num mundo abaixo de 2ºC

Conforme mencionado na introdução, o artigo #4 possui a peculiaridade de incluir seis IAMs, o que faz com que a descrição do procedimento metodológico relativo ao COFFEE seja bastante sucinta. A fim de evitar falta de informação, inclui-se a seguir uma explicação sobre o COFFEE e seu novo módulo de transporte marítimo internacional. Em seguida, transcreve-se normalmente o artigo #4, assim como nos capítulos anteriores.

5.1. O modelo COFFEE

5.1.1. Histórico

Até poucos anos atrás, as análises integradas do sistema energético desenvolvidas pelo CENERGIA limitavam-se ao âmbito nacional (num primeiro momento com o MESSAGE-Brasil e, posteriormente, com o BLUES). Uma lacuna relevante advinda dessa abordagem isolada do Brasil era a incapacidade de se avaliar, de forma dinâmica, a interação entre o país e o resto do mundo. Para se impor um orçamento de carbono ao BLUES, por exemplo, era necessário recorrer à literatura e adotar certas hipóteses, uma vez que a relação entre orçamentos globais e regionais não é direta. Analogamente, o comércio exterior de produtos energéticos e agrícolas deveria inexoravelmente pautar-se em variáveis exógenas [313].

Em 2016, a fim de preencher essa lacuna, uma tese de doutorado foi desenvolvida com o objetivo de construir, também com base na plataforma MESSAGE, um IAM global cujos resultados pudessem dialogar com a perspectiva nacional oferecida pelo BLUES [313]. De tal esforço resultou o COFFEE, principal ferramenta do presente trabalho. Mais recentemente, no contexto de uma dissertação de mestrado, o modelo foi aprimorado por meio de uma representação detalhada de qualidades de óleo cru e esquemas de refino nas diferentes regiões [314].

Assim como o BLUES, o COFFEE é um modelo de otimização baseado em programação linear, cuja função objetivo é um custo total. Ou seja, uma rodada do modelo procura encontrar o arranjo ótimo (i.e., menos custoso) dos sistemas nele representados que atenda às diversas demandas e restrições informadas como parâmetros de entrada. A Figura 12 ilustra essa dinâmica em detalhes: para cada uma de suas 18 regiões geográficas, o COFFEE recebe dados de evolução demográfica, demanda por serviços (e.g., alimentos, mobilidade, conforto térmico), evolução tecnológica (e.g., curvas de custo e eficiência de conversores energéticos) e disponibilidade de recursos (e.g., biomassa, carvão, petróleo). Paralelamente, o modelo recebe restrições associadas a aspectos ambientais (e.g., orçamento de carbono), institucionais (e.g., políticas públicas em vigor) e históricos (i.e., calibração[48]). A partir desses dados e de uma taxa de desconto predeterminada, o COFFEE cria e otimiza uma função objetivo, retornando ao usuário uma conformação supostamente ideal dos sistemas de energia, agricultura e uso do solo para as condições em questão [42], [313].

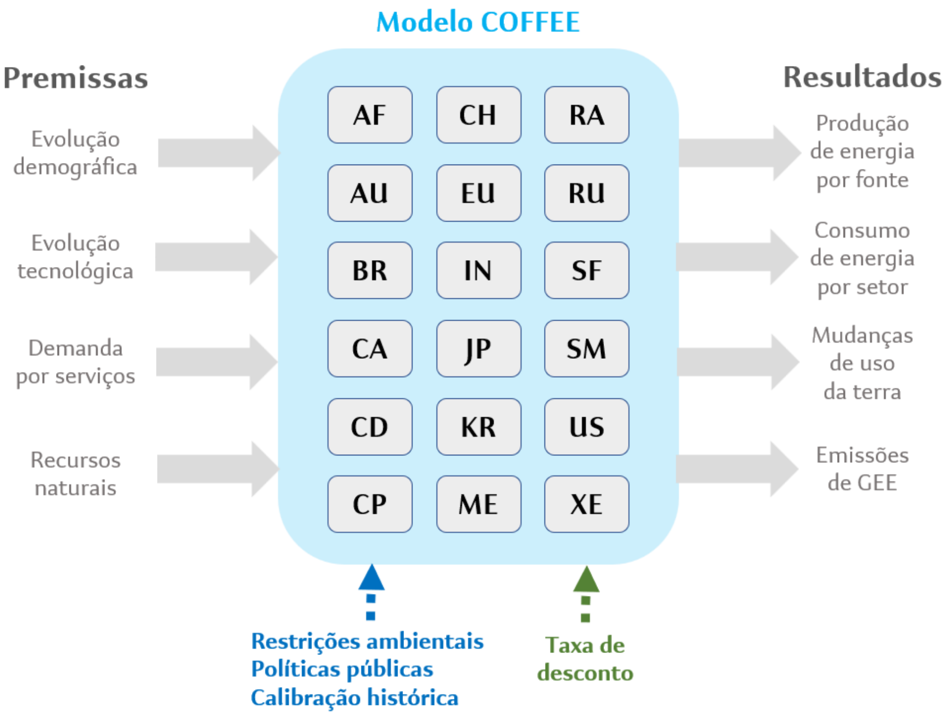

Figura 12: Funcionamento do modelo COFFEE

Nota: AF- África, exceto África do Sul; AU- Austrália e Nova Zelândia; BR- Brasil; CA- México e América Central; CD- Canadá; CP- Região do Cáspio/Ásia Central; CH- China; EU- União Europeia + Islândia, Noruega, Reino Unido, Suíça e Turquia; IN- Índia; JP- Japão; KR- Coreia do Sul; ME- Oriente Médio; RA- Resto da Ásia e Oceania; RU-

[48] Por "calibração" entende-se a adição de restrições ao modelo para forçá-lo a produzir resultados condizentes com a realidade em anos já passados. No caso do COFFEE, cujo horizonte temporal se estende atualmente entre 2010 e 2100, isso significa adicionar restrições para os anos de 2010, 2015 e 2020.

Rússia; SF- África do Sul; SM- América do Sul, exceto Brasil; US- Estados Unidos; XE- Resto da Europa. Fonte: elaboração própria

Como uma lupa sobre a Figura 12, a Figura 13 mostra a estrutura interna de uma região qualquer do COFFEE, evidenciando suas interconexões setoriais.

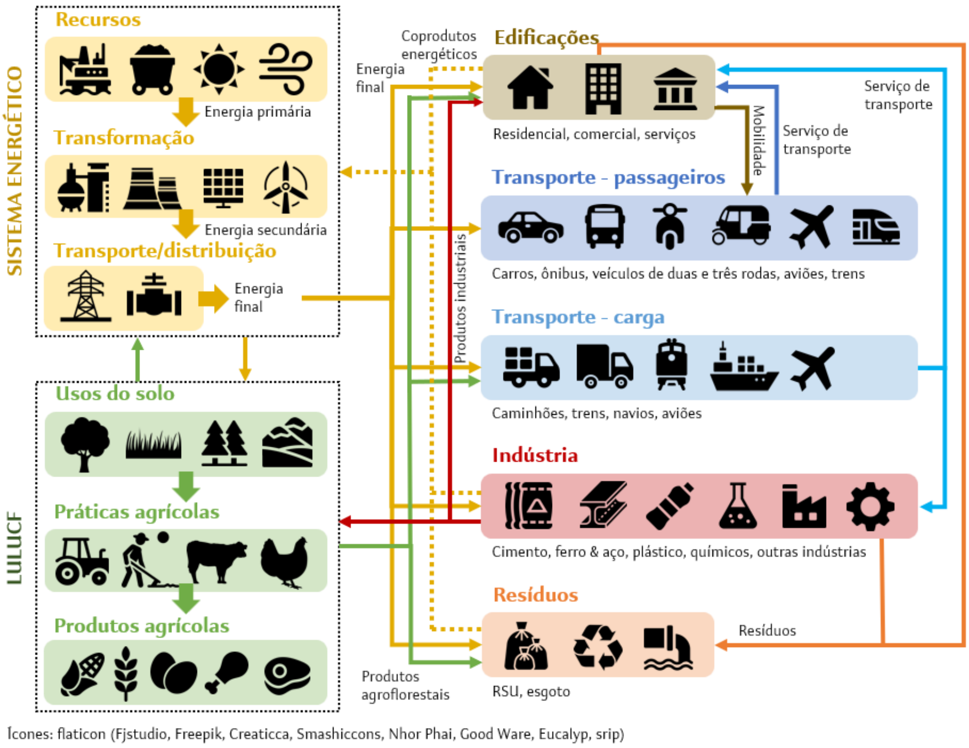

Figura 13: Representação esquemática de uma região do COFFEE

Fonte: elaboração própria

5.1.2. Estrutura e funcionamento

O COFFEE foi escrito a partir do MESSAGE, um programa criado pelo IIASA com o objetivo de avaliar sistemas energéticos de forma integrada. No caso do IIASA, o programa original recentemente evoluiu para uma plataforma *open-source* denominada MESSAGE*ix* [315]. Já o COFFEE, criado em 2016, foi baseado em uma versão anterior da ferramenta. Apesar dessa diferença, a conceptualização apresentada na página da plataforma MESSAGE*ix* [316] é, em grande medida, aplicável ao COFFEE.

A formulação matemática do COFFEE é uma otimização baseada em programação linear dinâmica (*Dynamic Linear Programming*, DLP). Um problema de DLP pode ser resumido como uma combinação de equações de estado, restrições e de uma função objetivo que abarca certo intervalo temporal T. Enquanto as equações de estado descrevem a mudança do sistema estudado ao longo do tempo (sendo conhecido o estado inicial), a função objetivo expressa a otimização do conjunto dessas equações de estado. Finalmente, as restrições delimitam o espaço de possíveis soluções [317].

No caso do COFFEE, enquanto as equações de estado refletem principalmente fluxos energéticos (e.g., conversão de energia primária em secundária – Figura 14), a função objetivo diz respeito ao custo total do sistema modelado. Por sua vez, esse custo total é obtido pela soma dos custos de investimento e operação das tecnologias[49] utilizadas com custos de eventuais externalidades socioambientais informados ao modelo[50]. Tendo em vista o caráter intertemporal da otimização (período 2010-2100), o cálculo do custo total inclui também uma taxa de desconto, reduzindo o peso relativo de fluxos financeiros futuros. Isso permite uma avaliação mais realista das opções de suprimento energético num contexto de mercado [313], [318]. Por sua vez, as restrições têm a função de tornar a otimização compatível com o mundo real, evitando soluções implausíveis que sejam matematicamente factíveis. Tipicamente, as restrições do COFFEE dizem respeito a disponibilidade de recursos, existência de infraestrutura de distribuição (e.g., linhas de transmissão, gasodutos), adição anual de capacidade (e.g., novas refinarias, novas plantas de geração elétrica) e, eventualmente, a restrições ambientais[51].

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[49] No contexto do modelo COFFEE, o termo "tecnologia" diz respeito aos diferentes processos por meio dos quais as formas de energia podem ser convertidas. Na maior parte das vezes (e.g., veículos, usinas de geração elétrica), essa nomenclatura parece bastante coerente. No entanto, alguns dos fenômenos representados não são exatamente tecnologias, mas simplesmente processos, o que pode gerar confusão. Diz-se, por exemplo, que a produção de carne a partir de pastagens é uma tecnologia. Isso ficará claro mais à frente, quando será abordada a adaptação feita no modelo para representar o setor de AFOLU. Por convenção, mantém-se o uso do termo "tecnologia" ao longo deste trabalho.

[50] Por exemplo, precificação de emissões de GEEs.

[51] Restrições de emissões de GEEs são uma alternativa à precificação, mencionada na nota anterior. Nesse caso, em vez de se atribuir às emissões um certo vetor de custo monetário, limita-se o total

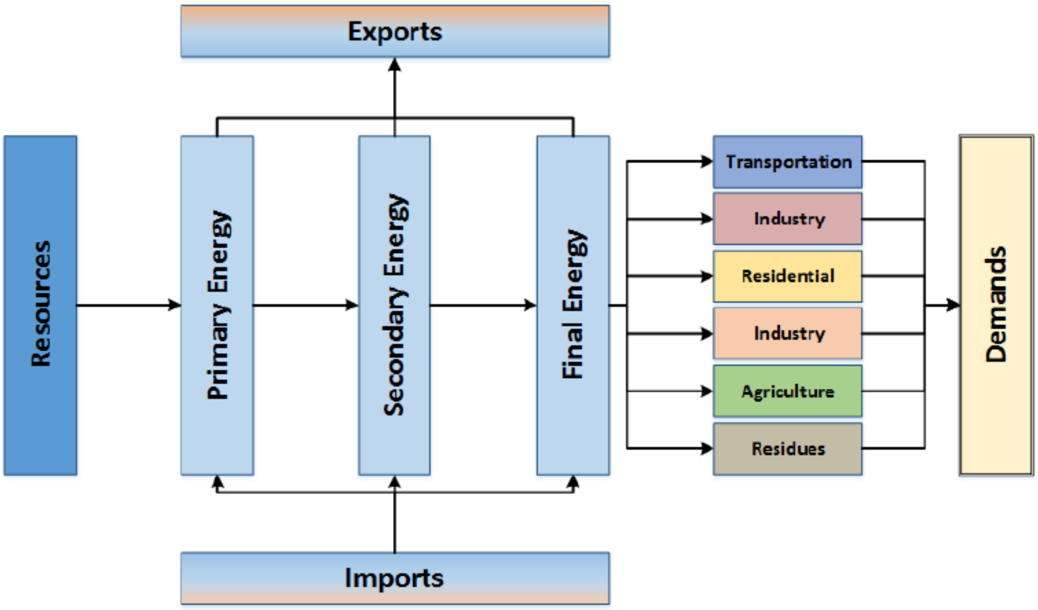

Figura 14: Estrutura do sistema energético de uma região do COFFEE

Fonte: [313]

Em suma, a formulação do COFFEE é estruturada em torno de tecnologias de conversão[52], cada qual com insumos e produtos específicos. A cada uma dessas tecnologias se associa uma série de parâmetros, estando os custos de investimento e operação (divididos em fixos e variáveis) entre os mais importantes. Como o objetivo final da otimização é atender a uma série de demandas (e.g., serviço de transporte, demanda por alimento, conforto térmico) a mínimo custo global, cada tecnologia pode ou não ser empregada em dado cenário, dependendo justamente de seus custos, mas também de parâmetros mais abrangentes, como a taxa de desconto e o eventual orçamento de carbono.

---

de emissões de determinado GEE ao longo do período considerado. Essa é a lógica por trás da implementação de orçamentos de carbono no COFFEE (e em alguns outros IAMs).

[52] Trata-se, em geral, de conversões energéticas. No entanto, conforme será explicado mais à frente, o modelo foi pensado para incluir outros tipos de conversão, notadamente aquelas associadas aos setores agrícola e industrial.

Ilustrativamente, considere-se a tecnologia mostrada na Figura 15, uma captura de tela que mostra linhas de código do COFFEE. Trata-se de uma das muitas tecnologias representadas no modelo, escolhida arbitrariamente. Essa tecnologia modela plantas de produção de etanol a partir de cana-de-açúcar, mais especificamente aquelas equipadas com meios de captura de CO_2. A linha *minp* informa ao modelo o insumo necessário para ativação dessa tecnologia (*l-F*, que representa a cana-de-açúcar), enquanto a linha *moutp* indica o principal output de *Ethanol_Prod_Sugarcane_CCS* (*A-s*, que representa energia secundária, *s*, sob a forma de etanol, *A*), bem como a eficiência de conversão envolvida (0,057). Os parâmetros *inv* e *fom* representam, respectivamente, o custo de investimento e o custo fixo de operação de uma tal planta, enquanto a linha *bdc up* constitui uma restrição à adição anual de capacidade[53]. Já o output secundário *outp b-A* foi incluído para modelar o bagaço de cana como um coproduto desse processo. Isso é importante porque o bagaço também possui potencial energético, podendo ser selecionado pelo modelo como insumo para outras tecnologias (e.g., geração elétrica a partir de biomassa). Assim, sua representação como coproduto contribui para que a otimização leve em conta algo mais próximo do real potencial da tecnologia. A linha *outp c-C* também representa um output secundário, o dióxido de carbono capturado na destilaria. As demais linhas de código, iniciadas por *con1a* e *conca,* são restrições com funções diversas, associadas a limites mais gerais do modelo (e.g., orçamento de carbono) ou simplesmente com efeito contábil (a restrição *con1a TBCC*, por exemplo, garante que o CO_2 capturado pela tecnologia *Ethanol_Prod_Sugarcane_CCS* seja considerado na soma global de CDR).

[53] Este é um exemplo do uso de restrições a fim de compatibilizar o resultado da otimização com limitações práticas. Ainda que matematicamente possível, não se deve admitir a entrada de uma quantidade implausível de plantas de etanol entre 2025 e 2030, por exemplo. Isso mostra a importância de incluir restrições à adição de capacidade. Conforme mostra a captura de tela, no caso ilustrativo, a limitação é relaxada ao longo do tempo, com um aumento da máxima capacidade anual permitida.

```
Ethanol_Prod_Sugarcane_CCS A
    minp     l-F 1
    moutp    A-s ts 0.057
    inv ts 530
    fom ts 26.5
    bdc up  ts 0 0 0 1000 2000 5000
    outp b-A     ts 0.3
    outp c-C     ts 0.062
    conla CO2    ts -1.088
    conla CCBT   ts 1.088
    conla PBIO-World     c 1
    conla GHG    ts -1.088
    conla TBCC-World     ts 1.088
    conca CBCC-World     ts 1.088
    conla CO2t-World     ts -1.088
    conla BCCS   ts 1.088
    conla WGHG-World     ts -1.088
    conca CO2a-World     ts -1.088
    conca aCO2-World     ts 0 -0.11424 -0.7616 -1.088
#   Ethanol yield   of  85  l/t of  feed.
*
```

Figura 15: Linhas de código selecionadas do COFFEE – tecnologia de produção de etanol

Fonte: COFFEE

Em última análise, o processo de otimização do COFFEE representa a busca por uma conformação ótima das tecnologias nele incluídas de forma a atender aos vetores de demanda sem que haja violação de restrições. Note-se que tal conformação pode envolver a não utilização de tecnologias representadas. Isso é esperado e natural, uma vez que certos serviços podem ser proporcionados por vários meios, cada qual associado a conversores e vetores energéticos específicos. Além disso, na otimização por programação linear, a solução deve ser um ponto de canto da região viável, o que tende a diminuir a diversidade tecnológica do sistema resultante. Ainda que essa tendência esteja sempre presente em modelos como o COFFEE, ela é consideravelmente amenizada pela presença de restrições [313], [317], [318].

Cabe ainda uma ressalva em relação às tecnologias presentes no modelo. Tendo sido programado com o objetivo de refletir o mundo real, o COFFEE representa um grande número de opções tecnológicas. Contudo, esse número não reflete a totalidade do que existe na literatura técnico-científica. Naturalmente, tecnologias amplamente disseminadas (círculos verdes na Figura 16) são parte central do modelo, fundamentais para a representação do passado recente, presente e futuro próximo (2010-2030). Um exemplo são os meios de transporte baseados em combustão interna, como carros a gasolina e ônibus a diesel. Ainda que certos aspectos de tecnologias consolidadas possam eventualmente não ter destaque, é seguro dizer que as principais opções comercialmente disponíveis estão, em algum grau, presentes no COFFEE.

Um segundo grupo é constituído por tecnologias de menor maturidade, com grau de prontidão tecnológica entre intermediário e avançado (círculos amarelos na Figura 16). Muitas das tecnologias pertencentes a esse grupo, como a captura de CO_2 via CCS (com TRL[54] entre 8 e 9) [319] e a síntese de Fischer-Tropsch (com TRL entre 5 e 9) [320] são modeladas pelo COFFEE, com algumas delas tendo papel crítico em cenários de mitigação profunda. Em alguns casos, no entanto, tecnologias de alta maturidade tecnológica ainda não têm representação detalhada no modelo. É o caso das bombas de calor, uma opção de mitigação reconhecidamente importante para o setor de edificações [321], e mesmo da micromobilidade no contexto dos transportes [322].

Finalmente, conceitos em estágios preliminares (círculos vermelhos), como carros voadores [323], captura de carbono a bordo de navios [153], geração elétrica térmico-oceânica [324] e fusão nuclear [325], constituem um terceiro grupo de tecnologias. Ao menos por ora, a baixa maturidade dessas opções parece incompatível com o horizonte de planejamento de cenários de mitigação climática. Assim, sua modelagem no COFFEE foi descartada.

[54] Nível de maturidade tecnológica (do inglês *Technology Readiness Level*)

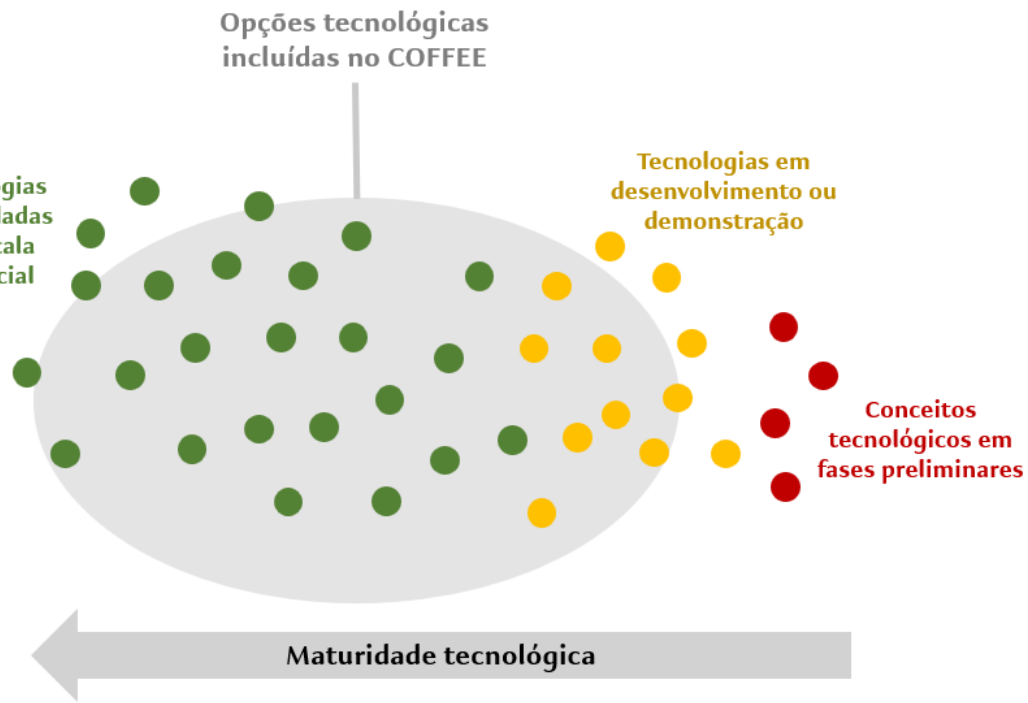

Figura 16: Ilustração das limitações do COFFEE em termos de tecnologias representadas

Fonte: elaboração própria

Conforme explicado no início desta seção, o COFFEE foi construído numa plataforma originalmente concebida para modelar o setor de energia, ou seja, para incluir tecnologias como geração elétrica, explotação de petróleo, produção de calor etc. Não por acaso, a estrutura apresentada na Figura 15 se adequa à lógica do setor energético[55]. No entanto, existem conexões importantes entre a energia e outros setores, em especial, indústria, agricultura e uso do solo. Uma das mais evidentes é o papel desses setores como consumidores de energia. Além disso, indústria, agricultura e uso do solo são a fonte do restante de emissões antrópicas de GEEs, ou seja, daquelas que não são originadas por meio de combustão fóssil [2]. Assim, um modelo que se preste à avaliação verdadeiramente integrada do problema da MGC deve procurar incluir essas emissões.

[55] Considere-se, por exemplo, a restrição *bdc up*, que permite limitar a adição de capacidade de forma bastante direta.

No caso do COFFEE, a integração do setor de AFOLU ocorreu no próprio desenho original do modelo, com a agricultura global sendo representada a partir de uma adaptação da "linguagem" MESSAGE: em vez de conversões entre formas de energia, as tecnologias de AFOLU foram criadas a partir de rendimentos agrícolas e possibilidades de conversão do uso da terra (e.g., desflorestamento, reflorestamento e recuperação de pastagens degradadas - Figura 17) [313]. Um exemplo de tecnologia AFOLU é mostrado na Figura 18: a partir de terras cultiváveis (*minp b-L*) e diesel agrícola (*inp D-G*), produz-se arroz (*moutp h-F*), com resíduos agrícolas (*outp 2-F*) como coproduto. Durante esse processo, ocorrem emissões de metano (*con1a CH4L*) e óxido nitroso (*con1a N2OL*).

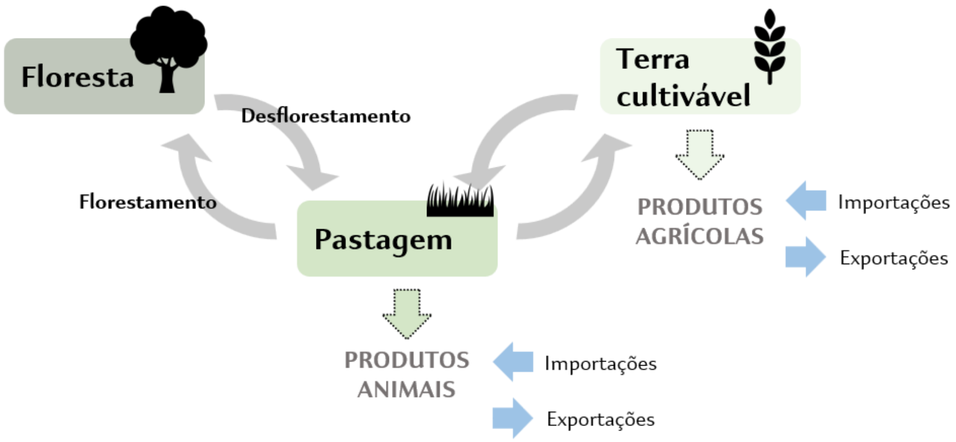

Figura 17: Representação geral do setor de AFOLU em cada região do COFFEE

Fonte: elaboração própria

```
Crop_Rice_B A
    minp    b-L 1
    moutp   h-F ts 3.345 3.361 3.378 3.395
    vom ts 593.2 596.2 599.1 602.1 605.2 60
    inp D-G ts 0.01
    outp 2-F    ts 0.423 0.423 0.422 0.422
    con1a GHG   ts 0.469
    con1a WGHG-World    ts 0.469
    con1a CH4L  ts 0.0084
    con1a N2OL  ts 0.00002 0.00002 0.00002
*
```

Figura 18: Linhas de código selecionadas do COFFEE – tecnologia de produção de arroz

Fonte: COFFEE

A modelagem das tecnologias de AFOLU como parte inseparável da otimização geral do COFFEE constituiu uma inovação metodológica importante, já que outros IAMs tipicamente representam a agricultura e o uso da terra separadamente, estabelecendo um *soft link* entre módulos computacionais de energia e AFOLU [43], [44]. Sob a ótica proposta pelo COFFEE, fontes de emissão de tipos completamente distintos (e.g., explotação de petróleo e desmatamento) são analisadas de forma conjunta. Em âmbito nacional, a utilização do modelo BLUES (que também conta com uma otimização conjunta energia-AFOLU) em um artigo de 2018 ilustra a nova perspectiva que essa integração pode oferecer [46]. Nesse trabalho, à luz de um orçamento de carbono fixo para o Brasil, analisam-se impactos de cenários de desmatamento sobre o esforço de mitigação necessário nos setores energético e industrial.

