

Investeringsaftale

(Innomission)

MissionGreenFuels

Sagsnummer: 3207-00004B
Side 1 of 20

Mellem

Innovationsfonden

Europahuset

Europaplads 2, 4. Sal

DK – 8000 Aarhus

CVR-nr.: 29 03 56 95

(herefter benævnt "Fonden")

og

Aalborg Universitet

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9220 Aalborg Ø

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(herefter benævnt "AAU")

er der med virkning fra 01-01-2025 indgået følgende investeringsaftale fra Fonden til partnerskabet MissionGreenFuels.

| | |
|--------------------------|-------------------------|
| Investering fra IFD | 57 643 750 DKK |
| Projektperiode | 01-01-2025 – 14-06-2028 |
| Administrator (P-nummer) | 1003888250 |

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1. Bilagsfortegnelse

Bilag 1: Beskrivelse af temaer under investeringen inkl. mål og milepæle for anvendelse af investeringen samt temaernes/disses bidrag til indfrielsen af mål i Roadmap

Bilag 2: Budget

Bilag 3: Governance for udvælgelse af projekter

Bilag 4: Roadmap for partnerskabet

2. Definitioner

Følgende definitioner finder anvendelse:

"Administrator": Den juridiske enhed, der i henhold til Aftalens øvrige vilkår, herunder afsnit 6 nedenfor, varetager en række praktiske funktioner i relation til Partnerskabets forvaltning og videreformidling af Innovationsfondens investeringsbeløb.

"Afslutningsrapport": En rapport udarbejdet af Partnerskabet ved Investeringsperiodens afslutning, som indeholder en beskrivelse af hvilke mål og milepæle, der er opnået med denne investering.

"Aftalen": Denne Investeringsaftale og dens tilhørende bilag, samt efterfølgende ændringer til nævnte dokumenter og det øvrige Bevillingsgrundlag.

"Annual Investment Review": Det årlige møde mellem Partnerskabet og Innovationsfondens bestyrelse, hvor Partnerskabets fremdrift og målopfyldelse diskuteres og vurderes.

"AIR rapport": Rapport som sendes forud for Annual Investment Review, som omfatter Partnerskabets resultater og læring fra de foregående år.

"Aktiviteter": De elementer som Partnerskabet har finansieret, som omfatter både forsknings- og udviklingsprojekter og missions- eller partnerskabsunderstøttende aktiviteter.

"Bevillingsgrundlag": Opslag og opslagsmateriale for Innomissions call 2 hhv. call 3 2023, herunder Innomission 2023 retningslinjer, ansøgningsmateriale, bevillingsbrev og denne aftale inkl. bilag.

"Budget"/"Budgettet": Investeringsens samlede budget vedlagt Investeringsaftalen som bilag 2.

"Fonden": Den af Uddannelses- og Forskningsministeren i medfør af Lov nr. 306 af 29. marts 2014 oprettede Danmarks Innovationsfond.

"Generalforsamling": Den samlede kreds af stemmeberettigede partnere, som bestemmer sammensætning af Partnerskabets bestyrelse og kan godkende ændringer til Partnerskabsaftalen.

"Investeringsaftalen": Denne investeringsaftale samt senere ændringer hertil, men eksklusive dens bilag. Se endvidere definitionen af "Aftalen".

"Investeringskriterier": Betyder de vilkår og kriterier, herunder vurderingskriterier, og de forudsætninger, som Fonden har lagt til grund for investeringen i Partnerskabet, og som fremgår af Innomission Call 2 og 3 i 2023 og de dertilhørende retningslinjer 'Guidelines Innomissions' offentliggjort 20 september 2023.

"Investeringsperioden": Perioden for Fondens investering i Partnerskabet defineret i punkt 11.1.

"Investment Officer": Den eller de af Fonden udpegede repræsentant(er) for Fonden, som undervejs i Investeringsperioden har løbende dialog med Partnerskabsdirektøren, og som deltager i bestyrelsesmøder i Partnerskabet.

"Koordinator": Den juridiske enhed, som repræsenterer Partnerskabet, og indgår aftale med Fonden om investeringen, og som indgår aftale med partnere om finansiering af projekter.