Em resumo, a utilidade do COFFEE como ferramenta de modelagem está associada ao fato de suas soluções matemáticas refletirem um custo mínimo global de expansão e operação dos sistemas de energia, indústria, agricultura e uso do solo. Assim, em vez de trajetórias isoladas de mitigação climática para cada setor da economia, é possível desenvolver uma estratégia integrada, levando em conta as conexões entre esses setores. Frequentemente, isso implica trajetórias de GEEs distintas do resultado esperado sob uma ótica estritamente setorial [21], [313]. Conforme discutido na introdução, esse aspecto é central nesta tese, que procura trazer a perspectiva integrada especificamente para o caso do transporte marítimo internacional.

5.1.3. Divisão geográfica

Em termos de desagregação regional (Figura 19/Tabela 3), o COFFEE se divide em 18 áreas geográficas, garantindo um detalhamento significativo sem comprometer a factibilidade do esforço computacional de otimização. Durante a concepção do modelo, a escolha das regiões baseou-se na importância econômica de determinados países (e.g., China, Coreia do Sul, Estados Unidos, Japão) e blocos (e.g., União Europeia), mas também em especificidades do mundo da energia (sendo icônico o caso do Oriente Médio). O Brasil é uma região à parte, assim como os demais BRICS, uma peculiaridade que permite análises focadas nesses países emergentes [313]. Conforme antecipado pela Figura 12, o COFFEE é estruturado de forma tal que o arquivo principal, *World*, englobe os arquivos correspondentes às 18 regiões geográficas da Figura 19.

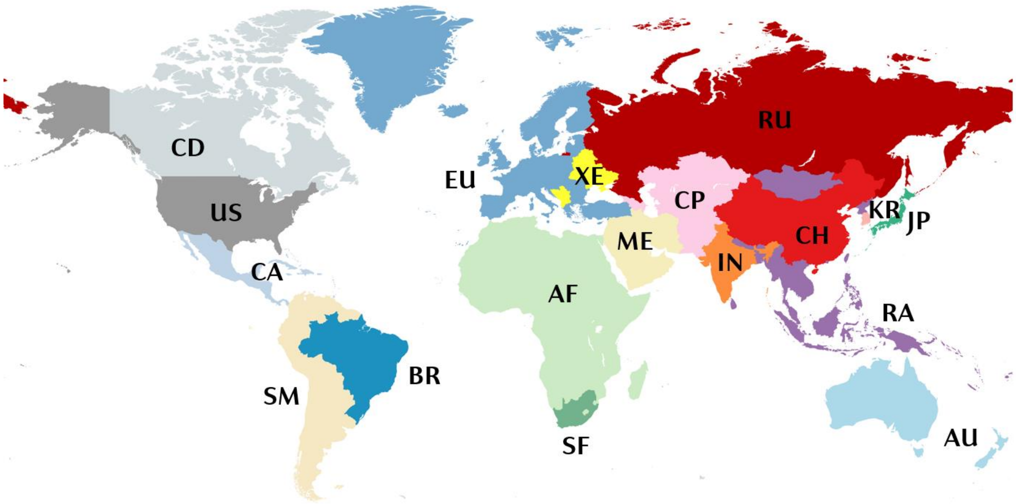

Figura 19: Divisão regional do mundo adotada no COFFEE

Fonte: elaboração própria

Tabela 3 – Descrição das 18 regiões do COFFEE

Região	**Descrição**
AF	África, exceto África do Sul
AU	Austrália e Nova Zelândia
BR	Brasil
CA	México e América Central
CD	Canadá
CP	Região do Cáspio/Ásia Central
CH	China
EU	União Europeia + Islândia, Noruega, Reino Unido, Suíça e Turquia
IN	Índia
JP	Japão
KR	Coreia do Sul
ME	Oriente Médio
RA	Resto da Ásia e Oceania
RU	Rússia
SF	África do Sul
SM	América do Sul, exceto Brasil
US	Estados Unidos
XE	Resto da Europa

5.2. Panorama do módulo de transporte marítimo internacional

5.2.1. Arquivo principal e conexões com regiões

Diante da sua participação relativamente pequena nas emissões globais de GEEs e do seu caráter *hard-to-abate*, o transporte marítimo foi modelado de forma simplificada na versão original do COFFEE (um esforço que envolveu numerosas frentes de trabalho simultâneas). A energia final do setor, por exemplo, era inteiramente provida por derivados de petróleo até 2100, independentemente de cenários e restrições climáticas [313].

Em anos recentes, a descarbonização do transporte marítimo ganhou maior destaque, especialmente após o estabelecimento da estratégia preliminar de GEEs da IMO. Assim, o trabalho desenvolvido no âmbito desta tese teve o objetivo de aperfeiçoar o módulo de transporte marítimo, com foco numa modelagem mais desagregada da demanda e em opções de mitigação. O principal objetivo desse esforço foi obter uma visão mais precisa do papel do setor em cenários de descarbonização profunda. A modelagem do transporte marítimo no COFFEE desdobrou-se em diversas etapas, exploradas ao longo dos itens 5.2.2 a 5.2.6. Neste item, apresenta-se a lógica geral da integração do setor ao resto do modelo.

Conforme mencionado, o arquivo *World* engloba as 18 regiões do COFFEE. Assim, ao se rodar o modelo, o que ocorre é uma otimização desse arquivo, composto por seu próprio código e pelas regiões, cada qual representando os sistemas de energia e uso do solo de uma dada área geográfica. O transporte internacional não está vinculado a nenhuma região geográfica específica, mas justamente a áreas inter-regionais. Por isso, assim como na versão do COFFEE anterior a esta tese, desenvolveu-se a modelagem das embarcações diretamente no arquivo principal. Essa modelagem envolveu uma série de conexões com as demais regiões, não apenas pelo suprimento energético dos navios como também por seu uso como meio de comércio internacional. A Figura 20 ilustra essa dinâmica: as linhas de código relativas ao transporte marítimo internacional foram escritas diretamente no arquivo *World*, mas se conectam com as outras regiões pelo fluxo internacional de mercadorias e pelo suprimento de combustíveis marítimos.

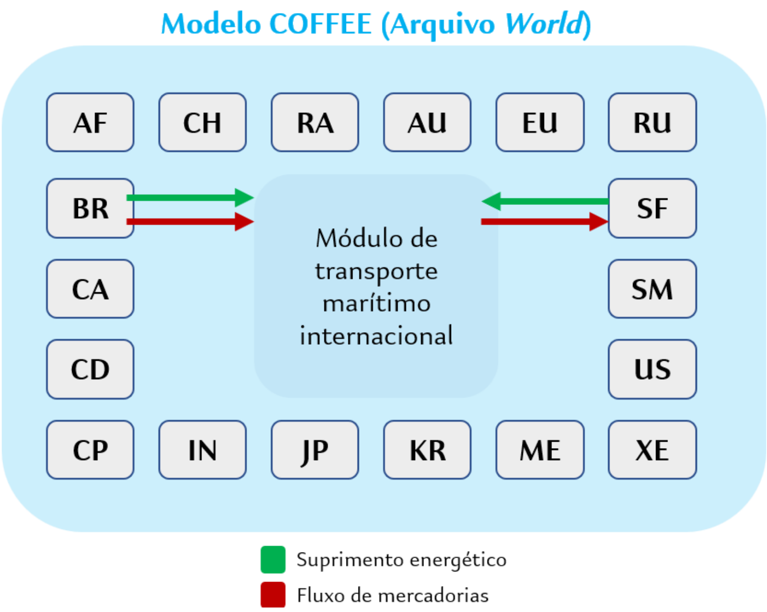

Figura 20: Integração do novo módulo de transporte marítimo internacional ao COFFEE

Nota: Por clareza, apenas as regiões Brasil (BR) e África do Sul (SF) são usadas para exemplificar as conexões com o módulo de transporte marítimo. Evidentemente, o mesmo se aplica a todas as outras regiões. Note-se que o sentido da seta de suprimento energético é sempre das regiões para o transporte marítimo. Por outro lado, as setas de comércio internacional podem ter esse mesmo sentido (representando exportação) ou o sentido inverso (representando importação). Fonte: elaboração própria

5.2.2. Cargas analisadas

Parte do desafio de modelagem do transporte marítimo é sua grande diversidade de cargas. De acordo com a classificação do Sistema Harmonizado de Designação e Codificação de Mercadorias (conhecido como HS), distinguem-se hoje mais de 5.000 grupos de produtos no comércio internacional [326], [327]. Assim, uma modelagem específica da demanda torna-se inviável, e alguma estratégia alternativa deve ser adotada. No caso desta tese, essa estratégia baseou-se nos seguintes pontos:

- Há uma diferença significativa entre a desagregação do comércio internacional de acordo com critérios físicos (massa) ou financeiros (valor). Do ponto de vista físico, a participação de commodities é muito relevante, já que esses são produtos comumente comercializados em grandes quantidades. Para se ter uma ideia, quase 60% do serviço de transporte marítimo internacional (i.e., toneladas-milhas náuticas[56]) de 2021 esteve associado aos mercados de petróleo e derivados, gás e principais graneis sólidos (minério de ferro, grãos, carvão) [86]. No entanto, o baixo valor desses produtos faz com que sua participação diminua consideravelmente na desagregação financeira. Por outro lado, itens pouco relevantes do ponto de vista mássico podem ter participações altas segundo essa perspectiva. O comércio internacional registrado em 2020 (17 trilhões de dólares), por exemplo, contou com participações relevantes de circuitos integrados (4%), computadores (2%), medicamentos (2%), instrumentos médicos (2%) e inúmeros outros produtos de alto valor agregado [328]. Do ponto de vista da modelagem energética deste trabalho, a desagregação física foi mais atrativa, não apenas pela alta heterogeneidade da perspectiva financeira, mas pela própria natureza *bottom-up* do COFFEE.

- O foco do COFFEE é o setor de energia. Sua representação de cadeias energéticas é bastante detalhada, não apenas no que se refere a vetores atualmente dominantes (e.g., carvão, petróleo e gás), como também em termos de recursos renováveis (e.g., bioenergia, energia eólica, energia solar). Ao mesmo tempo, cargas energéticas representam uma fração relevante das toneladas-milhas do transporte marítimo internacional. Assim, a modelagem de navios mercantes no COFFEE foi uma oportunidade de integração entre cadeias regionais e comércio global de energia. Por isso, determinou-se que o módulo de transporte marítimo deveria prioritariamente detalhar cargas energéticas. Essa perspectiva se combinou particularmente bem com o recente aprimoramento do setor petrolífero no modelo [29], [314]. Optou-se até mesmo pelo detalhamento de cargas marítimas pouco relevantes no mercado atual, como hidrocarbonetos de base renovável e hidrogênio. Essa escolha visa permitir ao modelo a adoção de estratégias baseadas no comércio internacional desses produtos em horizontes como 2050 e 2100.

[56] A partir daqui, por simplicidade, fala-se em "toneladas-milhas", e não em "toneladas-milhas náuticas" (termo mais preciso).

- Algumas cargas agrícolas, além de serem endogenamente representadas pelo COFFEE em tecnologias de AFOLU, constituem uma fração relevante do comércio internacional. Assim, para essas commodities, a demanda por transporte marítimo também foi modelada de forma endógena. Analogamente ao que se explicou para o caso da energia, a integração entre produção, transporte e consumo dessas commodities constituiu uma oportunidade de enriquecer o modelo.
- Conforme explorado na introdução, a partir dos anos 1980, o transporte de carga geral foi revolucionado pelo processo de conteinerização. Hoje, a carga conteinerizada responde por quase 15% das toneladas-milhas do transporte marítimo internacional [86]. Mais importante, os navios porta-contêineres são responsáveis por cerca de 30% do consumo de energia final no setor [62]. Uma boa representação dessas embarcações era, portanto, essencial. Contudo, é justamente nesse tipo de transporte que a enorme diversidade de mercadorias se expressa de forma mais contundente, constituindo uma barreira praticamente intransponível à modelagem específica de demanda. Como solução, optou-se por projeções de demanda baseadas nos fluxos históricos dos próprios contêineres, para qual há certa riqueza de dados. Isso será explorado no item 5.2.4.
- Algumas outras cargas importantes não têm representação explícita no COFFEE, a exemplo de minérios e do setor químico. Para tais produtos, a modelagem de demanda foi realizada de maneira exógena, usando hipóteses que serão detalhadas no item 5.2.4.
- Conforme antecipado pela Figura 5, o inventário de emissões da IMO utilizado como base para este trabalho inclui embarcações como navios de cruzeiro e balsas RoPax em sua contabilização de emissões do transporte marítimo internacional [62]. Apesar de não serem navios mercantes, essas embarcações foram incluídas de forma simplificada na modelagem, a título de consistência com o inventário. Para navios de cruzeiro, em que o consumo energético total é relativamente grande, a modelagem é feita de forma explícita. Nos demais casos, assume-se que o consumo residual esteja incluído na categoria “Outros”.

A partir dessas premissas, chegou-se à lista de produtos e embarcações da Tabela 4. Além de cinco tipos de petróleo, a tabela inclui quatro tipos de derivados (nafta, querosene, diesel e óleo combustível), bem como seus pares renováveis. O gás natural segue uma lógica similar, enquanto o carvão é separado por qualidades (betuminoso/sub-betuminoso). Etanol e hidrogênio completam a lista de produtos energéticos. Em seguida, aparecem trigo, milho, arroz, soja e outros cereais, os mais relevantes produtos agrícolas em termos de massa comercializada (artigo #3). Destaques do setor industrial, aço e minério de ferro figuram como importantes cargas secas. Já o setor químico, bastante heterogêneo [329], aparece de forma agregada, assim como os produtos conteinerizados. Veículos são o último produto específico da lista, concluída por duas categorias *sui generis* (navios de cruzeiro e outros).

Tabela 4 – Produtos e tipos de embarcações envolvidos na modelagem do transporte marítimo internacional no COFFEE

Produto	**Embarcação utilizada como referência**	**Tipo de demanda**
Petróleo leve	Petroleiro 300.000 dwt Petroleiro 150.000 dwt Petroleiro 100.000 dwt	Endógena
Petróleo médio doce	Petroleiro 300.000 dwt Petroleiro 150.000 dwt Petroleiro 100.000 dwt	Endógena
Petróleo médio azedo	Petroleiro 300.000 dwt Petroleiro 150.000 dwt Petroleiro 100.000 dwt	Endógena
Petróleo pesado	Petroleiro 300.000 dwt Petroleiro 150.000 dwt Petroleiro 100.000 dwt	Endógena
Petróleo extrapesado	Petroleiro 300.000 dwt	Endógena

	Petroleiro 150.000 dwt Petroleiro 100.000 dwt	
Nafta fóssil	Petroleiro de derivados 60.000 dwt	Endógena
Nafta verde	Petroleiro de derivados 60.000 dwt	Endógena
Querosene fóssil	Petroleiro de derivados 60.000 dwt	Endógena
Querosene verde	Petroleiro de derivados 60.000 dwt	Endógena
Diesel fóssil	Petroleiro de derivados 60.000 dwt	Endógena
Diesel verde	Petroleiro de derivados 60.000 dwt	Endógena
Óleo combustível fóssil	Petroleiro de derivados 60.000 dwt	Endógena
Óleo combustível verde	Petroleiro de derivados 60.000 dwt	Endógena
Gás natural fóssil	Gaseiro (*LNG Carrier*) 150.000 m^3	Endógena
Gás natural verde	Gaseiro (*LNG Carrier*) 150.000 m^3	Endógena
Carvão betuminoso	Graneleiro 100.000 dwt	Endógena
Carvão sub-betuminoso	Graneleiro 100.000 dwt	Endógena
Etanol	Petroleiro de derivados 60.000 dwt	Endógena

Hidrogênio	Hidrogeneiro (*LH_2 Carrier*) 250.000 m^3	Endógena
Trigo	Graneleiro 50.000 dwt	Endógena
Milho	Graneleiro 50.000 dwt	Endógena
Arroz	Graneleiro 50.000 dwt	Endógena
Soja	Graneleiro 50.000 dwt	Endógena
Outros cereais	Graneleiro 50.000 dwt	Endógena
Aço	Graneleiro 50.000 dwt	Endógena
Minério de ferro	Graneleiro 150.000 dwt	Exógena
Produtos químicos	Químico 10.000 dwt	Exógena
Contêineres	Porta-contêineres 3.000 TEU Porta-contêineres 6.000 TEU Porta-contêineres 11.500 TEU	Exógena

Veículos	*Pure Car Carrier* 11.000 CEU	Exógena
-	Navio de cruzeiro 40.000 GT	Exógena
Outros	Navio de carga geral 10.000 dwt	Exógena

5.2.3. Organização de tecnologias

Como explicado em 5.1.2, o COFFEE se estrutura em torno das chamadas “tecnologias”. No módulo de transporte marítimo, a utilização dessas unidades requereu uma abordagem bastante específica. Isso se deveu à necessidade de modelar, ao mesmo tempo, a transferência de produtos entre regiões (via *World*), o serviço de transporte associado e o consumo de energia atribuível a esses fluxos.

No caso de demandas endógenas, para cada produto, criaram-se tecnologias de transferência de carga por par de regiões[57] (Figura 21). Comunicando-se com as tecnologias auxiliares *InWorld* e *OutWorld*, que trazem e levam os produtos das regiões para o arquivo principal, as tecnologias de transferência (*Transfer*) representam um fluxo físico de energia (e.g., petróleo) ou massa (e.g., trigo). Como entrada, recebem uma variável de serviço de transporte, que reflete o valor de toneladas-milhas necessárias[58] para viabilizar o fluxo de exportação/importação. Para produzir essas toneladas-milhas, o COFFEE deve recorrer a um segundo grupo de tecnologias (*Ship*, na Figura 21). É nessas tecnologias que de fato ocorre a modelagem técnico-econômica das embarcações, produzindo toneladas-milhas a partir de energia final. Por sua vez, essa energia final vem de tecnologias auxiliares (*Bunkering*, na Figura 21), que a trazem das 18 regiões, onde são representados os processos de produção de combustíveis marítimos. Para produtos de

[57] Totalizando, portanto, 306 (18 x 17) tecnologias *Transfer* por produto.

[58] Note-se que esse valor depende da distância inter-regional considerada.

demanda exógena, a modelagem limita-se à parte inferior da figura, i.e., a embarcações mercantes atendendo a uma demanda por toneladas-milhas determinada *ex ante*. O método utilizado para projetar dessa demanda varia caso a caso (item 5.2.4).

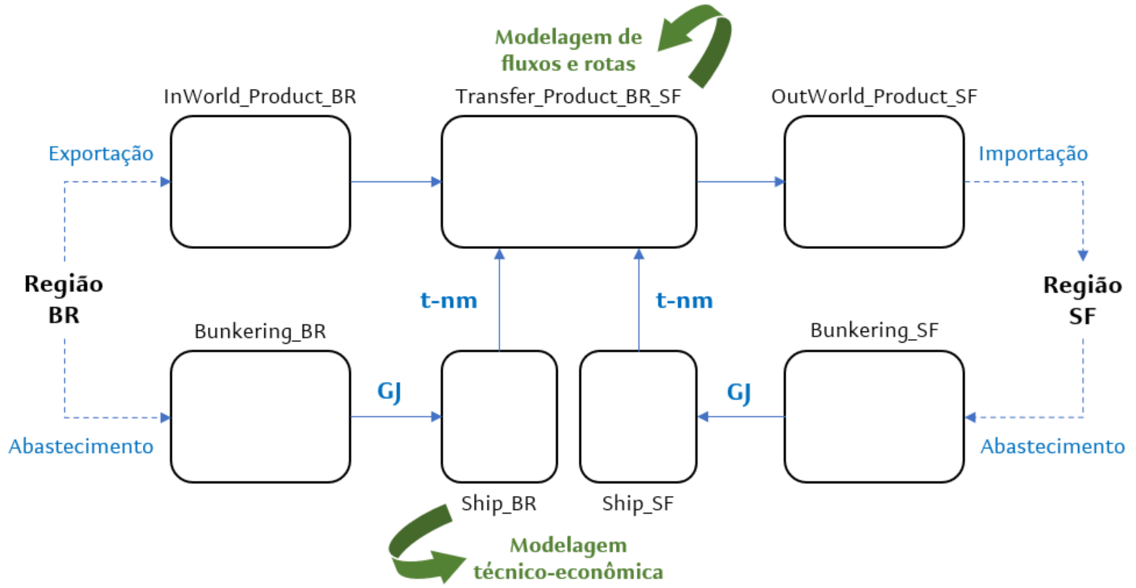

Figura 21: Estrutura geral de tecnologias do módulo de transporte marítimo

Nota: A estrutura apresentada refere-se a produtos de demanda endógena. No caso de produtos de demanda exógena, não há contabilização da transferência de mercadorias entre regiões e, assim, as tecnologias da parte superior da figura não existem. Este esquema pode ser visto como um detalhamento da Figura 20. Novamente, as regiões BR (Brasil) e SF (África do Sul) são utilizadas apenas como exemplo. Fonte: elaboração própria

5.2.4. Demanda por transporte marítimo

Em última análise, a demanda por transporte marítimo é sempre[59] um vetor de serviço de transporte (toneladas-milhas). No caso desta modelagem energética, tal vetor é o ponto de partida para o cálculo do consumo de combustível e, finalmente, das emissões de CO_2. Um vetor de toneladas-milhas é gerado pelo produto da massa transportada pela distância percorrida pela carga e, assim, para cada um dos produtos analisados (Tabela 4), essas

[59] Navios de cruzeiro são uma exceção.

duas informações devem ser providas. Os itens a seguir detalham a construção de vetores de toneladas-milhas para produtos de demanda endógena e exógena.

Produtos de demanda endógena

No caso de demanda endógena (19 energéticos, 5 agrícolas e 1 industrial), a ideia é que as quantidades trocadas entre regiões sejam um resultado da otimização geral do COFFEE. Assim, resta apenas fornecer ao modelo parâmetros associados a distâncias percorridas.

Além da variedade de cargas, a rede marítima global envolve centenas de complexos portuários que, formando pares, dão origem a dezenas de milhares de rotas [330]. Como ilustração, apenas o subsetor de granel líquido envolve algo como 4.900 terminais no mundo [331]. Por outro lado, o trabalho desenvolvido no âmbito desta tese traz uma visão essencialmente agregada do setor. O interesse primordial não é uma representação de alta resolução da navegação mercante, mas o estudo de sua interface com o resto do sistema energético.

Assim, a determinação de distâncias inter-regionais no COFFEE baseou-se em valores obtidos por meio de “portos representativos”: para cada par de regiões, assumiu-se que há uma rota fixa de navegação, que é também independente do produto comercializado[60]. Cada rota foi criada a partir da eleição de dois portos de destaque[61] (Apêndice A), como ilustra a Figura 22. Em seguida, os valores de distância foram calculados a partir de um banco de dados que lista os principais terminais portuários de cada país, bem como a distância navegável entre eles [332]. Assim, construiu-se a matriz numérica mostrada no Apêndice A (Tabela 3).

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[60] Exceto no caso de produtos de demanda exógena.

[61] Essa seleção de portos foi fortemente baseada no caso de combustíveis líquidos (principalmente petróleo).

Figura 22: Rotas de exportação selecionadas da região AF

Fonte: elaboração própria

Naturalmente, a abordagem baseada em portos representativos envolve uma imprecisão incontornável. Considere-se, por exemplo, o caso da distância AF-SF. Enquanto a rota representativa tem uma extensão de pouco mais de 1.500 mn, há diversas rotas possíveis partindo de outros pontos da região AF (e.g., 5.451 mn entre Argel e Saldanha). Contudo, esse efeito tende a ser minimizado quando se trata de áreas não adjacentes. A Tabela 5 ilustra tal fato para a rota ME-CH: variando-se origem e destino de sete formas distintas, incorre-se, na maior parte dos casos, em erros de não mais que 10%. Tendo em vista que a grande maioria[62] dos pares de regiões são separados por distâncias superiores a 3.000 mn (Apêndice A, Tabela 3), considera-se que as rotas representativas constituam uma hipótese razoável.

[62] 260 de 292, ou seja, 89%

Tabela 5 – Variação percentual da distância de rotas alternativas ME-CH em relação à rota representativa

Origem	**Destino**	**Distância (mn)**	**Variação (%)**
Juaymah	Qingdao	6.164	0,0
Juaymah	Tianjin	6.465	4,7
Juaymah	Xangai	5.938	-3,8
Juaymah	Hong Kong	5.161	-19
Dubai	Qingdao	5.893	-4,6
Dubai	Tianjin	6.194	0,5
Dubai	Xangai	5.667	-8,8
Dubai	Hong Kong	4.890	-26

Dados: [332]

De posse da matriz de distâncias, foi possível construir as tecnologias *Transfer* (Figura 21), que convertem exportação em importação demandando, para tanto, toneladas-milhas. No caso do comércio de energia, essa conversão envolve ainda o Poder Calorífico Inferior (PCI) (Tabela 6). Como os fluxos de produtos energéticos no COFFEE usam, por padrão, unidades de energia, o PCI é necessário para determinar corretamente o serviço de transporte (t-mn) específico de cada produto no módulo de transporte marítimo.