"Partnerskabet": Et af de fire Innomission partnerskaber, INNO-CCUS, MissionGreenFuels, AgriFoodTure eller TRACE, etableret i forbindelse med opslaget 'Call for Mission-driven green research and innovation partnerships' i efteråret 2021.

"Partnerskabets bestyrelse": Den af Partnerskabet nedsatte bestyrelse som valgt på partnerskabets Generalforsamling, og som kan tage beslutninger om tildeling og afslutning af projekter og sikrer, at Aktiviteterne bidrager til opfyldelse af Partnerskabets formål.

"Partnerskabsaftale": Den aftale mellem partnerne i Partnerskabet, som regulerer partnernes indbyrdes rettigheder og forpligtelser i relation til Partnerskabet.

"Partnerskabsdirektøren": Direktøren for Partnerskabets sekretariat, som er udpeget af Partnerskabets bestyrelse.

"Partnership Plan": Plan som indeholder og beskriver de elementer af Roadmap, som Partnerskabet fokuserer på gennem investeringer fra Fonden.

"Projekt": Betegnelse for et konkret forsknings- og innovationsprojekt, som bliver finansieret af investeringen til Partnerskabet.

"Projektaftalen": Aftalen om finansiering og udførelse af et Projekt indgået mellem Partnerskabet og en eller flere Projektpartnere. Aftalen skal beskrive hvilke aktiviteter, der finansieres og, hvilke vilkår der gælder for udførelsen.

"Projektpartner": Deltagere i et Projekt under Partnerskabet som projekt partner eller projektbidrager.

"Roadmap": Dokumentet, som beskriver Partnerskabets plan for at komme i mål med missionen. Roadmap gennemgår opdatering løbende, og kan bruges som styringsværktøj til udvælgelse af aktiviteter.

"Sekretariat": Medarbejdere, som er ansat i Partnerskabet til håndtering af den daglige drift af Partnerskabet og opfølgning på projekter.

"Styregruppe": Repræsentanter for de enkelte partnere i et projekt, som kan anmode partnerskabet om ændringer i projektets udførelse eller budget.

"Udbetalingsanmodninger": Anmodning om beløb til udbetaling til Administrator, som er baseret på udgifter afholdt af Partnere i forbindelse med projekter eller administration.

"Årsrapport": En rapport indeholdende den i punkt 9.2.4 specificerede årlige afrapportering.

Med mindre andet specifikt er angivet, skal henvisninger til punkter heri anses for henvisninger til punkter i Investeringsaftalen. Henvisning til bilag er, med mindre andet specifikt er angivet, henvisning til bilag til Investeringsaftalen. Henvisninger til love og regler skal anses for henvisninger til gældende love og regler med senere ændringer.

3. Baggrund og formål

Formålet med Aftalen er at fastlægge vilkårene for Fondens investering i Partnerskabet, herunder Partnerskabets modtagelse, administration og videre fordeling af Fondens investering.

4. Investeringens størrelse og anvendelse

4.1. Investeringens størrelse

Fonden investerer 57 643 750 DKK i Partnerskabet i Investeringsperioden.

4.2. Anvendelse af investeringen

4.2.1. Investeringen skal anvendes i overensstemmelse med Budgettet i bilag 2.
Investeringen skal dermed overordnet anvendes til følgende to formål:

- Investeringen skal videreformidles af Partnerskabet til konkrete Projekter, som bidrager til opfyldelse af investeringens mål og milepæle samt mål i Roadmap som specificeret i bilag 1.
- En mindre del af investeringen kan anvendes til at dække udgifter for Partnerskabet til eksterne vurderinger af projektforslag og forfølgelse af retslige krav imod partnere jf. afsnit 8.6.2.

4.2.2. Partnerskabet skal påse, at Partnerskabets videre fordeling af Fondens investering sker i overensstemmelse med den statsstøtteretlige regulering, og den videre fordeling kan således alene ske til ikke-økonomiske aktiviteter, til aktiviteter indeholdt i artikel 25 i Gruppefritagelsesforordningen eller i De Minimis-forordning. Fonden følger op på, at den statsstøtteretlige regulering overholdes, og Fonden har det overordnede ansvar for dette. Fonden håndterer indberetning- og registreringspligten for statsstøtten.

Den nærmere anvendelse af investeringen er fastlagt i punkt 8 Udførelse.

4.2.3. Partnerskabets videre fordeling af investeringen sker inden for en række temaer i henhold til Budgettet, som afgrænser anvendelse af midlerne. En beskrivelse af temaerne kan ses af bilag 1.

4.2.4. Partnerskabet kan anmode Fonden om en ændring af Budgettet, hvis afgrænsningen af midler på de respektive temaer viser sig ufordelagtig for indfrielse af målene i Roadmap. Fonden er ikke forpligtet til at godkende ændringsanmodningerne.

5. Partnerskabet

5.1. Aftaleparter

Denne aftale indgås mellem Fonden og Koordinator.

Koordinator er på Partnerskabets vegne bemyndiget til at lave Projektaftaler med Projektpartnere.

5.2. Partnerskabets bestyrelse skal udpege en Koordinator for investeringen, som skal forelægges Fonden til godkendelse. Afviser Fonden indstillingen af Koordinator, skal Partnerskabet indstille en anden Koordinator. Fonden skal begrunde en afvisning. Partnerskabet kan ikke modtage investeringen fra Fonden uden godkendt Koordinator.

5.3. Koordinator indestår ikke for aftalens opfyldelse, og påtager sig ikke hæftelses- eller erstatningsansvar for de enkelte partners forpligtigelser og rettigheder, medmindre der er tale om bedrag eller svig begået af Koordinator.

5.4. Flytning af aftalen til anden juridisk enhed

Aftalen kan ikke uden Fondens skriftlige godkendelse overdrages af Koordinator til en anden juridisk enhed. En anmodning om overdragelse skal være godkendt af et kvalificeret flertal på 2/3 af Partnerskabsbestyrelsen. Fonden er ikke forpligtet til at godkende overdragelse af Aftalen. Fondens godkendelse vil altid forudsætte den nye parts indtrædelse i allerede indgåede Projektaftaler.

5.5. Partnerskabsaftalen

5.5.1. Partnerskabet skal indgå en Partnerskabsaftale.

5.5.2. Partnerskabsaftalen skal beskrive den interne governancestruktur for Partnerskabet, og hvorledes medlemmer til bestyrelsen udpeges. Der skal ligeledes være en beskrivelse af, hvordan ændringer af Partnerskabsaftalen foretages, og disse kan

være betinget af en afstemning på Generalforsamlingen eller anden fastsat proces i Partnerskabsaftalen.

5.5.3. Partnerskabsaftalen skal beskrive, hvilke forpligtelser og rettigheder man som partner er underlagt som medlem af partnerskabet.

5.5.4. Fonden er ikke part i Partnerskabsaftalen og påtager sig intet ansvar i relation dertil. Dog vil Fonden fortsat sikre finansiering af Ph.D. studerende, jævnfør 12.9, hvis Partnerskabsaftalen opsiges af Partnerskabet, og Aftalen mellem Fonden og Partnerskabet dermed ophører

6. Administrator

6.1. Partnerskabets bestyrelse skal udpege en Administrator for investeringen, som skal forelægges Fonden til godkendelse. Afviser Fonden indstillingen af Administrator, skal Partnerskabet indstille en anden Administrator. Fonden skal begrunde en afvisning. Partnerskabet kan ikke modtage investeringen fra Fonden uden godkendt Administrator.

6.2. Administrator kan være Koordinator, men dette er ikke et krav.

6.3. For at Fonden kan godkende Administrator, skal en række betingelser være opfyldt, herunder at Administrator har en for Fonden acceptabel økonomisk soliditet, at en eller flere relevante tredjeparter garanterer for Administrators opfyldelse af forpligtelser under Aftalen, eller at Administrator er organiseret på en for Fonden betryggende måde set i forhold til Administrators forpligtelser under Aftalen.

6.4. Fonden kan til enhver tid kræve, at der udpeges en ny Administrator, såfremt den eksisterende Administrator efter Fondens vurdering ikke opfylder betingelserne i 6.3, eller der efter Fondens vurdering er risiko for, at den eksisterende Administrator ikke vil være i stand til at opfylde forpligtelserne under Aftalen.