Tabela 6 – Valores de conteúdo energético utilizados para conversão de fluxos energéticos em demanda por serviço de transporte (t-mn)

Produto	**PCI (MJ/kg)**
Petróleo leve	42,8
Petróleo médio doce	42,1
Petróleo médio azedo	42,3
Petróleo pesado	41,6
Petróleo extrapesado	40,8
Nafta fóssil	45,0
Nafta verde	45,0
Querosene fóssil	43,7
Querosene verde	43,7
Diesel fóssil	44,0
Diesel verde	44,0
Óleo combustível fóssil	42,6
Óleo combustível verde	42,6
Gás natural fóssil	48,0
Gás natural verde	48,0
Carvão betuminoso	22,0
Carvão sub-betuminoso	19,0
Etanol	27,0
Hidrogênio	120

Dados: [89]

A Tabela 7 ilustra a lógica das tecnologias *Transfer* energéticas para produtos selecionados. A partir do PCI do produto e da distância da rota, calcula-se um coeficiente que indica o serviço de transporte requerido para o comércio inter-regional de uma unidade de energia (t-mn/GJ). Tal coeficiente é a essência da modelagem endógena, pois ele informa ao modelo o custo de se transferir dado energético de uma região para outra. Durante a otimização do COFFEE, a comparação desse parâmetro com outras variáveis (e.g., custo de produção do energético em cada região) determina o nível de atividade de cada rota (i.e., de cada tecnologia *Transfer*). Na Tabela 7, mostra-se o efeito diretamente proporcional da distância sobre o coeficiente de serviço de transporte: a exportação de petróleo leve do Oriente Médio (ME) para a China (CH) requer 144 t-mn/GJ, enquanto para a Índia (IN), apenas 28 t-mn/GJ. Nessas mesmas rotas, os valores são levemente alterados (151 e 29 t-mn/GJ) quando se trata de petróleo extrapesado, cujo conteúdo energético mais baixo acarreta uma penalidade em termos de toneladas-milhas. Já no caso do hidrogênio, que tem elevado PCI em base mássica, esse coeficiente tende a ser muito mais baixo.

Tabela 7 – Coeficientes de serviço de transporte para tecnologias *Transfer* selecionadas de produtos energéticos

Tecnologia	**MJ/kg**	**Distância (mn)**	**t-mn/GJ**
Transfer_CrudeLight_ME_CH	42,8	6.164	144
Transfer_CrudeLight_ME_IN	42,8	1.177	27,5
Transfer_CrudeEHeavy_ME_CH	40,8	6.164	151
Transfer_CrudeEHeavy_ME_IN	40,8	1.177	28,8
Transfer_Hydrogen_ME_CH	120	6.164	51,4
Transfer_Hydrogen_ME_IN	120	1.177	9,8

Produtos de demanda exógena

No caso de demanda exógena, os vetores de demanda foram preestabelecidos com base em modelagem específica para cada setor (Tabela 8). A demanda global por serviço de transporte é mostrada, para cada caso, na Figura 23.

Tabela 8 – Produtos/setores de demanda exógena

Produto/setor	**Metodologia**
Minério de ferro	Considerando a agregação segundo as regiões do COFFEE, demandas históricas foram determinadas a partir da soma das importações dos respectivos países nos anos relevantes, conforme uma base de dados [180]. De forma simplificada, a evolução futura dessas demandas foi indexada à produção de aço de cada região (descontada por um aumento da participação da rota sucata + forno elétrico a arco). Em termos de exportadores, considerou-se a manutenção das fatias de mercado observadas atualmente, com destaque para Austrália, Brasil, África do Sul, Canadá, Europa Oriental e Índia. A demanda por serviço de transporte foi dividida entre exportadores e importadores.
Produtos químicos	Demandas históricas regionais foram determinadas com base em um relatório que destaca as 27 principais rotas de produtos químicos no mundo [329]. O crescimento do setor químico foi indexado ao cenário SSP2 do artigo #3 [241]. A demanda por serviço de transporte foi dividida igualmente entre exportadores e importadores.
Carga conteinerizada	Demandas históricas regionais foram determinadas a partir da soma da movimentação de TEUs conforme uma base de dados, sem distinção de exportadores e importadores [333]. Com coeficientes de Pearson na faixa 95-99% para os dados históricos entre 2000 e 2019, assumiu-se uma correlação entre o PIB das 18 regiões (uma das entradas do modelo) e sua movimentação de contêineres.
Veículos	A projeção do comércio de veículos se deu a partir daquela realizada para o artigo #3. Considerando-se as exportações totais (em dólares) dos principais países exportadores (Alemanha, Japão, Estados Unidos, México, Reino Unido, Canadá, Coreia do Sul, Espanha, Bélgica e França) e o preço médio de um veículo [334]–[336], determinou-se o número total de veículos comercializados internacionalmente no ano base. A evolução de atividade foi indexada à venda de novos veículos dos países importadores, um parâmetro advindo do modelo IMAGE [241].
Navios de cruzeiro	A partir de uma base de dados ligada ao setor [337], obteve-se o total de passageiros de navios de cruzeiro entre 1990 e 2019. Além da calibração do período-base, isso permitiu testar a correlação do crescimento do setor com três outras variáveis: população, PIB total e PIB per capita. A melhor correlação ocorreu com o PIB total (98%) e, assim, a atividade do setor foi indexada ao PIB. No período-base, assumiu-se uma divisão regional igual àquela observada em 2017, para a qual há dados de qualidade [338]. As regiões do COFFEE que concentram essa demanda são CA, EU, WE, CH, AU, RA e US, respondendo por 83% da atividade do setor de cruzeiros.
Outros	A categoria “Outros” foi criada a fim de preencher a lacuna de demanda observada no período-base. Ela inclui majoritariamente carga geral não conteinerizada e commodities cujo mercado tem menor escala, como bauxita, cimento e fosfato. De maneira simplificada, vinculou-se o crescimento dessa categoria ao CAGR[63] dos últimos 20 anos da categoria “Outras cargas secas”, do relatório da UNCTAD [86]. O valor calculado desse CAGR foi de 1,6%. A divisão da atividade total entre as 18 regiões utilizou os vetores de PIB que são entrada do modelo, associados ao SSP2.

[63] Taxa de crescimento anual composta, do inglês *Compound Annual Growth Rate.*

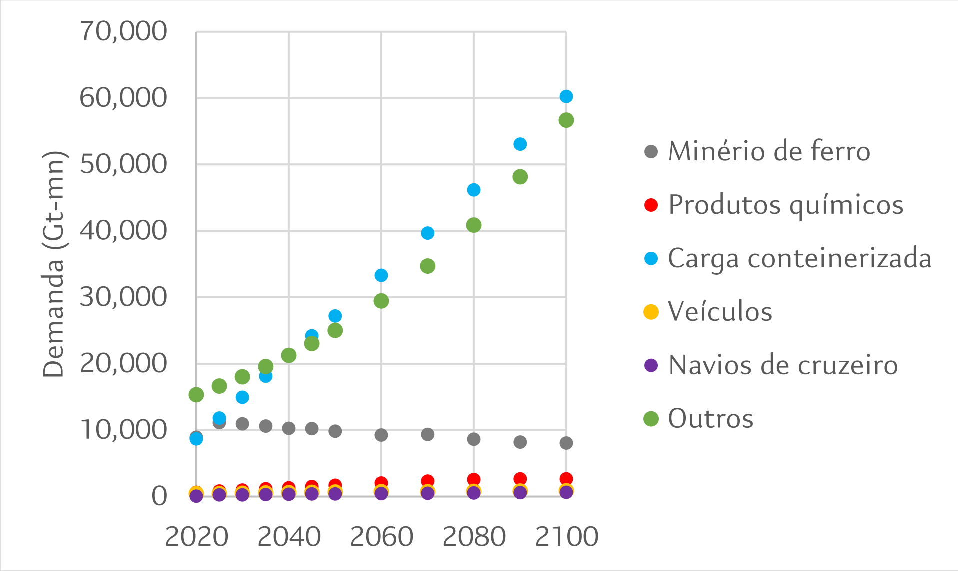

Figura 23: Demandas de produtos/setores exógenos

Nota: Apesar de não integrar o transporte de carga, o setor de cruzeiros é reportado no gráfico em termos de toneladas-milhas. Trata-se de uma adaptação destinada apenas a fins práticos. Isso foi feito criando uma relação entre o número total de passageiros do setor, seu EEOI e suas emissões totais. Em linhas gerais um passageiro de cruzeiro corresponde a cerca de 6.700 mn. Fonte: elaboração própria

5.2.5. Demanda por energia

Conforme explicado, as demandas dos 31 produtos/setores foram expressas por meio de vetores de serviço de transporte (toneladas-milhas). Para se atender a essa demanda, criaram-se as tecnologias *Ship*, já mostradas na Figura 21. É nessas tecnologias que de fato se modela a conversão energética que ocorre nas embarcações (i.e., utilização de combustível para produção de energia útil que, em última análise, proporciona o deslocamento de uma certa massa ao longo de dada distância - Figura 24).

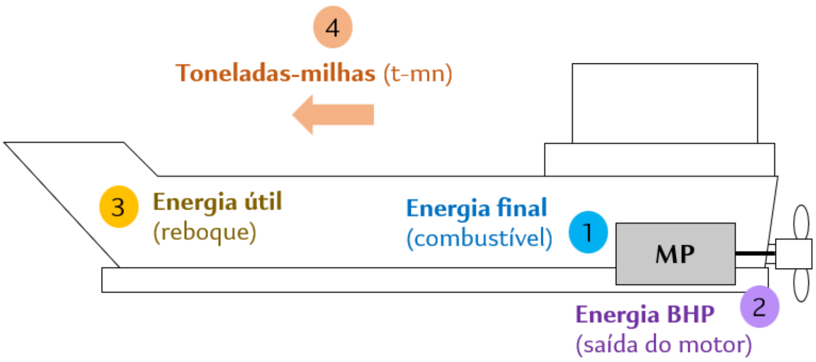

Figura 24: Conversões energéticas associadas à propulsão de embarcações

Nota: Por simplicidade, a figura mostra apenas as conversões associadas à demanda por energia mecânica (motor principal – MP). Diagramas similares poderiam ser construídos para motores auxiliares e caldeiras auxiliares. Fonte: elaboração própria

O parâmetro mais importante das tecnologias *Ship* é seu consumo específico, que reflete a energia final (1, na Figura 24) consumida por unidade de serviço de transporte (4). Esse parâmetro pode ser expresso pela seguinte equação[64]:

$$\text{Consumo específico [MJ/t-mn]} = \text{[kWh/t-mn]} \times \text{[MJ/kWh]} \qquad [1]$$

Enquanto o primeiro fator da equação 1 depende essencialmente do tipo de embarcação (2→4), o segundo diz respeito à conversão termodinâmica a montante (1→2), que pode ocorrer de diversas formas. Diante da necessidade de modelar o consumo específico para uma miríade de casos (diversas motorizações e combustíveis), optou-se, inicialmente, por determinar a relação entre a energia na saída do motor (2) e o serviço de transporte (4), um parâmetro que só varia em função do tipo de navio[65].

Para tanto, recorreu-se ao EEOI (*Energy Efficiency Operational Indicator*), um índice de intensidade de carbono semelhante ao EEDI, mas com viés operacional, e não construtivo. O EEOI expressa, com base em dados observados, o nível de emissões de CO_2 que dado navio ou frota emitiu para realizar uma unidade de serviço de transporte (t-mn) [62].

O mais recente relatório sobre GEEs da IMO [62] inclui um vasto detalhamento do EEOI médio por tipo de embarcação e porte entre os anos de 2012 e 2018. A Tabela 9 mostra os valores de 2018 para três subconjuntos da frota de petroleiros, tomados como ilustração.

[64] Seguindo a convenção de boa parte da literatura, adotam-se unidades distintas para energia final (MJ) e energia BHP (kWh) das embarcações. Isso permite uma distinção imediata entre duas grandezas conceitualmente diferentes.

[65] A não ser pela variação do espaço requerido para os tanques de combustível em função da densidade volumétrica dos energéticos utilizados, conforme será detalhado em 5.2.6.

Tabela 9 – EEOI médio de 2018 para tipos selecionados de embarcações

	EEOI (gCO_2/t-mn)
Petroleiro 300.000 dwt	5,7
Petroleiro 150.000 dwt	9,3
Petroleiro 100.000 dwt	12

Dados: [62]

Este trabalho utilizou valores de EEOI como os da Tabela 9 para criar, para cada tipo de embarcação da Tabela 4, um indicador que refletisse exclusivamente o primeiro termo da equação 1. Para tanto, baseou-se nas equações 2, 3 e 4.

$$i_p\ [\mathrm{kWh/t\text{-}mn}] = \frac{a_p\ \mathrm{EEOI}\ [\mathrm{gCO_2/t\text{-}mn}]}{\mathrm{SFC_{MP}}\ [\mathrm{g/kWh}]\ \mathrm{FE_{HFO}}\ [\mathrm{gCO_2/g}]} \qquad [2]$$

$$i_e\ [\mathrm{kWh/t\text{-}mn}] = \frac{a_e\ \mathrm{EEOI}\ [\mathrm{gCO_2/t\text{-}mn}]}{\mathrm{SFC_{MA}}\ [\mathrm{g/kWh}]\ \mathrm{FE_{MGO}}\ [\mathrm{gCO_2/g}]} \qquad [3]$$

$$i_h\ [\mathrm{kWh/t\text{-}mn}] = \frac{a_h\ \mathrm{EEOI}\ [\mathrm{gCO_2/t\text{-}mn}]}{\mathrm{SFC_{CA}}\ [\mathrm{g/kWh}]\ \mathrm{FE_{HFO}}\ [\mathrm{gCO_2/g}]} \qquad [4]$$

Ao se analisar as equações 2, 3 e 4, deve-se ter em mente que o EEOI reflete não apenas as emissões de CO_2 associadas à propulsão, mas também aquelas oriundas da produção de eletricidade e calor.

Na equação 2, o termo a_p representa a fração das emissões de CO_2 do EEOI que se deve à propulsão, o termo SFC_{MP}, a eficiência do motor principal e FE_{HFO} o fator de emissão de CO_2 do HFO. Conforme ilustra a Tabela 10, o valor de a_p também foi obtido com base no estudo da IMO [62], enquanto os valores de SFC_{MP} e FE_{HFO} seguem aproximadamente aqueles utilizados nos três primeiros artigos da tese (180 g/kWh e 3,114 gCO_2/g, respectivamente).

Tabela 10 – Proporções de emissões de CO_2 associadas a cada serviço energético

	Propulsão (a_p)	**Eletricidade (a_e)**	**Calor (a_h)**
Petroleiro 300.000 dwt	75%	9%	16%
Petroleiro 150.000 dwt	60%	14%	26%
Petroleiro 100.000 dwt	57%	13%	30%

Dados: [62]

Assim, i_p reflete a demanda por energia na saída do motor, por tonelada-milha, para tipos específicos de embarcações (e.g., Tabela 11). As equações 3 e 4 são análogas à equação 2, mas indicando intensidades energéticas associadas à produção de eletricidade (i_e) e calor (i_h).

Tabela 11 – Intensidades energéticas demandadas sob a forma de propulsão, eletricidade e calor

	Propulsão (i_p)	**Eletricidade (i_e)**	**Calor (i_h)**
Petroleiro 300.000 dwt	0,0076	0,0008	0,0010
Petroleiro 150.000 dwt	0,0099	0,0019	0,0026
Petroleiro 100.000 dwt	0,0122	0,0023	0,0037

Unidade: kWh/t-mn

5.2.6. Motorizações e combustíveis

Para enfim chegar aos valores de consumo específico (em MJ/t-mn) requeridos pelas tecnologias *Ship*, foi necessário combinar as intensidades calculadas no item 5.2.5 com informações sobre motorizações específicas.

Atualmente, a quase totalidade da frota mercante é composta por embarcações com motores principais do tipo Diesel, aptos a operarem com combustíveis como o HFO e MGO [62], [84]. No entanto, o horizonte temporal do COFFEE é o ano de 2100 e, assim, a modelagem de navios no IAM incluiu potenciais novas motorizações. Diante de uma grande possibilidade de variações em aspectos técnicos, decidiu-se, considerando uma perspectiva de modelagem integrada, trabalhar com 10 motorizações ditas ilustrativas

(Tabela 12). Tais motorizações não necessariamente correspondem de maneira fiel ao que se observa na indústria naval, mas procuram refletir arquétipos de sistemas propulsivos que indiquem os principais caminhos tecnológicos disponíveis.

Tabela 12 – Motorizações ilustrativas

Nome no COFFEE	**Descrição/racional/ressalvas**	**Referências**
CI	Motor Diesel convencional. Trabalha apenas com ignição por compressão. Blending com álcoois seria possível, mas assume-se que a motorização LGIM já abarca essa possibilidade. Eletricidade a partir de geradores Diesel.	[62], [84], [159]
LGIM	Motor dual com injeção direta de álcoois simples. Necessidade de combustível piloto. Série de motores já existe. Eletricidade a partir de geradores Diesel.	[339]
LGIP	Motor dual com injeção direta de LPG. Necessidade de combustível piloto. Série de motores já existe. Eletricidade a partir de geradores Diesel.	[339]
LGIA	Motor dual com injeção direta de LPG. Necessidade de combustível piloto. Série de motores disponível a partir de 2024. Eletricidade a partir de geradores Diesel.	[339]
HPDF	Motor dual de LNG com alta pressão e maior demanda por combustível piloto. Menores emissões de metano não queimado. Tecnologia mais recente. Eletricidade a partir de geradores Diesel.	[62], [116]
LPDF	Motor dual de LNG com baixa pressão e menor demanda por combustível piloto. Maiores emissões de metano não queimado. Tradicionalmente utilizados em navios metaneiros. Eletricidade a partir de geradores Diesel.	[62], [116]
H2DF	Motor dual de H_2. Essa motorização ilustrativa foi incluída a fim de permitir o uso de hidrogênio em motores de combustão	[340]

	interna, e não apenas em motorizações eletroquímicas, cuja maturidade tecnológica é menor. Contudo, o desenvolvimento dos principais fabricantes tem se concentrado na amônia. Eletricidade a partir de geradores Diesel.	
H2FC	Pilha a combustível de baixa temperatura combinada com motor elétrico, uso direto de H_2	[341]
NH3FC	Pilha a combustível de baixa temperatura combinada com motor elétrico, armazenamento de H_2 usando amônia	[119]
HTFC	Pilha a combustível de alta temperatura combinada com motor elétrico	[119], [155]

Conforme ilustra a Figura 25, cada motorização tem a capacidade de trabalhar com certos vetores energéticos (divididos, no arquivo *World*, em oito grupos - Figura 26). Navios CI só podem usar líquidos adequados à ignição por compressão convencional. Já os navios LGIM, LGIP e LGIA, além disso, podem trabalhar com pelo menos um combustível de baixo ponto de fulgor em ciclo Diesel (etanol/metanol, LPG e amônia, respectivamente). As embarcações HPDF (alta pressão) e LPDF (baixa pressão) representam duas formas de se utilizar o LNG adicionalmente aos combustíveis convencionais. A motorização H2DF é a última entre aquelas baseadas em combustão interna, com a possibilidade de uso de hidrogênio. Navios H2FC e NH3FC representam duas formas de se utilizar hidrogênio em pilhas a combustível de baixa temperatura (e.g., do tipo PEMFC[66]). Essas motorizações diferem entre si pelo uso da amônia como um intermediário no segundo caso. Finalmente, embarcações HTFC ilustram o uso de pilhas a combustível de alta temperatura (e.g., do tipo SOFC[67]), que permitem a utilização direta de combustíveis mais complexos que o hidrogênio. Como uma das principais características dessas pilhas é sua

[66] Do inglês *Proton-Exchange Membrane Fuel Cell*.

[67] Do inglês *Solid Oxide Fuel Cell.*

flexibilidade, optou-se por uma motorização ilustrativa única para amônia, diesel, metanol, etanol, LNG e LPG [62], [116], [119], [342].

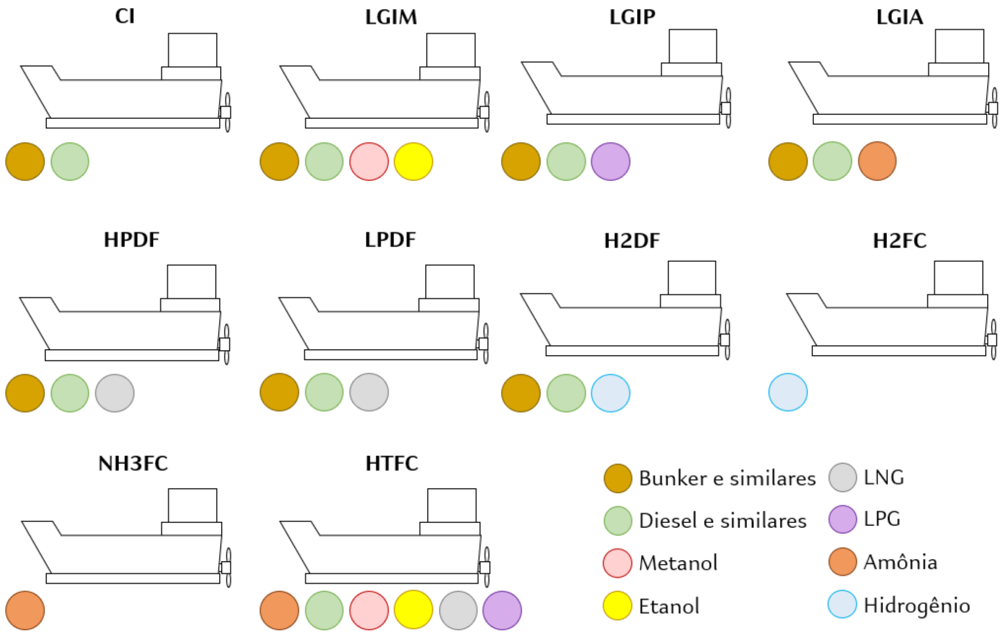

Figura 25: Combustíveis associados às motorizações ilustrativas

Nota: A figura diz respeito apenas a combustíveis utilizados no motor principal. Além do que é representado na figura, cada uma das motorizações envolve uma demanda por eletricidade. Nos casos de propulsão a combustão interna (CI, LGIM, LGIP, LGIA, HPDF, LPDF, H2DF), assume-se que essa geração de eletricidade é provida por combustíveis do grupo 2 (diesel e similares). Fonte: elaboração própria

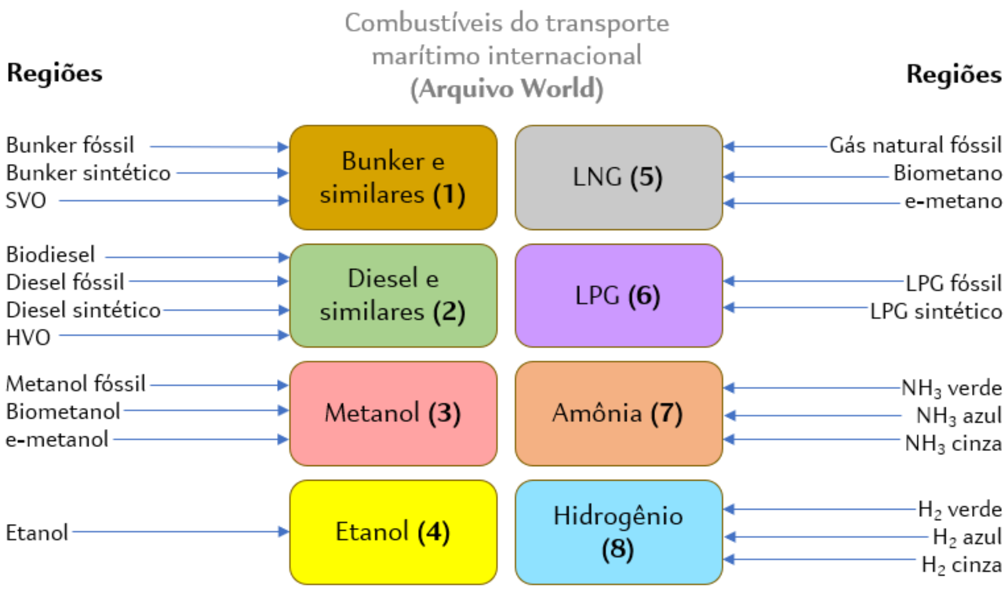

Figura 26: Agrupamento dos energéticos advindos das regiões do COFFEE em categorias de combustíveis marítimos

Fonte: elaboração própria

Tendo em vista o impacto significativo da densidade de alguns energéticos sobre o volume total ocupado por tanques de combustível a bordo, modelou-se, de forma simplificada, a perda de espaço disponível para carga útil. Para tanto, consideraram-se três níveis de perda, sendo amônia e hidrogênio os casos mais extremos (Tabela 13 e Tabela 14) [69]. No caso da motorização HTFC, representou-se ainda uma perda de espaço adicional devida à presença da pilha SOFC (Tabela 15), cujo volume é considerável (~200 m^3/MW). Os resultados (massa de carga efetivamente transportada de acordo com a motorização) são mostrados na Tabela 16. Seu impacto sobre as intensidades do item 5.2.5 são mostrados na Tabela 17.

Tabela 13 – Perda de espaço a bordo

		Espaço extra requerido (m^3)		
	Volume do tanque (m^3)	**Álcoois e gases**	**Amônia**	**Hidrogênio**
Petroleiro 300.000 dwt	9.564	12.433	28.691	47.818
Petroleiro 150.000 dwt	4.171	5.422	12.512	20.853
Petroleiro 100.000 dwt	2.919	3.794	8.756	14.594

Nota: Multiplicadores associados à perda de espaço: 1,3 (álcoois e gases), 3 (amônia) e 5 (hidrogênio líquido) [69]. Dados de volume do tanque original: [343]

Tabela 14 – Perda de carga associada à perda de espaço

	Perda de carga (toneladas)		
	Álcoois e gases	**Amônia**	**Hidrogênio**
Petroleiro 300.000 dwt	10.381	23.957	39.928
Petroleiro 150.000 dwt	4.527	10.447	17.412
Petroleiro 100.000 dwt	3.168	7.311	12.186

Densidade utilizada: 835 kg/m^3 (Brent)

Tabela 15 – Perda de espaço associada a pilhas SOFC

	Potência típica em embarcações de motorização convencional		Perda devida à presença de pilhas a combustível SOFC	
	Motor principal (MW)	**Motor auxiliar (MW)**	**Volume (m^3)**	**Carga (t)**
Petroleiro 300.000 dwt	30	4,1	6.820	5.696
Petroleiro 150.000 dwt	23	3,2	5.240	4.375
Petroleiro 100.000 dwt	17	2,7	3.940	3.290

Dados de volume da pilha SOFC: [119]

Tabela 16 – Massa de carga efetivamente transportada

	CI	**LGIM/LGIP/HPDF/LPDF**	**LGIA/NH3FC**	**H2DF/H2FC**	**HTFC**
Petroleiro 300.000 dwt	279.000	268.619	255.043	239.072	262.924
Petroleiro 150.000 dwt	139.500	134.973	129.053	122.088	130.597
Petroleiro 100.000 dwt	93.000	89.832	85.689	80.814	86.542

Tabela 17 – Intensidades energéticas intermediárias após correção associada à perda de espaço

	CI	**LGIM/LGIP/HPDF/LPDF**	**LGIA/NH3FC**	**H2DF/H2FC**	**HTFC**
Petroleiro 300.000 dwt	0,0076	0,0079	0,0083	0,0089	0,0081
Petroleiro 150.000 dwt	0,0099	0,0103	0,0107	0,0113	0,0106
Petroleiro 100.000 dwt	0,0122	0,0127	0,0133	0,0141	0,0131

Nota: Por simplicidade, mostram-se apenas as intensidades associadas à demanda propulsiva. Unidade: kWh/t-mn

O consumo específico (MJ/t-mn) da equação 1 foi finalmente calculado ao se combinar as informações da Tabela 17 com aquelas da Tabela 18, em que se mostram as eficiências de conversão (MJ/kWh) assumidas para cada motorização e modo de operação, incluindo eventual combustível piloto. A Figura 27 mostra um exemplo de tecnologia construída a partir dessas informações (*CrudeTanker_Lrg_CI_AF*, ou seja, petroleiro de 300.000 dwt, motorização convencional e associado à região "Resto da África" - AF). Para cada tipo de navio, 180 (18 regiões x 10 tecnologias) tecnologias similares a essa foram construídas.

Note-se que, além das linhas *moutp* e *inp*, que refletem o consumo específico da embarcação modelada, a tecnologia *Ship* envolve outros parâmetros, como o custo de investimento (*inv*) em um novo navio. Os principais dados utilizados para a modelagem desse custo são mostrados na Tabela 19, na Tabela 20 e na Tabela 21.

Tabela 18 – Eficiências de conversão de combustível em energia de saída do motor

		SFC (MJ/kWh)		
	Modo de operação	**Principal**	**Piloto**	**Combustível piloto**
CI	Bunker (1)	6,90	0,00	-
	Diesel (2)	7,17	0,00	-
LGIM	Bunker (1)	6,90	0,00	-
	Diesel (2)	7,17	0,00	-
	Metanol (3)	6,97	0,77	Diesel (2)
	Etanol (4)	6,97	0,77	Diesel (2)
LGIP	Bunker (1)	6,90	0,00	-
	Diesel (2)	7,17	0,00	-
	LPG (6)	7,36	0,39	Diesel (2)
LGIA	Bunker (1)	6,90	0,00	-
	Diesel (2)	7,17	0,00	-
	Amônia (7)	6,97	0,78	Diesel (2)
HPDF	Bunker (1)	6,90	0,00	-
	Diesel (2)	7,17	0,00	-
	LNG (5)	6,93	0,29	Diesel (2)
LPDF	Bunker (1)	6,90	0,00	-
	Diesel (2)	7,17	0,00	-
	LNG (5)	7,58	0,08	Diesel (2)
H2DF	Bunker (1)	6,90	0,00	-
	Diesel (2)	7,17	0,00	-
	Hidrogênio (8)	7,67	0,08	Diesel (2)
H2FC	Hidrogênio (8)	7,11	0,00	-
NH3FC	Amônia (7)	8,89	0,00	-
HTFC	Amônia (7)	6,51	0,00	-
	Diesel (2)	6,51	0,00	-
	Metanol (3)	6,51	0,00	-
	Etanol (4)	6,51	0,00	-
	LNG (5)	6,51	0,00	-
	LPG (6)	6,51	0,00	-

Nota: Por simplicidade, mostram-se apenas os consumos específicos associadas à demanda propulsiva. Tabelas análogas foram construídas para eletricidade e calor. Dados: [62], [116], [119], [155], [213], [339]

```
CrudeTanker_Lrg_CI_AF a
    minp    1-a 1
    moutp   a-a ts 437 458 481 495 506 522 5
    pll ts 30
    inv ts 3.58 3.58 3.58 3.58 3.58 3.58 3.5
    fom ts 0.018 0.018 0.018 0.018 0.018 0.0
    hisc    0   hc 1987 294781 1992 294781 1
    bdc up  ts 212628694
    inp 2-a ts 0.098 0.098 0.098 0.098 0.098
    con1a TWCI  ts 1
    con1a TWCO  ts 1
```

Figura 27: Linhas de código selecionadas do COFFEE – tecnologia *Ship*

Fonte: COFFEE

Tabela 19 – Equipamentos associados às motorizações ilustrativas

	CI	**LGIM**	**LGIP**	**LGIA**	**HPDF**	**LPDF**	**H2DF**	**H2FC**	**NH3FC**	**HTFC**
Motor principal convencional	●									
Motor principal *dual-fuel*		●	●	●	●	●	●			
Pilha a combustível PEMFC								●	●	
Pilha a combustível SOFC										●
Geradores a diesel	●	●	●	●	●	●	●			
Baterias íon-lítio								●	●	●
Conversor								●	●	●
Inversor de frequência variável (VFD)								●	●	●
Motor elétrico								●	●	●
Sistema criogênico de armazenamento – LNG					●	●				
Sistema criogênico de armazenamento – H_2							●	●		
Unidade de craqueamento de amônia									●	
Unidade de redução catalítica seletiva (SCR)	●	●	●	●	●	●	●			
Depurador de gases de exaustão (*Scrubber*)	●									

Tabela 20 – Custos de investimento de embarcações

Embarcação	**Custo (USD_{2010})**
Petroleiro 300.000 dwt	100.000.000
Petroleiro 150.000 dwt	70.000.000
Petroleiro 100.000 dwt	50.000.000
Petroleiro de derivados	30.000.000
Gaseiro (*LNG Carrier*)	160.000.000
Químico	30.000.000
Hidrogeneiro (*LH_2 Carrier*)	320.000.000
Graneleiro 150.000 dwt	70.000.000
Graneleiro 100.000 dwt	50.000.000
Graneleiro 50.000 dwt	30.000.000
Porta-contêineres 11.500 TEU	150.000.000
Porta-contêineres 6.000 TEU	80.000.000
Porta-contêineres 3.000 TEU	45.000.000
Veículos (*Pure Car Carrier*)	90.000.000
Navio de carga geral	15.000.000

Nota: Assumiu-se que esses custos correspondem à motorização CI. Custos de investimento em outras motorizações foram calculados a partir da combinação dessas informações com aquelas da Tabela 21

Tabela 21 – Custos de investimento de equipamentos

Equipamento	**Custo em 2020**	**Custo em 2050**	**Unidade**
Motor convencional	256	256	USD/kW
Motor *dual-fuel*	500	500	USD/kW
PEMFC	1368	256	USD/kW
SOFC	1709	427	USD/kW
Geradores a diesel	299	299	USD/kW
Baterias	117	17	USD/kWh
Conversor	171	171	USD/kW
VFD	171	171	USD/kW
Motor elétrico	115	115	USD/kW
Sistema criogênico de armazenamento – LNG	129	129	USD/kW
Sistema criogênico de armazenamento – H_2	387	387	USD/kW
Unidade de craqueamento de amônia	2,3	2,3	MUSD
SCR	38	38	USD/kW
Scrubber	2,9	2,9	MUSD

Nota: USD = $USD_{2010.}$ Dados: [119]

5.3. Manuscrito

Nesta seção, reproduz-se, enfim, o manuscrito submetido à revista *Nature Climate Change* para publicação do artigo *International shipping in a world below 2ºC.* Atualmente em fase de revisão por pares, esse trabalho se encontra disponível sob a forma de *preprint* no link https://www.researchsquare.com/article/rs-2958063/v1 (DOI: https://doi.org/10.21203/rs.3.rs-2958063/v1). Seu material suplementar foi incluído no Apêndice B.

INTERNATIONAL SHIPPING IN A WORLD BELOW 2ºC

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Abstract

In recent years, the decarbonisation of international shipping has become an important policy goal. While Integrated Assessment Models (IAMs) are often used to explore climate mitigation strategies, they typically provide little information on international shipping, which accounts for around 0.75 $GtCO_2$/yr. Here, we perform the first multi-IAM analysis of international shipping, drawing on the results of six global models. Results indicate the need for decreasing emissions in the next decades, with reductions up to 88% in 2050. This is primarily achieved through the deployment of low-carbon fuels. Models that represent several potential low-carbon alternatives tend to show a deeper decarbonisation of international shipping, with drop-in biofuels, renewable alcohols and green ammonia standing out as the main substitutes of conventional maritime fuels.

a. Introduction

The goal of limiting the increase in global mean temperature to *well below* 2ºC and preferably below 1.5ºC was reaffirmed at COP27 [344]. According to the Intergovernmental Panel on Climate Change (IPCC), pathways that meet these goals require rapid and deep greenhouse gas (GHG) emissions reductions in all sectors throughout the first half of this century. Decarbonisation efforts can, however, vary significantly across sectors [2], [21]. Some sectors, including cement and steel production and long-distance air and maritime transport, entail CO_2 emissions that are quite difficult to eliminate, especially with fast-growing demands [53], [345]. While 'hard-to-abate' sectors were responsible for around 29% of energy/industry CO_2 emissions in 2019 [55], [73], [345] , their share can drastically increase over the next few decades [2], [21]. Demand-side and efficiency measures can contribute to decarbonising these sectors [66], but face significant barriers and constraints their potential is intrinsically limited. Many model-based mitigation pathways consistent with the Paris Agreement, therefore, rely on Carbon Dioxide Removal (CDR) strategies to offset emissions [20].

Maritime shipping is a major hard-to-abate sector that accounted for CO_2 emissions between 0.95 and 1.06 Gt/yr during the 2012-2018 period. Around 71% of this total came from international shipping. Non-CO_2 gases currently play a minor role in the sector, typically accounting for no more than 2% of total CO_2-equivalent emissions [62]. While international shipping emissions have been fairly stable since 2008, it would be wrong to conclude that the sector has already reached its emission peak. The growth of shipping emissions was slowed down by the 2008-09 financial crisis, which brought international seaborne trade down from 42 to 40 trillion tonne-miles (Tt-nm) [86]. After this, emissions kept declining until 2014 due to considerable efficiency gains despite the recovery of demand, enabling a temporary decoupling of emissions and transport activity. Since then, however, further increased shipping activity outpaced efficiency gains, and emissions have gradually increased [62], [86]. Just as it went from 10 Tt-nm in 1970 to around 60 Tt-nm in 2020 [86], [346], international seaborne transport work could reach 90-180 Tt-nm by 2050 [62], [241], even if there are several sources of uncertainty [347]. With the current carbon intensity (11.7 gCO_2/t-nm in 2018), this would represent international shipping CO_2 emissions estimated at 1.1-2.1 Gt/yr in 2050.

In 2018, the International Maritime Organization (IMO), responsible for regulating global maritime transport, reached an agreement to reduce international shipping GHG emissions by at least 50% by 2050 compared to 2008 (hereinafter IMO2050). As part of a broader strategy that also involves energy efficiency and carbon intensity goals, IMO2050 aims to ensure an emission pathway compatible with the temperature limits defined by the Paris Agreement [110], [240] (since international shipping was not explicitly covered by the treaty).

However, the role of shipping in a world of deep decarbonisation is still unclear (Figure 1). First, while energy efficiency may still help lower the carbon intensity of ships, its potential is intrinsically limited. Measures already present in the sector (e.g., speed reduction, improvement of hull design and propulsion system optimization) and measures that are still to come (e.g., increased usage of digitalization to optimize shipping routes) can provide a significant abatement of CO_2 emissions [103], [126]. Still, an efficient shipping sector almost completely fuelled by fossil energy (as is the case today) would entail relatively high CO_2 emissions. As such, low-carbon fuels are regarded as a key mitigation option for shipping [97]. Candidate alternative fuels are diverse both in terms of production routes and final energy carriers [68]. Using some of them depends on implementing new motorisation options, such as dual-fuel engines and electrochemical powertrains. Contrastingly, the existing fleet is almost entirely based on compression ignition engines, which can only work with bunker- and diesel-like fuels [84]. The long lifespan of ships and the low average age of existing vessels therefore imply significant technological inertia. Furthermore, low-carbon shipping would require fuel-specific bunkering infrastructure [97], in contrast with today’s standard global hubs of Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO) [124]. In view of these challenges and of the important linkages between shipping and the global energy system, we argue that international shipping emissions scenarios should be put into the context of global GHG emissions scenarios.

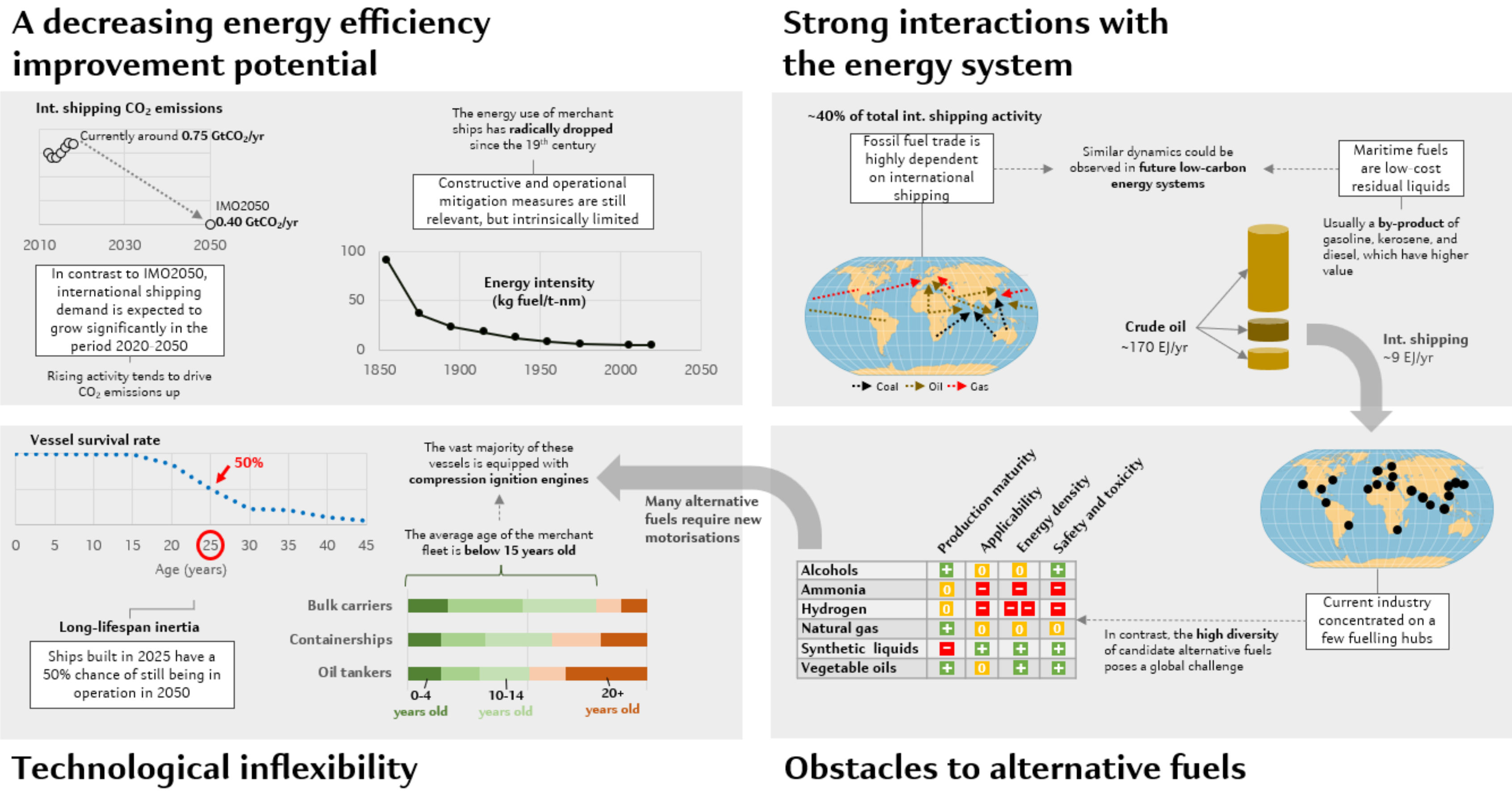

Figure 1: Decarbonisation challenges in the shipping sector

So far, only a few studies have looked at the decarbonisation of international shipping, and often based on sectoral modelling only [97], [161], [348], [349]. Economy-wide Integrated Assessment Models (IAMs) have historically paid little attention to shipping [241]. These models have been used to explore the consequences of different long-term climate mitigation strategies, with significant impacts on climate governance and policy [20], [21], [27], [37], [38], [40], [41], [304], [350]–[353]. Currently, IAMs are the backbone of scenario analyses reviewed by the Working Group III (WGIII) of the IPCC, which focuses on mitigation response strategies to global warming [20], [21], [31], [48]. In recent years, the IAM community has started to further explore the specificities of international maritime transport, which also made possible a better representation of the sector's demand and mitigation options within models [66], [241], [265], [354]. These improvements allow an integrated perspective of the sector's decarbonisation strategy, adding value to the existing literature. Instead of seeing shipping as an isolated sector, IAMs can treat maritime transport as part of a broader response strategy covering the rest of the energy sector (and, in some cases, agriculture and land use) and its complex linkages with maritime transport. Thereby, it becomes possible to evaluate the role of shipping in futures with varying storylines and climate targets.

In this paper, we explore possible futures of international shipping in terms of energy carriers and GHG emissions under an IAM framework. To that end, we perform the first multi-model comparison of this sector, relying on the results from six global IAMs. Rather than thinking of maritime emission reductions as the final objective, our analysis sees international shipping as part of a wider challenge, in which the goal is to halt the increase of global mean temperature. We argue that a myopic mitigation strategy in the shipping sector could not only cause harmful economic impacts but also imply spill-over effects on GHG emissions [265]. As such, one of the objectives of our analysis is to compare shipping emission reductions observed in IAM-based scenarios to that suggested by IMO2050, which is currently the landmark of maritime emissions.

Using the same socioeconomic assumptions and carbon budgets, we develop scenarios of the global energy system for 2020-2100 and concentrate our analysis on international shipping. The IAMs used in this exercise differ not only in terms of overall structure and modelling dynamics but also in the way they represent shipping mitigation options (see Supplementary Information). Four of our models (COFFEE, IMAGE, PROMETHEUS, and TIAM-UCL) have relatively high technological resolution in the shipping sector, meaning that they include numerous low-carbon maritime fuel production routes and vessel motorisation options. The other two models (IMACLIM-R and WITCH) focus on specific low-carbon alternatives in their modelling structure, with IMACLIM-R mainly relying on lignocellulosic biofuels and WITCH on hydrogen and hydrogen-based synthetic fuels. One of the purposes of our analysis is precisely to assess the impact of having a few or several mitigation options for shipping represented in IAMs.

Our scenario design does not impose any sectoral storyline but harmonises input data by using the Shared Socioeconomic Pathway no. 2 (SSP2) [173]. We work with three main scenarios groups, with the reference group (**NDC**) assuming the fulfilment of Nationally Determined Contributions (NDCs) as stated in the 2015 pledges. In these scenarios, total global emissions are not restricted in any way. The other scenario groups (**C1000** and **C600**) also assume the fulfilment of NDCs but additionally impose carbon budgets of 1,000 and 600 $GtCO_2$ for the period 2020-2100. While **C600** scenarios can be seen as in line with a warming slightly above 1.5^{o}C by 2100, **C1000** scenarios would reflect a world likely below 2^{o}C by that time (see Supplementary Information). Both **C1000** and **C600** scenarios follow a peak-budget dynamic, i.e., net negative emissions are not allowed after reaching the point of net zero [20].

In addition to our global analysis, in the Supplementary Information, we present detailed results for the European Union (EU). This regional analysis was performed using the PRIMES-Maritime model and is consistent with **C1000** and **C600** global carbon budgets.

b. Results

Stable or lower international shipping emissions in carbon budget scenarios

Under current policies (**NDC**), our IAMs project international shipping emissions to stabilise or rise in the long-term (Figure 2), with values in the range of 0.6-1.4 $MtCO_2$/yr in 2050, 0.7-1.7 $MtCO_2$/yr in 2070 and 0.8-2.0 $MtCO_2$/yr in 2090. From a decomposition perspective, this uptrend is due to total shipping activity, which is projected to continuously increase through the century (panel a). Higher reference emissions are associated with more pessimistic efficiency assumptions (e.g., TIAM-UCL).

On the other hand, most models show international shipping emissions to fall significantly in the Paris-compatible scenarios, even with rising activity. This is made possible by efficiency improvement and fuel switch. For instance, with a carbon budget of 1,000 $GtCO_2$, international shipping emissions lie between 0.3 and 1.2 $GtCO_2$/yr in 2050. Particularly, the most technology-detailed models indicate reductions relative to the 2008 level. While COFFEE and IMAGE show cutbacks lower than that of IMO2050 (26 and 34%), PROMETHEUS shows a reduction of 65%, going beyond IMO2050 and even the Sustainable Development Scenario (SDS) of the International Energy Agency (IEA) [224]. IMACLIM-R shows a lighter decrease (9%) in shipping emissions, while TIAM-UCL and WITCH show increases of 49 and 16% in 2050. In the case of TIAM-UCL, this effect is the combination of a fast-rising energy demand with a relatively slow development of low-carbon fuels, whose development takes place mostly after 2050. This time lag makes the variation of TIAM-UCL emissions go from the most positive in 2050 (+49%) to the most negative in 2070 (-58%). As such, WITCH is somehow the only exception, depicting international shipping emissions as approximately stable throughout the century in its **C1000** scenario. This is partly due to the low technological granularity of the shipping sector in WITCH, which mainly includes blue/green hydrogen-based fuels as potential energy alternatives. Considering these limited mitigation options, the inter-temporal economic growth optimization of the model prioritizes the abatement of CO_2 emissions elsewhere.

With a carbon budget of 600 $GtCO_2$, reductions are more pronounced in 2050. COFFEE and IMAGE show reductions of 43 and 59%, in line with IMO2050 and the SDS scenario, while PROMETHEUS depicts emissions as low as those of the IEA Net Zero Emissions by 2050 Scenario (NZE), with a cutback of 88%. In **C600** scenarios, even low-shipping-resolution models show at least stable emissions in 2050. The IMACLIM-R cutback is very close to that observed in its **C1000** scenario, in which the low-carbon fuel production already reaches its full potential. In TIAM-UCL, the more stringent carbon budget engenders a faster maritime fuel transition, making international shipping emissions 2% lower in 2050 compared to 2008. Finally, the **C600** scenario from WITCH is quite similar to its **C1000** scenario, with high fossil fuel deployment and a 2% increase in emissions in 2050.

The five models whose time horizon is 2100 project international shipping emissions to approximately stabilize, in both **C1000** and **C600** scenarios, in the second half of the century. This pattern is due to the rise of Bioenergy with Carbon Capture and Storage (BECCS) after 2040 (see Supplementary Information). As explained before, our carbon budget scenarios do not allow net negative emissions. However, this does not exclude the use of some level of CDR strategies in these mitigation scenarios. This finding should be tempered by the uncertainties surrounding the large-scale deployment of BECCS (e.g., land and water requirements [355], [356]). Restrictions on the diffusion and implementation of this technology would mean a higher decarbonisation pressure on the shipping sector.

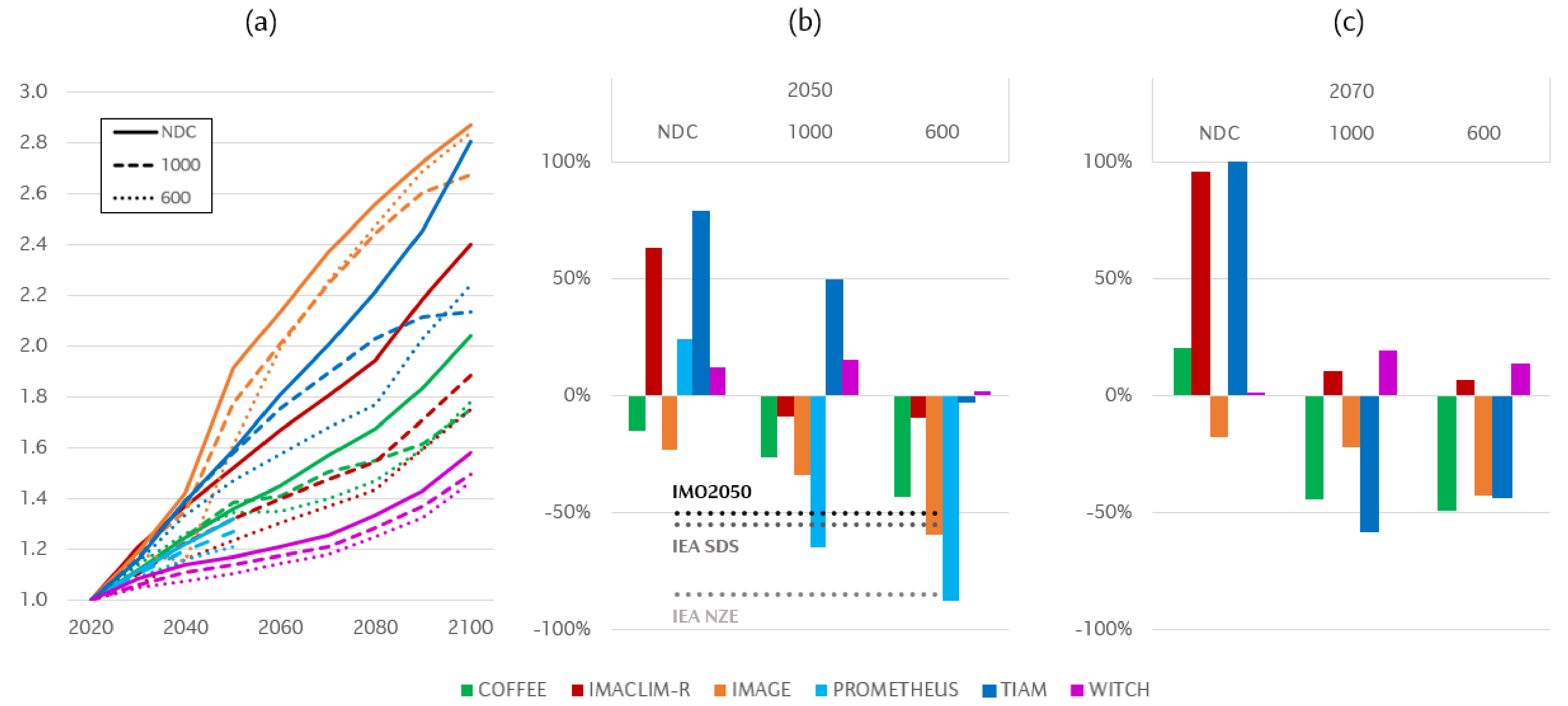

Figure 2: Panel (a) - International shipping activity level between 2020 and 2100 across scenarios (indexed to 2020). Panels (b) and (c) - Variation of the annual CO2 emissions from international shipping in 2050 and 2070 compared to 2008 across scenarios

Fossil fuel shift associated with model granularity for shipping

Total fuel demand for international shipping is relatively convergent across models, reaching 10-16 EJ/yr in 2030. Over a longer time, discrepancies are more relevant, with a range of 7-23 EJ/yr in 2050 and of 12-28 EJ/yr in 2070. This is due to differences in activity projections and energy efficiency assumptions. Scenarios with high activity and low efficiency gains (e.g., **NDC** scenarios from IMACLIM-R and TIAM-UCL) have a total annual demand of 20-23 EJ/yr in 2050, representing an increase of over 100% compared to current international shipping energy consumption. At the opposite end, IMAGE and PROMETHEUS, whose modelling includes demand responses to carbon pricing, have fuel demands of 7-8 EJ/yr in 2050, slightly below the current consumption. Compared to their **NDC** scenarios, this represents fuel demand reductions of 25-50%, with part of these reductions coming from avoided fossil fuel demand. In the case of COFFEE, although the transportation of coal, oil and gas is modelled in detail, no significant impact is observed on fuel demand in carbon budget scenarios. As shown in panel (a) of Figure 2, the variation of the activity level across scenarios in COFFEE is small, since the mitigation strategy indicated by the model includes the conservation of a relatively large international fossil fuel market.

As a hard-to-abate sector, international shipping tends to have higher shares of fossil energy in deep mitigation scenarios when compared to sectors such as electricity supply, heating, and road transportation. Our results confirm this (Figure 3), depicting conventional maritime fuels as relevant energy sources until the second half of the century. The magnitude of this fossil energy gap between shipping and the rest of the energy system is partly associated with the level of detail of the shipping sector in each IAM, most notably in carbon budget scenarios. For instance, in **C1000** scenarios, while high-shipping-resolution models show fossil energy with a share of 46-67% in international shipping in 2050 (versus 34-65% in global primary energy), low-shipping-resolution models indicate a fossil share of 64-96% in the same year (versus 46-55% in primary energy). Similarly, in **C600** scenarios, high-shipping-resolution models indicate maritime fossil shares in the range of 18-63% in 2050 (compared to 34-52% in primary energy), while low-resolution models point to higher values (58-88% in international shipping compared to 28-47% in primary energy). This finding is even more relevant when considering that total fuel demand is lower in carbon budget scenarios from COFFEE, IMAGE, and PROMETHEUS (which is also due, as explained, to detailed modelling of shipping demand and/or energy efficiency options). With higher maritime fuel demand, low-carbon energy carriers would likely have an even bigger share in carbon budget scenarios from these IAMs.

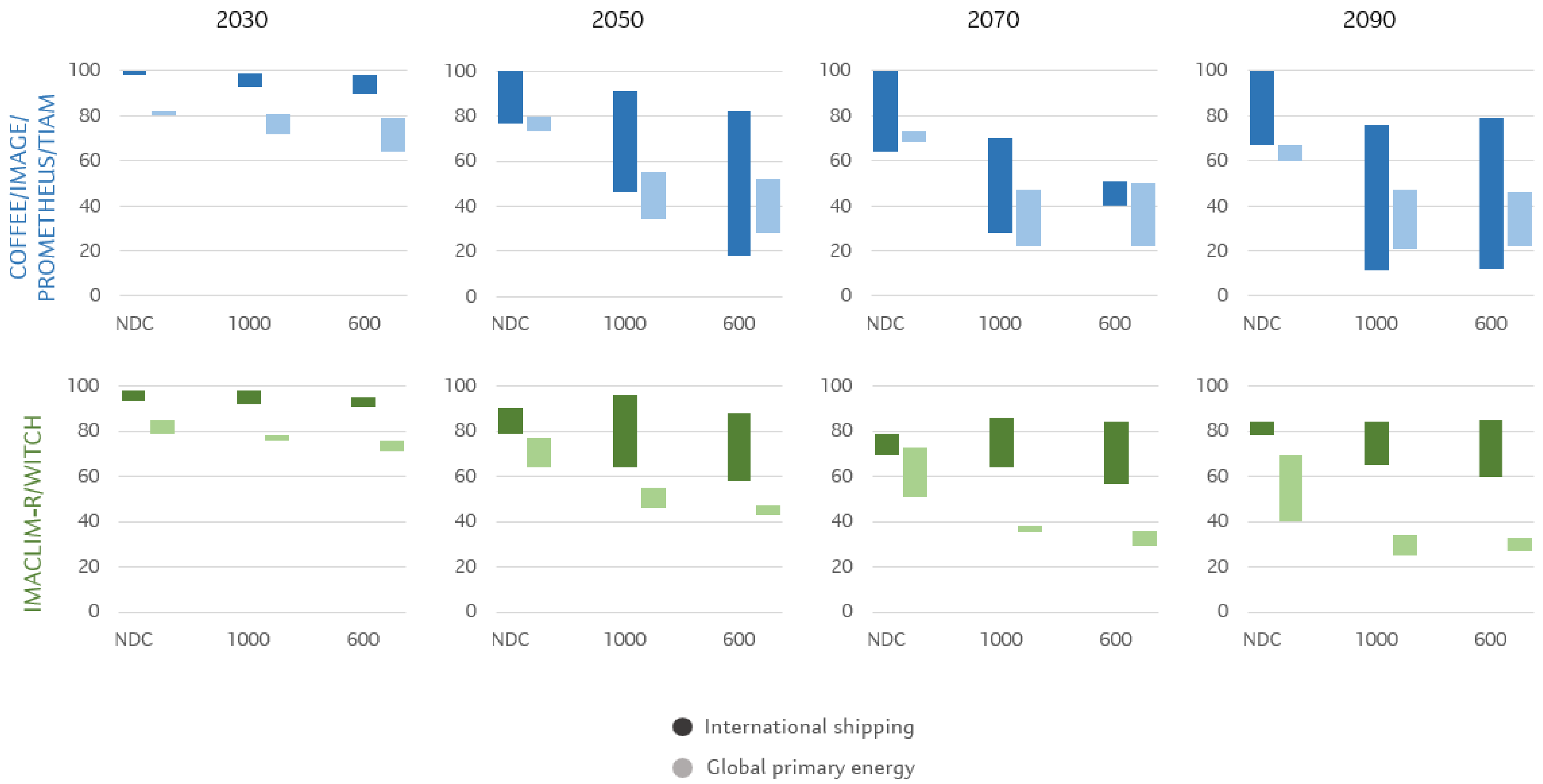

Figure 3: Ranges of fossil fuel share in international shipping and global primary energy across scenarios for high-shipping-resolution (blue) and low-shipping-resolution models (green)

A diverse portfolio of low-carbon fuels, with LNG playing a minor role

Our models point to a set of various mitigation responses, with the choice of specific alternative maritime fuels strongly related to the global trends observed in the different IAMs (Figure 4). Carbon budget scenarios from TIAM-UCL, for example, include aggressive electrification based on solar and wind power, with these sources reaching ~300 EJ/yr of primary energy in 2070 and ~350 EJ/yr in 2090. This context favours the adoption of maritime fuels based on renewable electricity, especially ammonia (with an energy density advantage compared to hydrogen), which reaches around 9 EJ/yr in 2070 and 18 EJ/yr in 2090. In contrast, pathways resulting in higher biomass shares in primary energy (such as IMACLIM-R and IMAGE) show a preference for bio-based maritime fuels, especially synthetic liquids (e.g., bio-alcohols and Fischer-Tropsch hydrocarbons). However, models that rely on bio-based fuels to decarbonize transports always face a competition for feedstock in generating negative emissions with the power sector [357]. This largely explains the limit reached by low-carbon maritime fuels in IMACLIM-R scenarios. Carbon budget scenarios from COFFEE and PROMETHEUS show lower fuel demand and a more diverse maritime energy mix. In COFFEE scenarios, for example, vegetable oils and renewable alcohols are the first options for fuel switch in the 2040s. This is due to their higher technological maturity both in terms of production and use. In the second half of the century, green ammonia (~3 EJ/yr) and residual lignocellulosic biofuels (~2 EJ/yr) become the dominant alternative energy carriers. PROMETHEUS scenarios depict a faster transition and richer fuel portfolio based on ammonia, hydrogen, and oilseed-based fuels, while lignocellulosic bioenergy rapidly become the most important low-carbon alternative, reaching more than 2 EJ/yr in 2050 in its **C600** scenario.

While some **NDC** scenarios indicate a relevant role for Liquefied Natural Gas (LNG) (2-5 EJ/yr in 2050), carbon budget scenarios do not show natural gas as a major energy alternative for shipping. As a fossil resource, LNG has a limited climate mitigation potential, and the investment in low-carbon fuels provides a more efficient decarbonisation pathway across models. TIAM-UCL is somehow an exception, using significant amounts of natural gas in carbon budget scenarios to cope with a fast-growing demand, which cannot be entirely met by renewable-based ammonia.

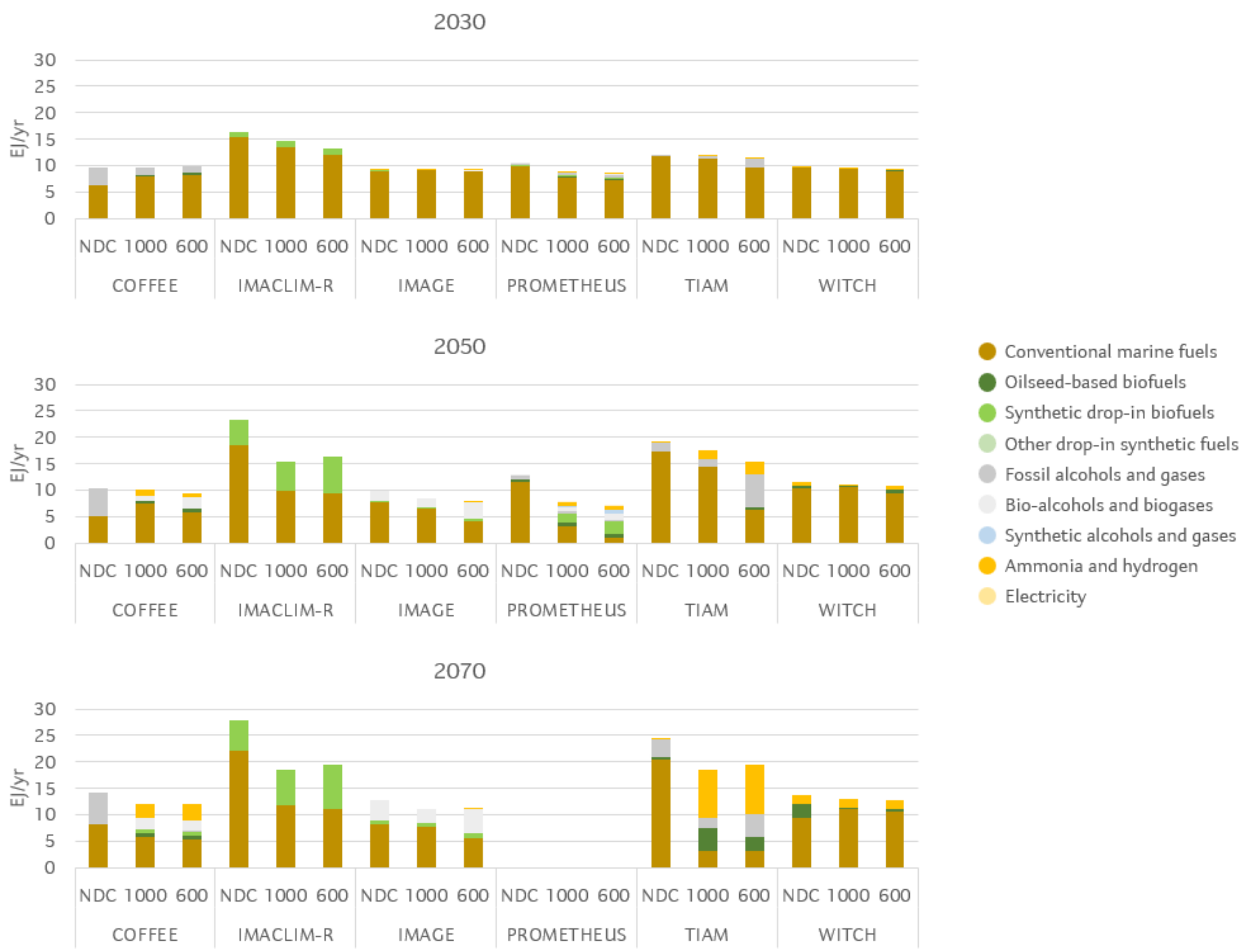

Figure 4: International shipping energy mix in 2030, 2050 and 2070 across models and scenarios

c. Discussion

The demand for international shipping is likely to increase over the century, bringing an upward trend to its GHG emissions. In contrast, deep mitigation scenarios of the global energy system show that international shipping emissions must stabilize or decrease to be compatible with the long-term temperature goals of the Paris Agreement. With decreasing energy efficiency potentials, this must be achieved with the deployment of low-carbon fuels from 2030 onwards, reaching up to 88% of the sector's final energy in 2050. While several fuel production routes and final energy carriers can be considered, they all face challenges upstream (e.g., high production costs, land use competition and low technological maturity) and/or downstream (e.g., low energy density and applicability to the existing fleet). This implies that no single fuel has an unlimited potential and that relying on a single option might limit the emission cutback of international shipping. As put into perspective by our results, models that represent only a few low-carbon maritime fuels tend to keep a larger share of fossil energy in vessels in carbon budget scenarios, possibly underestimating the true decarbonisation potential of the sector and contributing to higher reliance on CDR strategies. Drop-in biofuels (e.g., FAME-biodiesel, SVO, HVO-diesel) and renewable alcohols (e.g., ethanol and methanol) seem the most promising short-term candidates, while ammonia and synthetic energy carriers (especially lignocellulosic biofuels) become essential towards 2050 and beyond. International shipping has a high level of technological inertia, which means that if the industry is to be prepared for a significant amount of renewable energy from 2030 onwards, it is essential to start investing in low-carbon fuels and new motorisations as soon as possible.

d. Online Methods

Model exercise

Our work evaluates the role of international shipping as part of the much broader challenge of limiting global warming to relatively safe levels. To this end, we use IAMs to develop low-carbon scenarios for the energy and industrial systems (and, in some cases, for agriculture and land use systems as well), focusing our results analysis on international shipping, a sector whose modelling has been recently improved across these models.

Integrated Assessment Models

Integrated Assessment Models (IAMs) describe key processes in the interaction of human development and natural environment. Typically, they are designed to assess the implications of achieving climate objectives, such as limiting global warming to 1.5 or 2ºC[20], [358]. The six global models used in this study are COFFEE [313], [359], IMACLIM-R [357], [360], IMAGE [37], [241], PROMETHEUS [359], [361], TIAM-UCL [28], [362] and WITCH [363], [364].

COFFEE is a process-based IAM [31] that utilizes intertemporal linear programming optimization with perfect foresight to model global energy, agricultural, and land-use systems. The energy sector is at the core of the model. Each of the model's regions has a detailed representation of energy extraction and conversion technologies, and individualised estimates of energy resources (both in terms of volumes and costs) in the form of cost-supply curves. Divided into five main sectors (energy, industry, transportation, buildings, and agriculture), the model accounts for all primary energy produced by energy systems and its later transformation into secondary and final energy. The detailed modelling of international shipping is one of the most recent refinements in COFFEE. The approach used for modelling this sector focused on accurately representing the demand and potential alternative fuels. Shipping demand is based on the representation of 31 products/product groups, with most of them modelled endogenously. The energy modelling of ships is based on 10 illustrative motorizations, ranging from conventional two-stroke diesel engines to advanced electrochemical powertrains. Meanwhile, candidate fuels are grouped into eight categories, with each one potentially applicable to different powertrain types. In their turn, technological routes that produce these fuels are represented in each COFFEE region, ranging from technologically mature processes (e.g., oil refining, vegetable oil extraction) to advanced energy conversion processes (e.g., Fischer-Tropsch synthesis). The improvement of ship energy efficiency over time is modelled exogenously based on conservative assumptions. Detailed information on COFFEE can be found in the Supplementary Information.

IMACLIM-R is a multi-sectoral Computable General Equilibrium (CGE) model representing the global economy as a set of 12 production sectors with input-output trade links. It is primarily based on macroeconomic theory, featuring consistent input-output accounting of both economic and physical energy flows. The demand for international shipping is influenced by the trade volume of physical goods but also by the price of freight transport. In its turn, this price is strongly influenced by energy carrier prices and energy efficiency. Maritime energy sources are determined by the relative prices of energy, also considering carbon taxation and exogenous hypotheses for energy efficiency improvement. Detailed information on IMACLIM-R can be found in the Supplementary Information.

IMAGE is an intermediate complexity IAM that provides a process-oriented representation of human and earth systems, which are connected by emissions and land use. The model is driven by various factors, including demographic, economic, and technological development, as well as resource availability, lifestyle changes, and policy. The model's energy module simulates long-term trends in final energy use, depletion, energy-related GHG, and other air pollution emissions, as well as land-use demand for energy crops. The results are obtained using a single set of deterministic algorithms, which derive the system state in any future year entirely from previous system states. The model projects freight service demand using a constant elasticity of the industry value added for each transport mode, with international shipping being one of six freight transport modes. The competition between vessels with different energy efficiencies, costs, and fuel type characteristics is described using a multinomial logit equation. These substitution processes capture the price-induced energy efficiency changes, and over time, more efficient technologies become more competitive due to exogenous decreases in costs, representing the autonomous-induced energy efficiency changes. The model assumes that each type of vehicle uses only one fuel type. Therefore, this process also describes the maritime fuel selection. Detailed information on IMAGE can be found in the Supplementary Information.

PROMETHEUS is a global energy system model covering in detail the interactions between energy demand, supply, and prices. Its main objectives are to assess mitigation pathways, analyse the implications of policy measures and quantify impacts of climate policies on energy prices. The model quantifies CO_2 emissions and represents abatement technologies and policy instruments (e.g., carbon pricing, efficiency standards). In terms of mathematical formulation, PROMETHEUS is a recursive dynamic simulation model, with investment and operation decisions mostly based on the current state of knowledge of parameters such as cost and performance. Recently, PROMETHEUS was enhanced with an improved representation of international shipping. Several technologies and emission reduction options were included in the model, with focus on low-carbon fuels. Maritime activity is split by segments (i.e., dry bulk, general cargo, container, and tankers). For tankers, the demand is endogenously estimated from interactions with the energy sector, while other segments have exogenous projections based on the literature. Emission reduction options include energy saving alternatives, speed reduction and the deployment of a wide range of alternative fuels. Detailed information on PROMETHEUS can be found in the Supplementary Information.

TIAM-UCL is an energy-economy model of the global energy system that uses a linear programming optimization approach to explore cost-optimal systems. Features of its formulation include perfect competition and foresight. The representation of the global energy system encompasses primary sources from production through their conversion into final energy and utilization to meet service demands across a range of economic sectors. Using a scenario-based approach, the evolution of the system to meet future energy service demands can be simulated driven by the least-cost objective solution. Decisions around investments are determined based on cost-effectiveness, using the existing system in 2015 as a starting point. Energy resource potential, technological availability and policy constraints are other important aspects considered by the optimization. In TIAM-UCL, the transport sector is also fully based on this cost-optimisation paradigm, with international shipping being a part of the freight module. The demand for shipping is split by product group. For non-energy commodities, activity is exogenous, calculated and mapped using trade projections from an auxiliary sectoral model. For energy commodities, activity is endogenously estimated in TIAM-UCL, driven by the trade of fossil fuels and other energy carriers. Emission reductions are mostly achieved by the deployment of low-carbon fuels, whose selection is based on fuel and carbon prices. Ship and logistic efficiency are introduced exogenously in the model. Detailed information on TIAM-UCL can be found in the Supplementary Information.

WITCH is a comprehensive tool designed to examine the interplay between climate change, energy systems, and economic development. It has a hybrid structure, combining top-down and bottom-up features. The top-down component includes a macroeconomic intertemporal optimization model while the bottom-up component captures technological details of the energy sector. The model generates optimal mitigation and adaptation strategies in response to climate damage or emission constraints. Strategies result from a maximization process involving regional welfare, capturing free-riding behaviours and interactions induced by externalities. An iterative algorithm implements the open-loop Nash equilibrium in a non-cooperative, simultaneous, open membership game with full information. The model uses a social planner to maximize the sum of regional discounted utility, with a constant relative risk aversion (CRRA) utility function derived from per-capita consumption. Climate impacts affect gross output, with fossil fuel and GHG mitigation costs subtracted from them. Energy services are provided by a combination of physical energy input and a stock of energy efficiency knowledge. Shipping demand for each region is the total global demand allocated with respect to its GDP share. Then, future demand is estimated using the elasticity of GDP. Elasticities are distinguished for different cargo types. The international shipping module within WITCH is currently in its early stages and remains highly aggregated. On the supply side, the maritime sector has access to conventional oil-based fuels and a few alternative fuels. Energy efficiency improvement is modelled exogenously. Detailed information on WITCH can be found in the Supplementary Information.

Scenarios

We work with three sets of scenarios, resulting in a total of 18 scenarios. Reference scenarios (**NDC**) do not restrict total global emissions in any way but assume the fulfilment of Nationally Determined Contributions (NDCs) as stated in the 2015 pledges. These policies (e.g., GHG reduction targets, energy and land-use policies) are assumed to be fully implemented for the period 2010-2030 according to information from the NDCs [358], [365] and considering the regional aggregation of each model. For the longer term (2030-2100), we assume that mitigation efforts continue at a pace consistent with that observed during the period covered by the NDCs. Demographic, socioeconomic, and technological assumptions follow the Shared Socioeconomic Pathway (SSP) no. 2, which describes a middle-of-the-road development in mitigation and adaptation challenges space. In many aspects, SSP2 can be seen as in line with historical trends [173], [302].

The other two scenario groups (**C1000** and **C600**) derive from the first one, but additionally impose carbon budgets of 1,000 and 600 $GtCO_2$ for the global economy in the period 2020-2100. Net negative CO_2 emissions (and therefore temperature overshoot [20]) are not allowed, meaning that budgets refer to the sum of annual net CO_2 emissions until the year of net zero ("peak budget" scenarios). The choice of carbon budget values is based on model capabilities and warming categories defined by the IPCC in its most recent assessment report [2], [21] (see Supplementary Information). More stringent carbon budgets (e.g., 400 $GtCO_2$) were not assessed because most of our models do not find solutions for such low values.

In all three scenario groups, international shipping emissions are not restricted in any aprioristic way. As shipping is the focus of our analysis, leaving its emissions unconstrained is a way to compare the results of our models with existing sectoral targets such as IMO2050.

Results organization for shipping energy carriers

Since the modelling of fuel conversion processes is not identical across the six IAMs, we use energy carrier categories to harmonize and compare our results (see Supplementary Information). These categories seek to group energy carriers according to common features, such as feedstock type, energy density and applicability. The **Conv** category corresponds to conventional fuels based on petroleum, such as HFO and MDO. The **Oilseed** category represents fuels based on vegetable oils obtained from oily crops, such as palm, soybean, and sunflower, and eventually also from animal fats such as beef tallow. The **D-synt bio** and **D-synt other** categories include fully drop-in renewable fuels produced through advanced processes such as the Fischer-Tropsch synthesis that are often chemically indistinguishable from fossil products. While the former relates to biobased feedstocks, the latter includes every other type of resource, most notably renewable-based electricity. The three **AG** categories correspond to groups of alcohols and gases (e.g., ethanol, methanol, and LNG), whose use in ships is typically made possible using dual-fuel engines. As in the case of drop-in fuels, they differ from each other by the type of primary source. Finally, the **H_2/NH_3** category includes hydrogen and ammonia, while the **Elec** category refers to the direct use of electricity.

6. Conclusão

Diante de uma literatura com maior foco em análises setoriais, este trabalho se propôs a examinar a descarbonização do transporte marítimo sob a perspectiva mais ampla da transição energética. Para tanto, recorreu à modelagem integrada, um campo de estudo que produz cenários de longo prazo da matriz energética global e de suas emissões de GEEs. Por seu caráter abrangente, IAMs costumam incluir uma representação simplificada do setor marítimo e, assim, a pesquisa desenvolvida se concentrou em aperfeiçoar essa modelagem a fim de investigar com mais propriedade o papel do transporte marítimo em um mundo de baixo carbono.

Os objetivos específicos elencados na introdução foram trabalhados nas quatro produções científicas da tese. A seguir, reproduzem-se esses objetivos específicos, associando-os com essas produções.

- A avaliação de fontes energéticas alternativas para o transporte marítimo – **Artigos #1, #2 e #4**;
- A avaliação das possíveis rotas tecnológicas de produção desses energéticos marítimos alternativos, com especial atenção a rotas baseadas em recursos renováveis - **Artigos #1, #2 e #4**;
- O estudo do impacto de diferentes cenários de demanda sobre o esforço de descarbonização do setor marítimo internacional – **Artigo #3**;
- O desenvolvimento de uma modelagem total ou parcialmente endógena da demanda por transporte marítimo em IAMs – **Artigos #1, #2 e #4**;
- A produção, em nível nacional, de cenários de descarbonização do transporte marítimo concebidos sob a lógica sistêmica de IAMs – **Artigos #1 e #2**;
- A produção, em nível global, de cenários de descarbonização do transporte marítimo concebidos sob a lógica sistêmica de IAMs – **Artigo #4**;
- A análise da dinâmica de substituição dos combustíveis marítimos fósseis em cenários integrados de descarbonização do suprimento energético do transporte marítimo global – **Artigo #4**;

- A avaliação do papel de combustíveis marítimos alternativos específicos em cenários de descarbonização do setor – **Artigos #1, #2 e #4**;
- A comparação do resultado de cenários energéticos integrados do transporte marítimo com o nível de redução de emissões representado pela IMO2050 – **Artigo #4**;

Uma primeira análise (artigo #1) foi realizada em escopo nacional usando o modelo BLUES, um IAM que representa os sistemas energético, agrícola e de uso da terra no Brasil. Nesse estudo, suas cadeias energéticas foram aprimoradas a fim de ofertarem um maior número de potenciais combustíveis marítimos. Aliado a uma representação do comércio exterior brasileiro, isso permitiu desenvolver uma série de cenários de abastecimento energético de embarcações no país entre 2020 e 2050. Tendo a IMO2050 como referência, o artigo procurou relacionar a descarbonização do setor marítimo com as possíveis configurações do restante do sistema energético brasileiro, questionando uma visão limitada trazida pela meta setorial. De fato, verificou-se uma disparidade notável entre os cenários de expansão irrestrita do sistema energético e aqueles em que a economia brasileira era circunscrita por um orçamento de carbono. No primeiro caso, biocombustíveis baseados em oleaginosas (SVO/HVO) foram utilizados para descarbonizar o suprimento de energia marítima, com níveis consideráveis de vazamento de emissões. Já no cenário de baixa emissão, a descarbonização marítima ocorreu a par e passo com tendências estruturais, sendo alcançada por meio de biocombustíveis pesados coproduzidos em plantas *Biomass-to-Liquids* com captura de carbono. No artigo #1, analisaram-se também cenários em que a escolha de dado combustível alternativo era predeterminada, forçando o modelo a utilizá-lo independentemente do resto do setor energético. Em todos os casos (bunker de hidrogênio, amônia e metanol), houve vazamento contraproducente de emissões, com a redução do CO_2 emitido pelo transporte marítimo sendo largamente superada pelo aumento das emissões nacionais de GEEs.

Em um estudo complementar (artigo #2), estendeu-se a análise do artigo #1 para incluir o setor de aviação. Além de contribuir globalmente com emissões anuais de CO_2 comparáveis às do transporte marítimo, a aviação também é um setor de difícil descarbonização eminentemente internacional. Ademais, diversas rotas de produção de QAv renovável podem coproduzir combustíveis marítimos, analogamente ao que ocorre em refinarias de petróleo. Diante disso, o artigo #2 investigou se a descarbonização da aviação poderia ocorrer lado a lado com a do transporte marítimo, voltando-se especificamente para o caso brasileiro. Devido ao valor peculiar da proporção entre o consumo total dos dois setores no país (~7 Joules de bunker para cada 3 Joules de QAv), essa sinergia mostrou-se relativamente limitada nos cenários desenvolvidos com o BLUES. Notadamente, no cenário em que as emissões totais do Brasil são restringidas por um orçamento de carbono, apenas uma pequena fração dos combustíveis marítimos adveio de plantas de querosene de BtL. Uma sinergia muito mais relevante ocorreu entre os setores marítimo e rodoviário, cuja alta demanda por diesel gerou um excedente significativo de frações pesadas.

O terceiro estudo realizado no âmbito desta tese (artigo #3) ampliou seu escopo geográfico de análise, tratando não mais do caso brasileiro, mas do setor marítimo internacional em seu conjunto. Seu propósito foi, com base em cenários do IMAGE, projetar a atividade do transporte marítimo internacional segundo cinco diferentes trajetórias socioeconômicas (SSPs). Constatou-se que há uma variação significativa de demanda entre os SSPs já em 2050 (17 a 35 Gt/ano), mas principalmente no final do século (19 a 53 Gt/ano). Essas diferenças se deveram a ritmo de desenvolvimento econômico, nível de cooperação internacional, padrões de consumo e preferências por vetores energéticos. Em particular, a presença de uma política climática compatível com um mundo abaixo de 2ºC provocou uma redução de ~20% da atividade marítima em 2050, o que se explica pelo transporte evitado de carvão e petróleo. Devido a um crescimento de demanda que, em todos os casos, supera eventuais ganhos de eficiência energética em embarcações, projetou-se um aumento da demanda por energia do transporte marítimo internacional, alcançando 9-25 EJ/ano em 2050 e 13-46 EJ/ano em 2100. Diante da restrição imposta pela IMO2050 (não mais que 6 EJ/ano de energia fóssil a partir de 2050), isso implicaria um consumo de energéticos renováveis superior à demanda total de biocombustíveis do mundo atual.

Embora tenha sido um passo importante desta tese, o artigo #3 constituiu uma análise estática, não concretizando plenamente o objetivo de integrar o transporte marítimo internacional a um IAM global. Tal objetivo foi cumprido na etapa subsequente, por meio da representação do setor no modelo COFFEE. Com foco numa abordagem *bottom-up* da demanda e na representação do maior número possível de potenciais combustíveis marítimos, a modelagem desenvolvida se integrou a cadeias energéticas e agrícolas preexistentes no COFFEE, possibilitando gerar demandas endógenas de transporte marítimo para produtos como carvão, petróleo, gás natural, biocombustíveis, hidrogênio e grãos. Dessa forma, o setor marítimo passou a ser parte integrante do modelo, com seu nível de atividade e suas escolhas tecnológicas vinculadas à otimização geral dos sistemas globais de energia, agricultura e uso do solo.

O desenvolvimento do módulo de transporte marítimo internacional no COFFEE permitiu a elaboração do artigo #4, em que os resultados do modelo foram comparados aos de outros cinco IAMs, cada qual com sua própria metodologia de representação do setor. O estudo revelou a necessidade de se estabilizar ou reduzir as emissões de CO_2 do transporte marítimo internacional entre 2020 e 2050 para que seu impacto climático seja compatível com um mundo abaixo de 2ºC. Os cenários desenvolvidos se mostraram relativamente consistentes com a IMO2050, cuja ambição é considerável quando analisada no contexto das projeções de demanda. Combustíveis marítimos alternativos tiveram papel essencial nos cenários mais restritivos, respondendo, na maior parte dos casos, por ao menos 40% da energia final consumida pelo setor a partir de 2050.

Tendo gradualmente ampliado seu escopo, o trabalho desenvolvido no âmbito desta tese de doutorado gerou contribuições relevantes sobre o papel do transporte marítimo em um mundo de descarbonização profunda. Ao mesmo tempo, trouxe novas perguntas e potenciais temas de investigação científica, especialmente no campo da modelagem integrada.

As principais conclusões podem ser resumidas a partir dos seguintes pontos:

- Integrando um grupo de setores cuja descarbonização é particularmente desafiadora, o transporte marítimo internacional tem o desafio de produzir um pico definitivo em suas emissões anuais de CO_2, reduzindo-as de forma compatível com o Acordo de Paris.
- Um aspecto particularmente desafiador dessa tarefa é a perspectiva de aumento da demanda por transporte marítimo em médio e longo prazo. Tanto IAMs como projeções setoriais têm indicado níveis crescentes de atividade marítima nas

próximas décadas, com o incremento global de toneladas-milhas em 2050 variando entre 20 e 200% em relação ao patamar atual. Ademais, isso poderia ser catalisado por outros aspectos da transição energética, na medida em que esse processo representará uma substituição intensa de bens de capital, com potencial impacto sobre o comércio global de metais e minerais, assim como de conversores energéticos.

- A maior parte das medidas de mitigação do transporte marítimo pode ser lida como um meio de aumento de eficiência energética. Isso é mais evidente quando se trata de motores com menor consumo, recuperação de calor residual ou aumento do tamanho do hélice, mas também é verdade para reduções de velocidade, uso de energia eólica auxiliar e aumento do porte das embarcações. Em última instância, todas essas medidas representam uma diminuição da razão entre a energia demanda pelo sistema principal de propulsão e o serviço de transporte proporcionado (toneladas-milhas).
- Apesar de numerosas, essas possíveis medidas de eficiência energética não indicam um potencial combinado capaz de transformar a ordem de grandeza do consumo anual de combustíveis marítimos nas próximas décadas. Com retornos marginais decrescentes desde o século 19, ganhos de eficiência na navegação tendem a ser cada vez menos expressivos, ao menos diante das atuais perspectivas tecnológicas.
- Assim, níveis mais profundos de descarbonização do transporte marítimo dependem do uso em larga escala de energia de baixo carbono, como aquela baseada em biomassa e/ou eletricidade renovável. A indústria e a literatura vêm cogitando uma ampla gama de combustíveis marítimos alternativos.
- Associados a um sistema mais amplo de produção de energéticos, potenciais combustíveis marítimos alternativos são bastante diversos tanto em termos de rotas de produção quanto de vetores finais. Em geral, esses combustíveis enfrentam barreiras de aplicabilidade, custos de produção/distribuição, densidade energética, maturidade tecnológica e segurança operacional. Isso os torna pouco competitivos ante o bunker, um energético associado às economias de escopo da indústria do petróleo.

- Ainda não é possível afirmar com segurança que energéticos e rotas de produção deveriam prevalecer no sistema de abastecimento marítimo de um mundo de baixo carbono. Contudo, algumas tendências podem ser apontadas. A principal delas é a sobrevivência do petróleo por um período mais longo em comparação com o setor rodoviário. Combinada com a longa vida útil das embarcações, a existência de uma frota mercante relativamente nova e quase inteiramente baseada em motores Diesel torna mais lenta a ascensão de novos combustíveis, especialmente aqueles sem caráter *drop-in*. O fato de o bunker fóssil ser um produto residual do refino exacerba essa tendência, já que a obtenção de cortes pesados do petróleo é tecnicamente inevitável enquanto houver produção de frações de maior valor agregado (e.g., nafta e querosene). Mesmo os cenários mais restritivos de IAMs globais mostram o petróleo detendo fração significativa (ainda que, em alguns casos, minoritária) do mercado de combustíveis marítimos pelo menos até 2050.
- Uma segunda tendência é a diversificação de vetores energéticos. Enquanto o atual suprimento se caracteriza por homogeneidade em nível global, as limitações associadas aos potenciais combustíveis alternativos tornam provável a coexistência de dois ou mais vetores energéticos marítimos ao longo do século 21. Isso poderia favorecer uma lógica de rotas ou corredores marítimos associados a combustíveis específicos. Ademais, é provável que um mesmo vetor envolva diferentes rotas de produção de acordo com a disponibilidade local de recursos (e.g., biomassa ou eletricidade renovável).

Em relação a vetores energéticos específicos, pode-se dizer que:

- Por dependerem de processos tecnologicamente dominados, biocombustíveis baseados em lipídios e triglicerídeos (e.g., biodiesel, SVO e HVO) podem ser estratégicos para uma redução em curto prazo das emissões de CO_2 do setor marítimo. Sua principal vantagem é a adequação a motores Diesel, o que possibilita o *blending* com combustíveis fósseis. No entanto, alguns desses combustíveis possuem qualidade inferior, o que limita o teor da mistura. Além disso, as culturas agrícolas que lhes dão origem, como a soja e a palma, envolvem risco de mudança do uso da terra (o que pode produzir aumento de emissões de GEEs).

- Em contraste com seu papel benéfico no contexto da IMO2020, o gás natural é um combustível com baixo potencial de mitigação climática. Ainda assim, boa parte das embarcações mercantes em construção utilizará motores aptos a operar com LNG, representando uma espécie de lock-in tecnológico. No cenário mais estrito produzido pelo COFFEE, por efeito de calibração, o LNG é marginalmente utilizado ao longo dos anos 2030 e 2040, dando em seguida espaço para combustíveis de menor intensidade de carbono (sobretudo bioálcoois e amônia verde). Uma possível rota tecnológica que se contrapõe a esse resultado é a gradual migração de LNG fóssil para LNG de base renovável (e.g., biometano).
- Inadequados à utilização em motores marítimos convencionais, etanol e metanol não se aplicam à maior parte da frota existente. Contudo, a acelerada disseminação de motores duais e a existência de uma infraestrutura dedicada a esses energéticos os torna uma solução interessante em médio prazo. Particularmente, o metanol, que possui rotas de produção a partir do metano, tem vantagens logísticas em comparação com o LNG, como o fato de ser líquido à temperatura ambiente. No cenário de mitigação profunda do COFFEE, álcoois renováveis representam mais de 20% da energia final do setor marítimo em 2050 (Tabela 22).
- Aventado como um meio de "eletrificação indireta" do transporte marítimo, o hidrogênio enfrenta diversas barreiras à sua utilização direta em larga escala, sendo sua baixa densidade energética volumétrica a principal delas. A conversão do gás em amônia atenua esse problema, já que o composto nitrogenado carrega mais átomos de hidrogênio do que o próprio hidrogênio molecular, além de ter menor ponto de fulgor. Contudo, a amônia também requer novas motorizações e é um combustível bastante tóxico. Nos cenários produzidos pelo COFFEE, em longo prazo (especialmente depois de 2050), o composto se torna o energético dominante do mix de combustíveis marítimos. Associada à ascensão de motorizações eletroquímicas (com melhor eficiência de conversão em comparação à combustão interna), a amônia responde, no cenário **C600**, por 22% da energia final do setor em 2070.

- A economia do hidrogênio também pode envolver combustíveis sintéticos *drop-in*, como eletrodiesel e eletrobunker. Embora tais energéticos sejam totalmente aplicáveis ao atual padrão tecnológico das embarcações, sua produção em eletrorrefinarias parece um conceito relativamente distante (baixa maturidade tecnológica, custo elevado e indisponibilidade de CO_2). Assim, esses combustíveis têm um problema de *timing*, pois sua maturação tecnológica ocorreria num momento em que seu grande diferencial já não seria tão relevante (e.g., pelo surgimento de motorizações adequadas a amônia e metanol).
- Finalmente, rotas avançadas de produção de bioenergia (e.g., síntese de Fischer-Tropsch e oligomerização de álcoois) têm condições de produzir combustíveis de alta qualidade a partir de recursos menos associados a riscos de mudanças de uso da terra (e.g., resíduos agrícolas e florestais). Limitadas por questões de maturidade tecnológica (e.g., gaseificação da biomassa lignocelulósica e posterior limpeza do gás de síntese), essas rotas ganham proeminência em cenários de mitigação a partir de 2040, quando a produção de nafta, querosene e diesel sintéticos se combina à captura de carbono a fim de prover emissões negativas (chegando a ~8 $GtCO_2$/ano de BECCS em 2070). No setor marítimo, isso se reflete pela presença de biobunker sintético, cuja participação no mix de energia final chega a 8% no mesmo ano. Analogamente ao que ocorre no setor petrolífero, esse combustível é um coproduto de biorrefinarias focadas em energéticos de maior valor agregado.

Tabela 22 – Participação de grupos de combustíveis marítimos no cenário C600 do COFFEE (%)

	2020	**2030**	**2050**	**2070**	**2100**
Bunker e diesel fóssil	97	83	61	44	47
Oleaginosas	0	3	7	6	4
LNG fóssil	3	14	0	0	0
Bioálcoois	0	0	21	15	13
Amônia e hidrogênio	0	0	8	27	19
Biocombustíveis avançados	0	0	3	8	17
Energia final (EJ/ano)	**9,0**	**10,0**	**9,5**	**12,1**	**15,6**

Especificamente em relação à modelagem integrada do transporte marítimo internacional, constatou-se que:

- O propósito de descarbonizar a navegação vem do objetivo mais amplo de limitar o aumento da temperatura superficial média global a níveis relativamente seguros. Embora metas setoriais como a IMO2050 sejam importantes, é essencial garantir uma integração intersetorial, de forma que a adição de tais metas implique uma alocação de recursos consistente e uma trajetória de emissões globais efetivamente descendente. O foco exclusivo em metas setoriais pode acarretar escolhas tecnológicas subótimas e até mesmo vazamento de emissões.
- Em cenários restritivos de IAMs, a penetração de combustíveis marítimos de baixo carbono é bastante acelerada entre 2030 e 2070, mas perde força no último terço do século. Isso se deve ao patamar alcançado globalmente por tecnologias de CDR (notadamente BECCS), cuja remoção de dióxido de carbono se encontra uma ordem de grandeza acima das emissões residuais do transporte marítimo. No cenário **C600** do COFFEE, há até mesmo um crescimento do consumo de combustíveis marítimos convencionais, que passa de ~5 EJ/ano em 2070 para ~7 EJ/ano em 2100.
- Conforme já discutido na literatura, a dependência de BECCS é um aspecto crítico dos cenários produzidos por IAMs. Neste trabalho, demonstrou-se que uma representação mais completa das opções de mitigação de um setor *hard-to-abate* pode reduzir suas emissões residuais, contribuindo para um emprego mais moderado de tecnologias de CDR, cuja escalabilidade é incerta. No artigo #4, por exemplo, verificou-se que IAMs globais que modelam um menor número de combustíveis marítimos tendem a promover uma descarbonização mais tímida da navegação. No entanto, o transporte marítimo é apenas um entre diversos setores *hard-to-abate*. Seguindo a mesma lógica do artigo #4, é provável que melhorias contínuas na representação de setores como aviação e indústria contribuam para uma atenuação da dependência de CDR.
- Especificamente no caso do COFFEE, a modelagem mais detalhada do transporte marítimo teve um interessante impacto de segunda ordem sobre o emprego de BECCS. Na versão anterior do modelo, a representação mais agregada da

navegação mercante permitia trocas inter-regionais de energéticos de forma relativamente livre. Assim, dado que o potencial associado à produção de bioenergia se concentra em algumas poucas regiões (como o Brasil), o COFFEE via bastante espaço para a exportação dessa bioenergia para o resto do mundo. Com a modelagem associada a esta tese, a otimização geral do modelo passou a levar em conta os custos de construção e operação das embarcações, restringindo de forma mais realista a troca de combustíveis líquidos. Combinado a outras atualizações do modelo, isso reduziu o emprego global de BECCS em cenários de descarbonização profunda.

- IAMs indicam que o nível de ambição refletido pela IMO2050 se revela consistente com o Acordo de Paris, especialmente diante da perspectiva de aumento da demanda por transporte marítimo. Por outro lado, premissas menos otimistas em relação a tecnologias de CDR possivelmente implicariam uma descarbonização mais intensa do setor. Isso é ilustrado pelos resultados do modelo PROMETHEUS (artigo #4). Por ter seu horizonte temporal limitado a 2050, esse modelo não vê grande espaço para tecnologias de CDR. Assim, em seu cenário mais restritivo, o PROMETHEUS projeta uma redução de emissões de 88% em 2050, indo além da IMO2050. Tal redução é possibilitada por um portfólio bastante diverso de combustíveis marítimos de baixo carbono.

Restringindo-se ao âmbito da modelagem desenvolvida no COFFEE, as principais limitações deste trabalho podem ser sumarizadas de acordo com os seguintes pontos:

- Conforme explorado no artigo #3, diferentes narrativas socioeconômicas têm impacto considerável sobre a demanda por transporte marítimo. Atualmente, os cenários produzidos pelo COFFEE adotam o SSP2, cujas premissas socioeconômicas são um meio-termo em relação aos outros quatro SSPs. Variações nas projeções de população, crescimento econômico, desenvolvimento tecnológico e nível de cooperação internacional poderiam alterar significativamente os resultados obtidos.
- Embora tenha aprimorado a representação do setor marítimo internacional em IAMs, a pesquisa desenvolvida ainda possui simplificações intrínsecas à modelagem integrada. Nesse sentido, apresenta grau de detalhamento inferior ao

de modelos setoriais ou à análise de embarcações/rotas específicas. Isso se expressa pelo grau de agregação de certas cargas (e.g., carga conteinerizada), pelo caráter exógeno de parte das projeções de demanda (e.g., minério de ferro, produtos químicos) e pela determinação *ex ante* da evolução da eficiência energética.

- IAMs inevitavelmente adotam hipóteses sobre a evolução futura da disponibilidade, do custo e da difusão de certas tecnologias. Diante do potencial disruptivo do desenvolvimento tecnológico, grandes transformações desses parâmetros no espaço de poucos anos podem alterar as perspectivas de cenários de mitigação. No caso do transporte marítimo, isso poderia ocorrer, por exemplo, com a rápida disseminação de motorizações alternativas ou com avanços nos sistemas de captura a bordo. Por outro lado, o desenvolvimento tecnológico pode ser mais lento do que o esperado, inviabilizando a consecução de objetivos fundamentados em cenários. Esse risco é particularmente relevante para tecnologias de CDR.

Em relação a estudos futuros, alguns pontos de interesse são:

- O desenvolvimento de cenários com premissas socioeconômicas mais variadas, incluindo, por exemplo, os outros quatro SSPs. Em particular, cenários de sustentabilidade global (e.g., SSP1) permitiriam análises de aspectos como reduções de demanda associadas a um consumo mais local ou regionalização do transporte marítimo.
- O desenvolvimento de cenários que restrinjam adicionalmente tecnologias de CDR, a fim de examinar o impacto de um menor potencial de emissões negativas sobre os requisitos de descarbonização do transporte marítimo.
- Uma melhor integração do transporte marítimo internacional com o setor industrial, criando demandas endógenas para produtos como minério de ferro, bauxita, fosfato e produtos químicos.
- A utilização do módulo de transporte marítimo do COFFEE para análise de potenciais mercados globais de energia renovável (e.g., hidrogênio e biocombustíveis lignocelulósicos) e de dióxido de carbono.

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Apêndice A

Portos representativos e matriz de distâncias

As informações são mostradas nas Tabelas 1, 2 e 3.

Tabela 1 – Portos representativos por região - origem

	AF	AU	BR	CA	CD	CP	CH	EU	IN	JP	KR	ME	RA	RU	SF	SM	US	XE
AF	-	Luanda	Luanda	Luanda	Luanda	Luanda	Luanda	Luanda	Luanda	Luanda	Luanda	Luanda	Luanda	Luanda	Luanda	Luanda	Luanda	Luanda
AU	Dampier	-	Dampier	Dampier	Dampier	Dampier	Dampier	Dampier	Dampier	Dampier	Dampier	Dampier	Dampier	Dampier	Dampier	Dampier	Dampier	Dampier
BR	Açu	Açu	-	Açu	Açu	Açu	Açu	Açu	Açu	Açu	Açu	Açu	Açu	Açu	Açu	Açu	Açu	Açu
CA	Dos Bocas	Dos Bocas	Dos Bocas	-	Dos Bocas	Dos Bocas	Dos Bocas	Dos Bocas	Dos Bocas	Dos Bocas	Dos Bocas	Dos Bocas	Dos Bocas	Dos Bocas	Dos Bocas	Dos Bocas	Dos Bocas	Dos Bocas
CD	Montréal	Vancouver	Montréal	Montréal	-	Montréal	Vancouver	Montréal	Montréal	Vancouver	Vancouver	Montréal	Vancouver	Montréal	Montréal	Montréal		Montréal
CP	Batumi	Batumi	Batumi	Batumi	Batumi	-		Batumi	Batumi	Batumi	Batumi		Batumi		Batumi	Batumi	Batumi	Batumi
CH	Qingdao	Qingdao	Qingdao	Qingdao	Qingdao		-	Qingdao	Qingdao	Qingdao	Qingdao	Qingdao	Qingdao	Qingdao	Qingdao	Qingdao	Qingdao	Qingdao
EU	Rotterdam	Rotterdam	Rotterdam	Rotterdam	Rotterdam	Rotterdam	Rotterdam	-	Rotterdam	Rotterdam	Rotterdam	Rotterdam	Rotterdam		Rotterdam	Rotterdam	Rotterdam	
IN	Kandla	Kandla	Kandla	Kandla	Kandla	Kandla	Kandla	Kandla	-	Kandla	Kandla	Kandla	Kandla	Kandla	Kandla	Kandla	Kandla	Kandla
JP	Chiba	Chiba	Chiba	Chiba	Chiba	Chiba	Chiba	Chiba	Chiba	-	Chiba	Chiba	Chiba	Chiba	Chiba	Chiba	Chiba	Chiba
KR	Busan	Busan	Busan	Busan	Busan	Busan	Busan	Busan	Busan	Busan	-	Busan	Busan	Busan	Busan	Busan	Busan	Busan
ME	Juaymah	Juaymah	Juaymah	Juaymah	Juaymah		Juaymah	Juaymah	Juaymah	Juaymah	Juaymah	-	Juaymah	Juaymah	Juaymah	Juaymah	Juaymah	Juaymah
RA	Singapore	Singapore	Singapore	Singapore	Singapore	Singapore	Singapore	Singapore	Singapore	Singapore	Singapore	Singapore	-	Singapore	Singapore	Singapore	Singapore	Singapore
RU	Novorossiysk	Kozmino	Novorossiysk	Novorossiysk	Novorossiysk		Kozmino		Novorossiysk	Kozmino	Kozmino	Novorossiysk	Kozmino	-	Novorossiysk	Novorossiysk	Novorossiysk	
SF	Saldanha	Saldanha	Saldanha	Saldanha	Saldanha	Saldanha	Saldanha	Saldanha	Saldanha	Saldanha	Saldanha	Saldanha	Saldanha	Saldanha	-	Saldanha	Saldanha	Saldanha
SM	Puerto Miranda	Puerto Miranda	Puerto Miranda	Puerto Miranda	Puerto Miranda	Puerto Miranda	Puerto Miranda	Puerto Miranda	Puerto Miranda	Puerto Miranda	Puerto Miranda	Puerto Miranda	Puerto Miranda	Puerto Miranda	Puerto Miranda	-	Puerto Miranda	Puerto Miranda
US	Galveston	Galveston	Galveston	Galveston		Galveston	Galveston	Galveston	Galveston	Galveston	Galveston	Galveston	Galveston	Galveston	Galveston	Galveston	-	Galveston
XE	Rijeka	Rijeka	Rijeka	Rijeka	Rijeka	Rijeka	Rijeka		Rijeka	Rijeka	Rijeka	Rijeka	Rijeka		Rijeka	Rijeka	Rijeka	-

Tabela 2 – Portos representativos por região - destino

	AF	AU	BR	CA	CD	CP	CH	EU	IN	JP	KR	ME	RA	RU	SF	SM	US	XE
AF	-	Brisbane	São Sebastião	Panama	Montréal	Batumi	Qingdao	Rotterdam	Kandla	Chiba	Busan	Juaymah	Singapore	Novorossiysk	Saldanha	San Antonio	Galveston	Rijeka
AU	Abidjan	-	São Sebastião	Panama	Montréal	Batumi	Qingdao	Rotterdam	Kandla	Chiba	Busan	Juaymah	Singapore	Novorossiysk	Saldanha	San Antonio	Galveston	Rijeka
BR	Abidjan	Brisbane	-	Panama	Montréal	Batumi	Qingdao	Rotterdam	Kandla	Chiba	Busan	Juaymah	Singapore	Novorossiysk	Saldanha	San Antonio	Galveston	Rijeka
CA	Abidjan	Brisbane	São Sebastião	-	Montréal	Batumi	Qingdao	Rotterdam	Kandla	Chiba	Busan	Juaymah	Singapore	Novorossiysk	Saldanha	San Antonio	Galveston	Rijeka
CD	Abidjan	Brisbane	São Sebastião	Panama	-	Batumi	Qingdao	Rotterdam	Kandla	Chiba	Busan	Juaymah	Singapore	Novorossiysk	Saldanha	San Antonio		Rijeka
CP	Abidjan	Brisbane	São Sebastião	Panama	Montréal	-		Rotterdam	Kandla	Chiba	Busan		Singapore		Saldanha	San Antonio	Galveston	Rijeka
CH	Abidjan	Brisbane	São Sebastião	Panama	Montréal		-	Rotterdam	Kandla	Chiba	Busan	Juaymah	Singapore	Kozmino	Saldanha	San Antonio	Galveston	Rijeka
EU	Abidjan	Brisbane	São Sebastião	Panama	Montréal	Batumi	Qingdao	-	Kandla	Chiba	Busan	Juaymah	Singapore		Saldanha	San Antonio	Galveston	
IN	Abidjan	Brisbane	São Sebastião	Panama	Montréal	Batumi	Qingdao	Rotterdam	-	Chiba	Busan	Juaymah	Singapore	Novorossiysk	Saldanha	San Antonio	Galveston	Rijeka
JP	Abidjan	Brisbane	São Sebastião	Panama	Montréal	Batumi	Qingdao	Rotterdam	Kandla	-	Busan	Juaymah	Singapore	Kozmino	Saldanha	San Antonio	Galveston	Rijeka
KR	Abidjan	Brisbane	São Sebastião	Panama	Montréal	Batumi	Qingdao	Rotterdam	Kandla	Chiba	-	Juaymah	Singapore	Kozmino	Saldanha	San Antonio	Galveston	Rijeka
ME	Abidjan	Brisbane	São Sebastião	Panama	Montréal		Qingdao	Rotterdam	Kandla	Chiba	Busan	-	Singapore	Novorossiysk	Saldanha	San Antonio	Galveston	Rijeka
RA	Abidjan	Brisbane	São Sebastião	Panama	Montréal	Batumi	Qingdao	Rotterdam	Kandla	Chiba	Busan	Juaymah	-	Kozmino	Saldanha	San Antonio	Galveston	Rijeka
RU	Abidjan	Brisbane	São Sebastião	Panama	Montréal		Qingdao		Kandla	Chiba	Busan	Juaymah	Singapore	-	Saldanha	San Antonio	Galveston	
SF	Abidjan	Brisbane	São Sebastião	Panama	Montréal	Batumi	Qingdao	Rotterdam	Kandla	Chiba	Busan	Juaymah	Singapore	Novorossiysk	-	San Antonio	Galveston	Rijeka
SM	Abidjan	Brisbane	São Sebastião	Panama	Montréal	Batumi	Qingdao	Rotterdam	Kandla	Chiba	Busan	Juaymah	Singapore	Novorossiysk	Saldanha	-	Galveston	Rijeka
US	Abidjan	Brisbane	São Sebastião	Panama		Batumi	Qingdao	Rotterdam	Kandla	Chiba	Busan	Juaymah	Singapore	Novorossiysk	Saldanha	San Antonio	-	Rijeka
XE	Abidjan	Brisbane	São Sebastião	Panama	Montréal	Batumi	Qingdao		Kandla	Chiba	Busan	Juaymah	Singapore		Saldanha	San Antonio	Galveston	-

Tabela 3 – Matriz de distâncias entre portos representativos

	AF	AU	BR	CA	CD	CP	CH	EU	IN	JP	KR	ME	RA	RU	SF	SM	US	XE
AF	0	8652	3481	5898	5929	6281	9519	4977	6301	9958	9559	6616	7202	6151	1548	6313	6681	5503
AU	7852	0	8509	10363	11196	7475	3582	9377	3990	3682	3535	4890	1660	7345	5233	8639	11700	7357
BR	3015	8128	0	4516	5472	6706	11252	5373	8034	11412	11292	8349	8935	6576	3363	3548	5410	5928
CA	5513	9165	5385	0	3318	7205	10025	5104	9688	9151	9523	9894	11746	7075	7404	4093	622	6427
CD	4689	6496	5472	3270	0	5566	5115	3290	8049	4275	4623	8255	7078	5436	7065	5873	1000	4788
CP	5039	9630	6706	7205	5566	0	1000	3747	4328	9293	8889	1000	6386	1000	6768	9394	7111	1698
CH	10595	4464	11252	10025	5115	1000	0	10751	5264	1115	502	6164	2463	1001	7976	10286	10100	8731
EU	3730	12018	5373	4893	3290	3747	10751	0	6230	11195	10791	6436	8288	1000	6113	7484	5009	1000
IN	7377	6549	6230	9307	8049	4328	5264	6230	0	5708	5304	1177	2801	4198	4758	12043	9594	4210
JP	11034	3945	11412	7889	4275	9293	1115	11195	5708	0	673	6608	2907	952	8415	9314	9226	9175
KR	10635	4182	11292	8261	4623	8889	502	10791	5304	673	0	6204	2503	509	8016	9883	9598	8771
ME	7692	7453	8349	9513	8255	1000	6164	11169	1177	6608	6204	0	4416	4404	5073	12936	9800	4416
RA	8278	3842	8935	10682	7078	6386	2463	8288	2801	2907	2503	4416	0	3007	5659	9961	11652	6268
RU	4909	4676	6576	6694	5436	1000	1001	1000	4198	952	509	4404	3007	0	6638	9264	6981	1000
SF	2628	7109	3363	6536	7065	6768	7976	6113	4758	8415	8016	5073	5659	6638	0	12271	7432	6647
SM	4106	8423	3886	808	2987	6263	9283	4413	8746	8409	8781	8952	10804	6133	5903	0	1789	5485
US	5468	9240	5410	1484	1000	7111	10100	5009	9594	9226	9598	9800	11652	6981	7432	4168	0	6333
XE	4261	9998	5928	6046	4788	1698	8731	1000	4210	9175	8771	4416	6268	1000	6647	8616	6333	0

Nota: Valores em milhas náuticas

Apêndice B

Material suplementar do artigo #4

Short description of global IAMs and their approach of international shipping

Table 1 shows key characteristics of the six global IAMs, while Table 2 reveals the energy carrier options for the international shipping sector represented in each model.

Table 1 – Key features of global IAMs

	Version	# of regions	Time horizon	Time step	Type	Solution method	Solution concept	Discount rate (%)	International shipping demand
COFFEE	1.5	18	2100	5 years until 2050, then, 10 years	Bottom-up	Intertemporal optimization with perfect foresight solved through linear programming	Partial equilibrium, focusing on energy, agriculture, and land use	5	Endogenous for main energy and agricultural products. General cargo driven by GDP
IMACLIM-R	2.0	12	2100	1 year	Hybrid	Recursive dynamic (myopic)	General equilibrium (closed economy)	n/a	Endogenous to trade activities of all economic sectors
IMAGE	3.2	26	2100	1 year	Bottom-up	Recursive dynamic	Partial equilibrium (price elastic demand)	10	Demand is projected with constant elasticity of the industry value added, and demand sensitivity to transport prices depends on its share of energy costs in

									the total service costs
PROMETHEUS	1.2	10	2050	1 year	Hybrid	Recursive dynamic	Energy system simulation model, focusing on demand and supply	8	Semi-endogenous driven by trade of energy products and GDP developments
TIAM		15	2100						
WITCH	5.0	17	2100	5 years	Hybrid	Intertemporal optimization with perfect foresight	General equilibrium	Ramsey rate (3-5%)	Demand evolution is based on calibrated income and price elasticities

Table 2 – Energy carrier options represented across IAMs

	COF	IMC	IMG	PMT	TIA	WTC
Heavy Fuel Oil (HFO)	**X**	**X**	**X**	**X**	**X**	**X**
Marine Diesel Oil (MDO)	**X**	**X**	**X**	**X**	**X**	**X**
Straight Vegetable Oil (SVO)	**X**			**X**		
Hydrotreated Vegetable Oil (HVO)	**X**		**X**	**X**		
Fatty Acid Methyl Esters (FAME)	**X**			**X**	**X**	
Biomass-to-Liquids Diesel (BtL-Diesel)	**X**	**X**	**X**	**X**		
Biomass-to-Liquids Heavy (BtL-Heavy)	**X**					
Hydrogen-Based Diesel (H_2-Diesel)	**X**			**X**		**X**
Hydrogen-Based Heavy (H_2-Heavy)	**X**					
Fossil Liquefied Natural Gas (Fossil LNG)	**X**			**X**	**X**	
Fossil Liquefied Petroleum Gas (Fossil LPG)	**X**					
Fossil Methanol	**X**					
Bio-Based Liquefied Natural Gas (Bio-LNG)				**X**		
Biomass-to-Liquids Liquefied Petroleum Gas (BtL-LPG)	**X**					
Biomethanol	**X**		**X**	**X**		**X**
Ethanol	**X**		**X**			
Hydrogen-Based Liquefied Natural Gas (H_2-LNG)				**X**	**X**	
Hydrogen-Based Liquefied Petroleum Gas (H_2-LPG)	**X**					
Hydrogen-Based Methanol	**X**					

Hydrogen	X		X	X	X	X
Ammonia	X			X	X	
Electricity				X		

COFFEE is a process-based [31] Integrated Assessment Model (IAM) based on intertemporal linear programming optimization. The model is designed to represent the global energy, industrial, agricultural, and land-use systems, which are divided into 18 geographical regions. In essence, COFFEE seeks to find the least costly configuration of the represented systems that satisfies the various demands and constraints specified as input. For each geographical region, the model receives a range of input data, including demographic trends, demand for services (e.g., food, mobility, and thermal comfort), technological developments (e.g., cost and efficiency curves of energy converters), and resource availability (e.g., biomass, coal, and oil). At the same time, COFFEE receives a variety of constraints associated with environmental aspects (e.g., carbon budget), institutional aspects (e.g., existing public policies), and historical aspects (calibration). Using this data and a predetermined discount rate, COFFEE returns the optimal configuration of the global energy, industrial, agricultural, and land-use systems over the period 2010-2100 for the given conditions [29], [42], [359].

In summary, the value of COFFEE as a modelling tool lies in its ability to identify the global minimum cost for expanding energy, industrial, agricultural, and land-use systems. By taking an integrated approach that considers the connections between these sectors, the model indicates mitigation strategies that are not limited to isolated sectors of the economy. As a result, the greenhouse gas (GHG) trajectories developed using this IAM are often distinct from those expected under a strictly sectoral perspective[36], [313].

Modelling maritime transportation presents a challenge due to the immense diversity of cargo (the Harmonized System lists over 5,000 product groups in international trade). In COFFEE, the modelling of the demand for international shipping is based on the following premises:

- The disaggregation of international trade according to physical (mass) or financial (value) criteria reveals significant differences. While commodities make up a considerable proportion of tonne-miles transported, their low added value causes their share to decrease considerably in the financial disaggregation. From the energy perspective adopted in COFFEE, a physical disaggregation of international shipping is more attractive.

- COFFEE is a modelling tool that places a strong emphasis on the energy sector, and its representation of energy chains is highly detailed. Given that energy cargoes account for nearly 40% of all international maritime transport tonne-miles [91], the maritime transport module places significant importance on these products.
- Some agricultural products (especially grains) are endogenously represented in COFFEE while also accounting for a significant fraction of international trade. For these commodities, demand for maritime transport is modelled endogenously.
- Container ships play a major role in international maritime transport, accounting for roughly 15% of total tonne-miles and consuming about 30% of the sector's final energy. Hence, an accurate representation of these vessels in the model is crucial.

Based on these premises, the list of products and associated vessels represented in COFFEE is shown in Table 3. The IMO GHG emissions inventory is used as a basis for historical calibration.

Table 3 – International shipping products represented in the COFFEE model

Product	**Vessel type**	**Demand type**
Light crude oil	Tankers	Endogenous
Medium sweet crude oil	Tankers	Endogenous
Medium sour crude oil	Tankers	Endogenous
Heavy crude oil	Tankers	Endogenous
Extra-heavy crude oil	Tankers	Endogenous
Fossil naphtha	Tankers	Endogenous
Green naphtha	Tankers	Endogenous
Fossil kerosene	Tankers	Endogenous
Green kerosene	Tankers	Endogenous
Fossil diesel	Tankers	Endogenous
Green diesel	Tankers	Endogenous

Fossil fuel oil	Tankers	Endogenous
Green fuel oil	Tankers	Endogenous
Fossil natural gas	Gas carriers	Endogenous
Green natural gas	Gas carriers	Endogenous
Bituminous coal	Bulk carriers	Endogenous
Sub-bituminous coal	Bulk carriers	Endogenous
Ethanol	Chemical tankers	Endogenous
Hydrogen	LH_2 ships	Endogenous
Wheat	Bulk carriers	Endogenous
Maize	Bulk carriers	Endogenous
Rice	Bulk carriers	Endogenous
Soybean	Bulk carriers	Endogenous
Other cereals	Bulk carriers	Endogenous
Steel	General cargo ships	Endogenous
Iron ore	Bulk carriers	Exogenous
Chemical products	Chemical tankers	Exogenous
Containers	Containerships	Exogenous
Vehicles	Pure Car Carriers	Exogenous
-	Cruise ships	Exogenous
Other	Bulk carriers	Exogenous

The energy modelling of ships is based on actual Energy Efficiency Operational Index (EEOI) values from the 4th IMO GHG inventory[62]. Combined with emission factors of conventional fuels, EEOI values can provide an estimation of engine brake energy per transport work (kWh/t-nm) for different cargoes/ship types. Combined with information on shipping distances and costs, these values allow the modelling of ten illustrative vessel motorizations. Each of these motorizations can work with specific fuels. In their turn, these fuels are divided into eight groups (bunker-like, diesel-like, ethanol, methanol, LNG, LPG, ammonia, and hydrogen). Like the rest of the energy system, the production of these fuels is modelled in the 18 regions of the COFFEE model. Most groups consist of fuels that can originate from either fossil or renewable sources.

IMACLIM-R is a **multi-sectoral Computable General Equilibrium (CGE) model**, hybrid with bottom-up sectoral modules (fossil fuel extraction, electricity, buildings, and transport). It represents the global economy as a set of 12 interconnected regional and national economies, each composed of 12 production sectors (also connected by input-output and trade links). It is primarily based on macroeconomic theory and draws inspiration from the Arrow-Debreu model, specifically regarding its emphasis on equilibria. It features consistent input-output accounting of both economic and physical energy flows, achieved by reconciling energy balances and national accounting data. The model simulates dynamic trajectories in yearly steps through the recursive and hard-linked succession of static macroeconomic equilibria and bottom-up sectoral modules. It explicitly represents the constraints affecting technical flexibilities and their interplay with macroeconomic trajectories by describing economic patterns in a world with market imperfections, partial use of production factors (labour and capital) and imperfect expectations for investment decisions. Within macroeconomic equilibria, a representative household in each regional economy aims to maximize its utility while considering economic and time budget constraints. To meet demand, productive sectors operate under short-term technical and productive capacity limitations. Between two economic equilibria, bottom-up modules use explicit technologies for the electricity and transport sectors to simulate technical adjustments to demand and price changes, considering imperfect foresight. The model utilizes a bottom-up approach for the representation of different power-producing technologies in the electricity sector, while energy-related technologies for buildings and road transport are taken into account on the demand side [360], [366].

The IMACLIM-R model represents the dynamics of the **maritime sector** through several distinct processes. Firstly, freight demand is influenced by international trade volumes of physical goods, particularly industrial and energy goods, which are determined by the structure of the world economy (including the degree of openness and distribution of production and consumption poles). Additionally, the price of freight transport, which is strongly influenced by energy carrier prices and energy efficiency, also affects freight demand. The technological advancement of the maritime fleet, such as the energy sources used and energy efficiency, is mainly determined by the relative prices of energy, including carbon taxation, and exogenous hypotheses for energy efficiency improvements. The current version of the model considers two types of energy carriers: conventional marine fuels and synthetic drop-in biofuels [360], [366].

IMAGE (Integrated Model to Assess the Global Environment) is a process-oriented integrated assessment model (IAM), providing an intermediate complexity representation of human and earth systems. The key components of the human system that largely contribute to greenhouse gas emissions are the energy system and the agricultural and land systems. The main drivers for the human system are demographic, economic, and technological developments, as well as resource availability, lifestyle changes and policy. For the earth system, the modelling framework is used to describe land cover, crop growth, carbon and water cycles and climate. The human and earth systems are interconnected by emissions and land use. The socio-economic processes and most of the human system parameters are described at the level of 26 world regions, while the earth system is modelled on a 5x5 minute grid for land use and land-use changes and on a 30x30 minute grid for plant growth and the carbon and water cycles. IMAGE operates in annual time steps and, as such, is suitable for long-term climate mitigation assessments up to 2100 [367].

The IMage Energy Regional (TIMER) model has been developed to explore scenarios for the energy system in the broader context of the IMAGE framework. TIMER describes 12 primary energy carriers in 26 world regions and is used to analyse long term trends in energy demand and supply in the context of the sustainable development challenges. The model simulates long-term trends in energy use, issues related to depletion, energy-related greenhouse gas and other air polluting emissions, together with land-use demand for energy crops. Based on historical trends, the demand for travel, housing, and specific materials described and related to regional economic and price developments, cultural factors, and demographic development. These services can be provided or produced in various ways, depending on resource availability, technology development, operation, and availability, amongst other things. The focus is on dynamic relationships in the energy system, such as inertia and learning-by-doing in capital stocks, depletion of the resource base and trade between regions. Like other IMAGE components, TIMER is a simulation model. The results obtained depend on a single set of deterministic algorithms, according to which the system state in any future year is derived entirely from previous system states.

The transport submodule consists of two parts – passenger and freight transport. Passenger transport modes include buses, bicycles, motorcycles, walking, trains, passenger vehicles and aircraft, and which mode people choose may depend on personal preferences, as well as on costs. If, for example, air travel would become more expensive due to the implementation of air passenger tax, or conversely would become cheaper due to technological developments, the kilometres travelled by air may decrease or increase, respectively. The freight transport submodule has a simpler structure. Service demand is projected with constant elasticity of the industry value added for each freight transport mode. In addition, demand sensitivity to transport prices is considered for each mode, depending on its share of energy costs in the total service costs. There are six freight transport modes: international shipping, domestic shipping, train, heavy truck, medium truck, and aircraft. In both passenger and freight submodules, vehicles with different energy efficiencies, costs, and fuel type characteristics, compete based on preferences and total passenger-kilometre costs, using a multinomial logit equation. These substitution processes describe the price induced energy efficiency changes. Over time efficient technologies become more competitive due to exogenous assumed decrease in cost, representing the autonomous induced energy efficiency. The efficiency of the transport fleet is determined by a weighted average of the full fleet (a vintage model, giving an explicit description of the efficiency in all single years). As each type of vehicle is assumed to use only one (or in case of a hybrid vehicle two) fuel type, this process also describes the fuel selection [54].

PROMETHEUS is a global energy system model covering in detail the complex interactions between energy demand, supply, and energy prices at the regional and global level. Its main objectives are: (1) to assess climate change mitigation pathways and low-emission strategies for the medium and long term; (2) analyse the energy system, economic, technology, and emission implications of a wide spectrum of energy and climate policy measures, differentiated by region and sector; and (3) quantify the impacts of climate policies on the evolution of global energy prices. PROMETHEUS quantifies CO2 emissions and incorporates emission abatement technologies (such as renewable energy, electric vehicles, Carbon Capture and Storage, energy efficiency, green hydrogen) and policy instruments, such as carbon pricing schemes or energy efficient standards that may differentiate by region and economic activity. The model can be used to assess energy and climate policies, as it endogenously represents detailed world and regional supply/demand dynamics and technology dynamics mechanisms focusing on low-carbon technologies (e.g., wind, solar PV, electric cars, CCS, advanced biofuels, hydrogen). PROMETHEUS is a recursive dynamic energy system simulation model. The economic decisions regarding the investment and operation of energy system are based on the current state of knowledge of parameters (costs and performance of technologies, etc.) or with a myopic anticipation of future costs and constraints. The PROMETHEUS model assumes market equilibrium, where each representative agent (e.g., energy producer or consumer) uses information on prices and makes decisions about the allocation of resources. The interactions of representative agents are governed by market dynamics with market derived prices to balance energy demand and supply in each sector (e.g., electricity production, transport, and energy industries). The regional fuel markets are integrated to form an international (global or regional) market equilibrium for crude oil, natural gas, and coal. The model produces projections of global and regional fuel prices, which depend on demand, supply, technology, and resources. PROMETHEUS is designed to provide medium- and long-term energy system projections and system restructuring up to 2050, both in the demand and the supply sides. The model produces analytical quantitative results in the form of detailed energy balances in the period 2020 to 2050 annually. The model can support impact assessment of specific energy and environment policies and measures, applied at regional and global level, including price signals, such as taxation, subsidies, technology, and energy efficiency promoting policies, RES supporting policies, environmental policies, and technology standards.

PROMETHEUS is significantly enhanced with an improved representation of international maritime, based on more granular modelling, the inclusion of various technologies, emission reduction options and low-emission fuels, and the integration of new data and information on mitigation potentials and activity projections from recent literature. In the shipping sector, PROMETHEUS distinguishes inland navigation and international shipping; activity in the latter is split by shipping segments, i.e., dry bulk carriers, general cargo, containers, and tankers. In the latter, activity is endogenously estimated in PROMETHEUS, driven by the regional trade of fossil fuels, while in other shipping segments activity is exogenous, calculated using GEM-E3 bilateral trade projections [368] mapped into PROMETHEUS regions. The activity of tankers depends on the evolution of fossil fuel trade across regions, which is determined endogenously as part of the global energy demand and supply projections of PROMETHEUS. This allows us to analyse the linkages between domestic climate policy and international shipping through the reduction of demand and thus international trade of fossil fuels.

In addition to the conventional fossil fuels (RFO, marine gas oil or LNG), new, low-emission, sustainable fuel types and clean vessel technologies are introduced in the model (e.g., biofuels, synthetic e-fuels, ammonia, hydrogen), whose uptake is triggered by ambitious climate policies and the introduction of emission or technology standards. The different technologies and fuels compete based on the evolution of their total costs, including capital, operating, fuel and carbon costs, technical efficiencies, energy densities and other characteristics (e.g., infrastructure barriers, innovation potentials). Energy efficiency is represented endogenously, based on technological improvement, operational efficiency, engine improvements, and increased energy prices. The various emission reduction options, including energy saving possibilities, speed reduction, and use of alternative low-emission fuels are introduced in the model, based on data from PRIMES-Maritime model [369], enabling PROMETHEUS to quantify the transformational dynamics in the shipping sector towards deep decarbonization.

TIAM-UCL [362] is an energy-economy model of the global energy system. It is built in the TIMES framework, a modelling framework that uses a linear programming optimisation approach to explore cost-optimal systems. Features of this formulation include perfect competition (no market power held by specific firms) and perfect foresight (market players have all information, now in the future, to inform investment decisions).

The representation of the global energy system includes primary energy sources (oil, gas, coal, nuclear, biomass, and renewables) from production through to their conversion (e.g., electricity production), their transport and distribution, and their eventual use to meet energy demands across a range of economic sectors. Using a scenario-based approach, the evolution of the system to meet future energy service demands (including mobility, lighting, residential and industrial heat and cooling), can be simulated, driven by the least-cost objective solution.

The model splits the globe up into 16 regions which allows for a detailed characterisation of regional energy sectors, and the trade flows between them. Future demands for energy services, which vary due to population, economic growth, and behavioural changes, drive the evolution of the energy system that must meet these demand requirements. These demands are dynamic, in that they can rise or fall in response to changes in the cost of providing energy services via the use of long run price elasticities. The model can also be hard linked to a simple CGE model to assess impacts of the energy system on the broader economy, and the subsequent feedback on energy demand. These two last features were not used in the present research.

Decisions around what energy sector investments to make across regions to meet these demands are determined based on the most cost-effective investments, considering the existing system in 2015, energy resource potential, technology availability, and crucially policy constraints such as emissions reduction targets or carbon budgets. The model solves to minimise the discounted total system cost over the full-time horizon of the model (ending in 2100), based on a discount factor of 3.5%.

The transport sector in TIAM-UCL is fully based on a cost-optimisation paradigm; it does not capture the preferences of consumers, vehicle purchase decisions are made based on capital, maintenance, and fuel costs alone. The model provides useful insights into the evolution of the transport sector and its implications on the whole energy system. The transport sector is characterized by 14 energy-services plus one non-energy use demand segment. The road transport sector considers two- and three-wheels vehicles, cars, light duty vehicles, commercial, medium, and heavy trucks, and buses. Additionally, the model considers rail transport of passengers and freight, domestic and international navigation as well as domestic and international aviation. The shift between transport modes is not possible in the standard TIAM-UCL version; each service demand is an exogenous model input (except for part of the international shipping sector as explained later). There is a range of fuels represented in TIAM-UCL to supply existing and new transport technologies, for all transport service demands: coal, natural gas, LPG, gasoline, diesel, kerosene, heavy fuel oil, electricity, bioethanol, biodiesel, hydrogen, various synthetic fuels, and methanol. These fuels have a supply chain and system architecture associated, from the upstream sector through to end-use services.

More precisely, for the shipping sector, TIAM-UCL distinguishes domestic and international shipping, the latter is the sector analysed in this study. The activity in the international shipping is split by trade types as followed: non-energy commodities transport and energy related commodities. For the first subsector (non-energy commodities) activity is exogenous, calculated and mapped into TIAM-UCL regions using trade projections from the sectoral model GloTraM [370] developed at UCL. For the energy commodities related trade, activity is endogenously estimated in model, driven by the international trade of fossil fuels and other energy vectors (e.g., low carbon fuel or biomass for bioenergy feedstock). In addition to conventional fossil fuels (HFO, diesel, gasoline, and LNG) the sector can access new, low-emission, sustainable fuel types (biodiesel, synfuels (diesel, gasoline, or LNG), ammonia or hydrogen). The emission reduction by use of alternative low-emission fuels is based on fuel price, carbon prices and feedstock/policy constraints introduced in the model. Ship and logistic efficiency (technological and operational improvements) are introduced exogenously in the model extracted from GloTraM scenarios.

The WITCH integrated model is a comprehensive tool designed to examine the complex interplay between climate change, energy systems, and economic development. With a hybrid structure that combines top-down economic representation and bottom-up energy system detail, it is a valuable resource for policymakers and researchers.

WITCH is a hybrid model that merges a top-down representation of the economy with a bottom-up representation of the energy system. The top-down component includes an intertemporal optimization model that accounts for macroeconomic interactions and dynamics, while the bottom-up component captures the technological details of the energy sector. The model employs a cost-effectiveness optimization method to minimize total discounted global costs associated with meeting specific climate and energy objectives. This approach considers various factors, such as investment, capital, and operational costs, in addition to climate change damages and policy costs like carbon pricing.

The model divides the world into representative native regions or coalitions and generates optimal mitigation and adaptation strategies from 2005 to 2100 in response to climate damage or emission constraints. Strategies result from a maximization process involving regional welfare, capturing regional free-riding behaviours and strategic interactions induced by global externalities. An iterative algorithm implements the open-loop Nash equilibrium in a non-cooperative, simultaneous, open membership game with full information.

WITCH features endogenous R&D diffusion and innovation processes for energy efficiency and carbon-free technologies, capturing multiple externalities in climate and innovation. Technology externalities are modelled through international spill overs of knowledge and experience. Low carbon mitigation technologies and energy productivity in each country depending on the region's energy R&D stock and global cumulative installed capacity. The model uses a social planner to maximize the sum of regional discounted utility, with a constant relative risk aversion (CRRA) utility function derived from per-capita consumption. The economy produces a single commodity, with final goods produced via a nested CES function combining capital, labour, and energy services. Climate impacts affect gross output, with fossil fuel and GHG mitigation costs subtracted from them. Energy services are provided by a combination of physical energy input and a stock of energy efficiency knowledge.

The energy system in WITCH is characterized by a detailed representation of primary energy sources, conversion technologies, and end-use sectors. It includes a wide range of energy carriers (e.g., coal, oil, natural gas, nuclear, and renewables) and technologies for power generation, transportation, and other end-use sectors. The model also captures technological progress and energy efficiency improvements over time.

The transportation sector in the model includes road transport (both passenger-duty vehicles and heavy-duty vehicles), international aviation, and a preliminary version of international shipping. Currently, Shipping demand for each region in the base year is the total global demand allocated with respect to its GDP share [tonne. mile/year]. Then, demand for future time steps is estimated by using the elasticity of GDP (as a proxy of income). Elasticities are distinguished for different cargo types in the model. Also, regions are divided into high-income, mid-income, and low-income, and each one of them has specific income elasticity on demand. Efficiency improvement of the fleet is exogenous, kept constant at around 2%/year. On the supply side, the sector has only access to oil-based traditional fuels, biofuels, hydrogen, and renewable hydrocarbons, and ships have fixed investment expenses.

The international shipping module within the model is currently in its early stages and remains highly aggregated. Ongoing development aims to enhance the module by incorporating bilateral trade analysis between regions/countries, identifying elasticities affecting individual trade demand types, modelling port demand areas for future expansion and associated investment requirements, vessel categories and their specific parameters as well as potential cost reduction, establishing production infrastructure and supply chains for more alternative fuels options (e.g., ammonia, bio-LNG, etc.).

Comparison of adopted carbon budgets with the Sixth Assessment Report of the IPCC

The choice of carbon budget values is based on model capabilities and warming categories, as defined by the IPCC in its latest assessment report [2], [21]. As indicated by Table 4, **C600** scenarios can be seen as in line with a warming of 1.5°C or slightly above (since it lies between C1 and C2) while **C1000** scenarios would reflect a world likely below 2°C (lying between C3 and C4). More ambitious carbon budgets (e.g., 400 $GtCO_2$) are not used because most of our models are currently not able to find solutions below 600 $GtCO_2$, especially with a peak budget (i.e., without overreliance on CDR). Finally, it is worth noting that none of the scenarios include IMO2050 as a restriction, since one of our aims is to compare the model results to this target.

Table 4 – IPCC AR6 warming categories

Category	Description	Cumulative CO_2 emissions (Gt)	
		2020 to net zero CO_2	2020-2100
C1	Limit warming to 1.5°C (>50%) with no or limited overshoot	510 [330 to 710]	320 [-210 to 710]
C2	Return warming to 1.5°C (>50%) after a high overshoot	720 [530 to 930]	400 [-90 to 620]
C3	Limit warming to 2°C (>67%)	890 [640 to 1,160]	800 [510 to 1,140]
C4	Limit warming to 2°C (>50%)	1,210 [970 to 1,490]	1,160 [700 to 1,490]

Detailed results for BECCS

Except for PROMETHEUS (whose time horizon is 2050), all models project international shipping emissions to approximately stabilize in the second half of the century, both in **C1000** and **C600** scenarios. This pattern is due to the rise of Bioenergy with Carbon Capture and Storage (BECCS) after 2040. As explained before, our carbon budget scenarios do not allow net negative emissions. However, this does not exclude the use of some level of CDR strategies in these scenarios. In a peak-budget scenario, once the carbon budget is depleted, eventual residual emissions must necessarily be compensated by CDR strategies to hold net CO_2 emissions equal to zero. In the pathways modelled by our IAMs, this is ensured by the deployment of BECCS, with CO_2 removals in the range of 1.6-9.6 Gt/yr in 2050, 4.1-14.5 Gt/yr in 2070 and 3.6-18.4 Gt/yr in 2090. In the case of WITCH, Direct Air Capture with Carbon Storage (DACCS) also plays a relevant role, with global removals in 2070 around 1.0 $GtCO_2$/yr (**C1000** scenario) and 1.7 $GtCO_2$/yr (**C600** scenario). Typically, BECCS and DACCS gradually escalate between 2040 and 2060, reaching their height towards the end of the century. In Figures 1-6, we compare the annual CO_2 removal by BECCS with residual CO_2 emissions from shipping in 2050, 2070 and 2090. While shipping annual emissions are comparable to BECCS in 2050, they are no more than 13% of the CDR achieved by BECCS in 2090. This finding should be tempered by the uncertainties surrounding the large-scale deployment of BECCS (e.g., land and water requirements[355], [356]) and DACCS (e.g., chemicals availability, technological maturity and water requirements[254], [371]). Restrictions on the diffusion and implementation of these technologies would mean a higher decarbonisation pressure on the shipping sector.

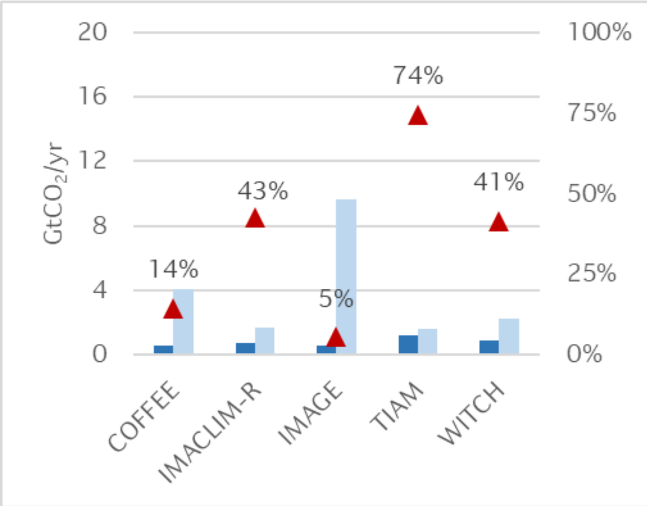


Figure 1 – International shipping emissions (dark) compared to annual CO_2 removal through BECCS in 2050 (light). Red triangles indicate the proportions between these two values – C1000 scenarios

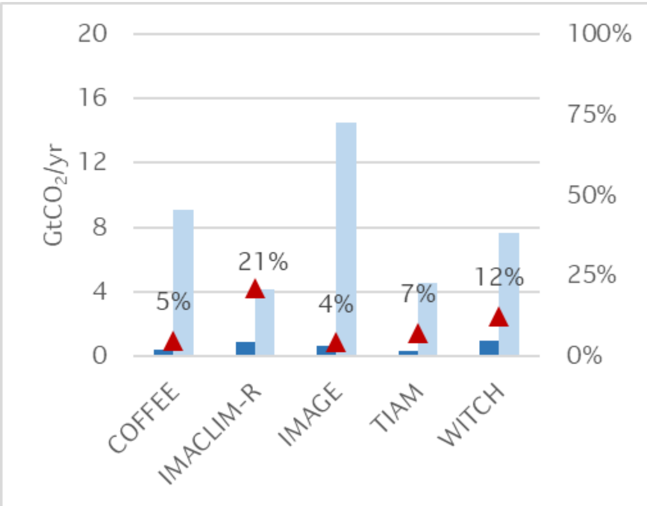


Figure 2 – International shipping emissions (dark) compared to annual CO_2 removal through BECCS in 2070 (light). Red triangles indicate the proportions between these two values – C1000 scenarios

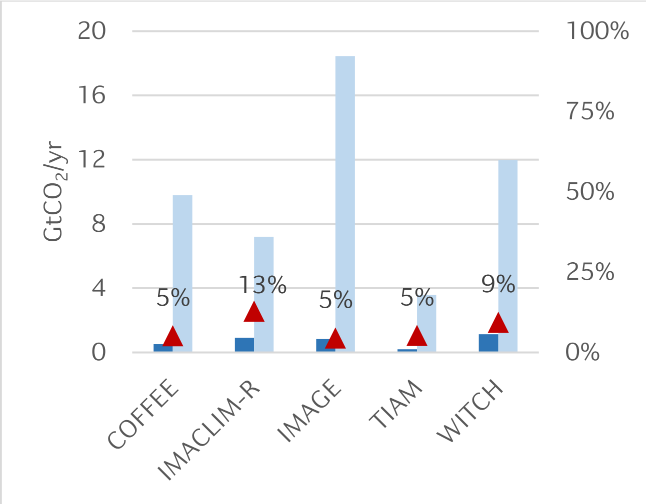


Figure 3 – International shipping emissions (dark) compared to annual CO_2 removal through BECCS in 2090 (light). Red triangles indicate the proportions between these two values – C1000 scenarios

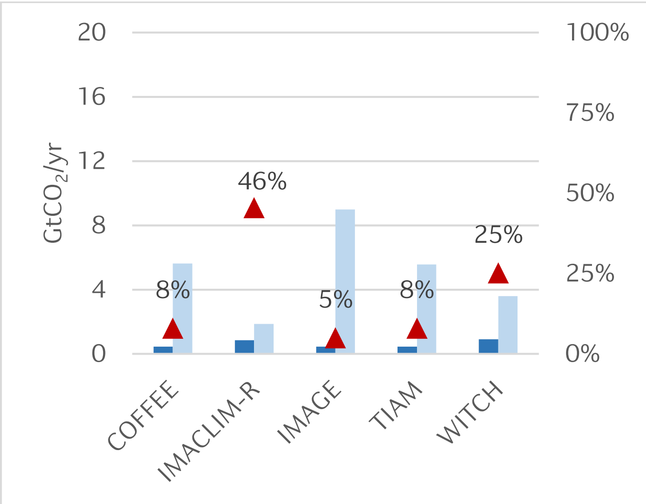


Figure 4 – International shipping emissions (dark) compared to annual CO_2 removal through BECCS in 2050 (light). Red triangles indicate the proportions between these two values – C600 scenarios

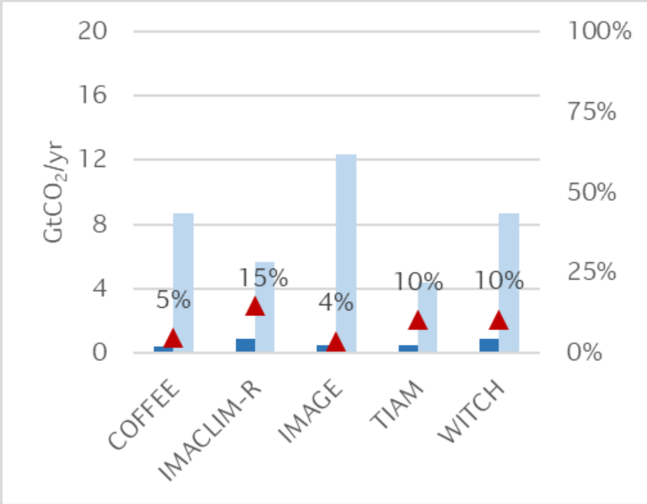


Figure 5 – International shipping emissions (dark) compared to annual CO_2 removal through BECCS in 2070 (light). Red triangles indicate the proportions between these two values – C600 scenarios

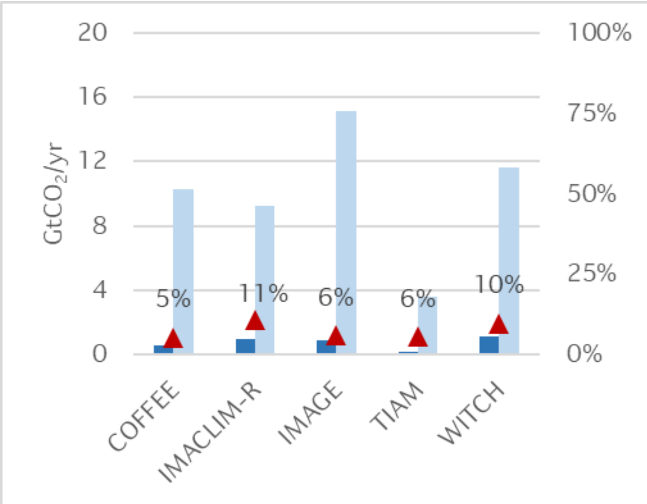


Figure 6 – International shipping emissions (dark) compared to annual CO_2 removal through BECCS in 2090 (light). Red triangles indicate the proportions between these two values – C600 scenarios

Fuel aggregation

In recent years, international shipping demanded on average 9 EJ/yr of fossil energy, with 95% of this total coming from two petroleum products, Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO)[62]. In terms of gross tonnage, 95% of the existing fleet and 67% of the order book are composed by vessels based on conventional powertrains, i.e., compression ignition engines suited to HFO, MGO and similar fuels [101]. Moreover, most oceangoing ships in operation are less than 15 years old, meaning that the world fleet will likely maintain its fuel technological standard until 2035, at the very least.

Over the last decade, LNG started to be regarded as the main alternative to conventional bunker fuels, especially because of its low impact when it comes to atmospheric pollution (e.g., SOx). Although HFO and MGO are still dominant, the dissemination of dual-fuel engines has been gradually increasing LNG's share in the world fleet. As of today, more than 5% of the existing fleet and 30% of the order book correspond to vessels designed to use LNG. Nevertheless, the mitigation potential of natural gas is relatively poor, with a carbon intensity slightly lower than that of petroleum products[116]. Furthermore, depending on engine types, methane slip can make LNG's overall climate performance equal or worse than that of HFO and MGO [116].

In scenarios projecting a deep decarbonization of shipping, there is typically a marine fuel switch towards low-carbon alternatives. However, across scenarios, these alternatives vary widely both in terms of primary resources and final energy carriers, making the role of low-carbon fuels relatively unclear. Since energy balances and low-carbon technologies lie at the heart of IAMs, we concentrate our analysis on this aspect, investigating how the marine fuel mix should evolve throughout the next decades to be compatible with carbon budgets of 600 and 1,000 $GtCO_2$.

Since the modelling of fuel conversion processes is not identical across the six IAMs, we use energy carrier categories to harmonize and compare our results (Table 5). These categories seek to group fuels according to common features, such as feedstock type, energy density and applicability. The **Conv** category, for example, corresponds to conventional fuels based on petroleum, such as HFO and MDO. The **Oilseed** category represents fuels based on vegetable oils obtained from the seed of plants such as palm, soybean, and sunflower, and eventually also from animal fats such as beef tallow. The **D-synt bio** and **D-synt other** categories include fully drop-in renewable fuels produced through advanced processes such as the Fischer-Tropsch synthesis that are chemically indistinguishable from HFO/MDO. While the former relates to biobased feedstocks, the latter includes every other type of resource, most notably renewable-based electricity. The three **AG** categories correspond to groups of alcohols and gases (e.g., ethanol, methanol, and LNG), whose use in ships is typically made possible using dual-fuel engines. As in the case of drop-in fuels, they differ from each other by the type of primary source. Finally, the **H_2/NH_3** category corresponds to hydrogen and ammonia, while the **Elec** category refers to the direct use of electricity.

Table 5 – Fuels

Group	Description	Examples
Conv	Conventional marine fuels	Heavy Fuel Oil (HFO) Marine Diesel Oil (MDO) Marine Gas Oil (MGO)
Oilseed	Animal fats- and oilseed-based fuels	Biodiesel Hydrotreated Vegetable Oil (HVO) Straight Vegetable Oil (SVO)
D-synt bio	Synthetic drop-in biofuels	Biomass-to-Liquids diesel (BtL-diesel) Biomass-to-Liquids heavy (BtL-heavy)
D-synt other	Other drop-in synthetic fuels	Power-to-Liquids diesel (e-diesel) Power-to-Liquids heavy (e-heavy)
AG-fos	Fossil alcohol and gases	Fossil Liquified Natural Gas (LNG) Fossil Liquefied Petroleum Gas (LPG) Fossil methanol
AG-bio	Bio-alcohols and biogases	Bio-LNG Biomethanol Ethanol
AG-synt	Synthetic alcohols and gases	Power-to-Gas LNG (e-LNG) Power-to-Gas LPG (e-LPG) Power-to-Liquids methanol (e-methanol)
H_2/NH_3	Hydrogen and ammonia	Hydrogen Ammonia
Elec	Electricity	Electricity

Detailed results for Europe

The aim of the PRIMES-Maritime model is to perform long-term energy and emission projections, until 2050, for each EU MS separately. The coverage of the model includes the European intra-EU maritime sector as well as the extra-EU maritime trade. PRIMES-

Maritime focuses only on the EU MS and the extra-EU trade coming in and out of the EU. The model consists of a modular structure:

1. The **demand module** projects maritime activity for each EU MS by type of cargo and by corresponding partner. Econometrical functions relate future demand for maritime transport services with economic drivers including GDP, energy demand (oil, coal, LNG), international fuel prices, and bilateral trade by type of product.
2. The **supply module** simulates a virtual operator controlling the EU fleet, which performs the requested maritime transport services and allocates the vessels to activities in the various markets (the EU MS and the extra-EU area that trades with the EU) where different regulatory regimes may apply (e.g., ECA zones).

The policy input includes emissions (CO_2, air pollution) and energy efficiency standards (EEDI for new vessels, SEEMP), fuel standards and potential fuel mandates. The fleet of vessels disaggregates into several categories depending on cargo types.

The model is dynamic solving for the balance between supply and demand, considering vessel vintages and fleet renewal requirements with a stock-flow relationship. Capital turnover is explicit in the model influencing the pace of fuel substitution. Choice of fuel mix for new vessels is based on technoeconomic assumptions applying discrete choice modelling. The model projects bunkers consumption across fuel types and derived WtT and TtW GHG emissions, including methane slippage emissions from combustion. Energy consumption is based on specific fuel consumption functions, which use cost-efficiency curves to summarize efficiency possibilities.

This subsection presents results for the EU region based on the bottom-up model PRIMES-Maritime. The model projects energy and ship-generated emissions until 2050, covering intra-European and extra-European maritime shipping activity. While regional in scope, the modelling results can shed light onto the fuel and technology portfolio required to decarbonize the European maritime sector[372].

Three scenarios are quantified with PRIMES-Maritime and are aligned with the scenario narratives of the global IAMs presented in the article, namely:

- **NDCi**: represents a "no policy change" scenario largely aligned with the EU Reference scenario 2020[373], reflecting EU and national policies adopted by the end of 2019
- **NDCi_1000**: aligned with an ambitious emission reduction trajectory in which policies are in place (e.g., technology neutral GHG emissions reduction target for the bunker fuel mix, carbon price), and is closely aligned with the region's ambition to achieve net zero emissions by mid-century[374]
- **NDCi_600**: which includes a more ambitious GHG emissions reduction trajectory compared to NDCi_1000, such that the international maritime sector complies with more stringent carbon budgets in the period to 2050

The results show a reduction in energy demand, owing primarily due to the adoption of more efficient technologies and partly due to a reduction in activity of about 2% lower in the decarbonization scenarios compared to NDCi in 2050. The reduction in energy demand in the decarbonization scenarios compared to the no policy change scenario is already noticeable in 2025, when alternative and more costly fuels penetrate the bunker fuel mix, and the difference increases over the time horizon (i.e., about 14% in 2050) (Figure 7).

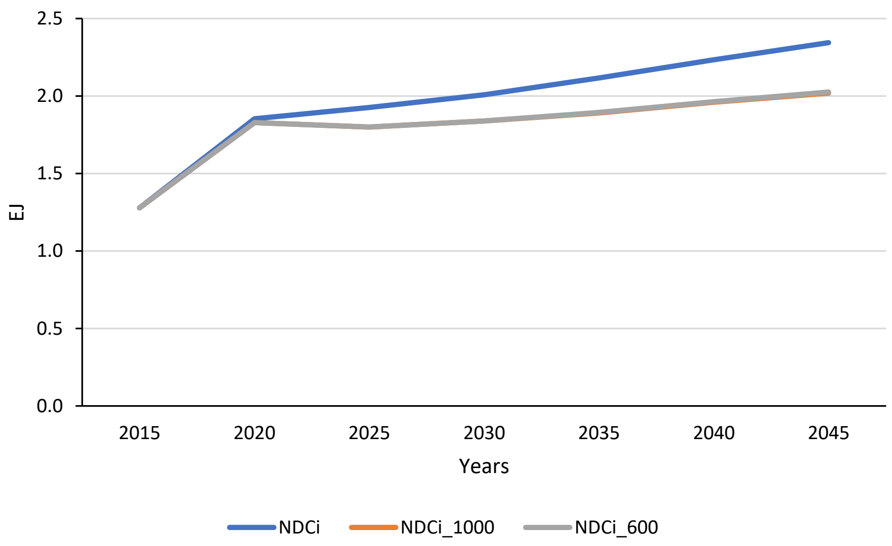


Figure 7 – Energy demand in the EU international maritime sector

In 2050, the composition of bunker fuels differs drastically between the scenarios. In the NDCi, fossil fuels maintain their high share, as they comprise 99% of the fuel mix (80%

conventional liquid and 19% gaseous fuels). In the decarbonization scenario NDCi_1000, biofuels make up about 46% of the mix, in their majority as drop-in liquid fuels, synthetic fuels contribute about 33% and electricity makes up the reminder 2% of the alternative fuel mix. In NDCi_600 the more stringent carbon budget leads to an additional uptake of synthetic fuels mainly to the detriment of fossil fuels, but also to biomethane and H2 and NH3 (Figure 8). Consumption of alternative fuels is about 12% higher in NDCi_600 compared to NDCi_1000.

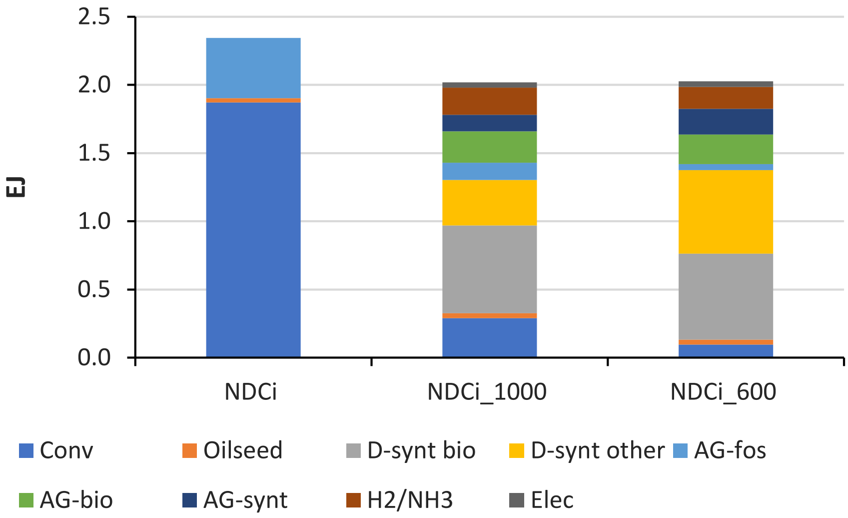
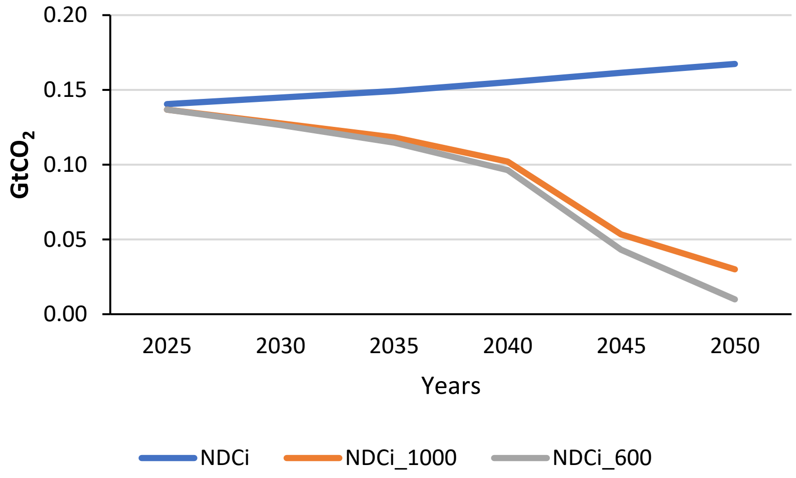


Figure 8 – EU international maritime bunker fuel composition in 2050

The projections show that in NDCi, without efforts to decarbonize the EU maritime sector, emissions may reach 0.17 $GtCO_2$ in 2050, growing by 0.7% annually. Cumulative emissions may reach almost 4 $GtCO_2$ in the period 2021-2050. With long-term decarbonization efforts, the emissions peak in 2025 and decline by 6% annually in NDCi_1000 or 10% annually in NDCi_600 so as to reach 0.03 $GtCO_2$ and 0.01 $GtCO_2$ in 2050, respectively. The difference on cumulative emissions between the decarbonization scenarios is comparably small as NDCi_600 leads to lower cumulative emissions by 7% (or 0.16 $GtCO_2$ in 2021-2050) compared to NDCi_1000. Compared to NDCi, cumulative emissions are notably lower (i.e., between 38 and 42%), driven by the early adoption of measures that lead to the decarbonization of the bunker fuel mix (Figure 9).



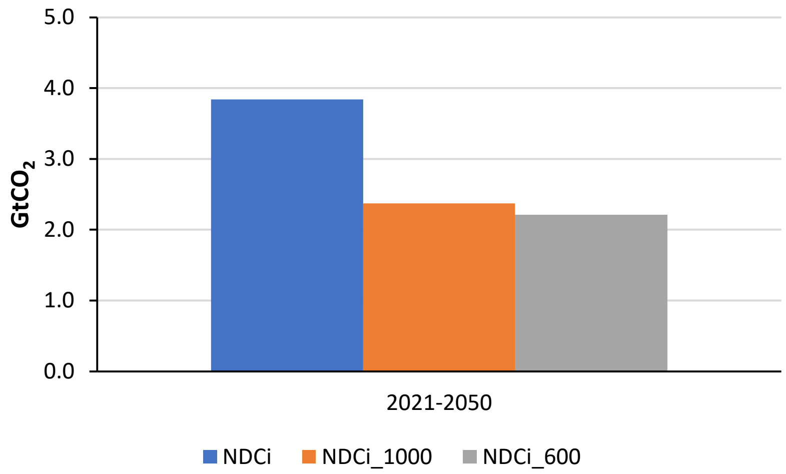


Figure 9 – CO_2 emissions trajectory and cumulative CO_2 emissions across scenarios