6.5. Udbetaling af Fondens investeringsbeløb sker ved overførsel til Administrator i henhold til indsendte Udbetalingsanmodninger. Administrator har ansvaret for at sikre, at de af Fonden udbetalte beløb til Administrator udbetales til Projektpartnerne i henhold til godkendte regnskaber og øvrige afrapporteringer fra projekterne, som skal indsendes til Administrator. Udbetaling til konkrete projekter er nærmere reguleret i punkt 9 om Udbetaling.

6.6. Administrator skal sørge for enhver regulatorisk påkrævet dokumentation fra Projektpartnerne, herunder de nødvendige erklæringer om ikke-kriseramt virksomhed, [SMV](#) og De Minimis, der følger af de gældende EU statsstøttere regler. Det er den enkelte Projektpartners ansvar, at dokumentationen er korrekt udfyldt.

- 6.7.** Administrator vil ikke blive stillet til økonomisk ansvar på vegne af Partnerskabet, med mindre der er tale om bedrageri og/eller svig begået af Administratoren.
- 6.8.** Hvis Administrator bliver bekendt med, at der er lavet uretmæssige udbetalinger til en Projektpartner, så skal Administrator kræve midlerne tilbage fra pågældende Projektpartner. Ved manglende efterlevelse af tilbagebetalingskrav, kan Administrator gøre brug af bestemmelsen i 8.6.2.
- 6.9.** Hvis Fonden kræver, at Administrator udskiftes, jf. 6.4, eller hvis Partnerskabets Bestyrelse med Fondens godkendelse beslutter at udskifte Administrator, skal den hidtidige Administrator sikre, at den nye Administrator modtager alle relevante oplysninger og alt relevant materiale, samt at eventuelle økonomiske midler fra Innovationsfonden, der henstår hos Administrator, overføres til den nye Administrator.

7. Revisionsregler

- 7.1.** De enkelte Projektpartneres delregnskaber skal revideres separat. Kravene til revision af en Projektpartneres delregnskab varierer afhængigt af, om Projektpartneren skal modtage et investeringsbeløb, størrelsen af investeringsbeløbet fra Innovationsfonden samt af Projektpartnerens organisationsform.
- 7.2.** Revisionen skal ske efter gældende revisionsinstruks, som er offentliggjort på [Innovationsfondens hjemmeside](#).
- 7.3.** Administrator skal sikre, at regnskaber fra Projektpartnerne i et Projekt revideres i henhold til gældende revisionsinstruks, såfremt nedenstående gør sig gældende:
- Regnskab for perioder, hvor de samlede midler udbetalt af Partnerskabet vil udgøre mere end 500.000 kr.
 - Regnskab for hele projektperioden, som revideres ved projektets afslutning.
- 7.4.** Regnskaber fra Projektpartnere, der ikke modtager finansiering fra Partnerskabet, skal ikke revideres, men alene godkendes af en tegningsberettiget medarbejder hos Projektpartneren.
- 7.5.** Er en Projektpartner en statsinstitution eller statsfinansieret selvejende institution, kan en erklæring af institutionens øverste økonomiansvarlige om bekræftelse af overholdelse af de gældende regler for Projektet træde i stedet for en revisorerklæring for Projektpartnerens aktiviteter i Projektet. En sådan erklæring kan alene dække Projektpartnerens egne aktiviteter i Projektet, og eventuelle andre Projektpartnere er således fortsat underlagt kravet om revisorerklæring. Skabelonen til denne erklæring skal godkendes af Fonden inden indsendelse af regnskab, og kan med fordel følge Fondens gældende skabeloner.

8. Udførelse

8.1. Roadmap

- 8.1.1. Partnerskabet skal have defineret et Roadmap, som beskriver, hvordan partnerskabet når i mål med målsætningerne om reduktion af udledningen af drivhusgasser og om jobskabelse, både i forhold til 2030 og til 2050. Dette Roadmap skal vedlægges som bilag 4 til Aftalen.
- 8.1.2. Partnerskabets Roadmap skal løbende genbesøges, og Partnerskabet skal sørge for, at Roadmap er relevant og relaterer sig til andre nationale initiativer. Bliver Roadmap opdateret, så skal det nye Roadmap godkendes af Fonden, inden det kan erstatte den godkendte version i bilag 4.
- 8.1.3. Der skal altid refereres til Roadmap, når Partnerskabet udvælger, hvilke aktiviteter der skal finansieres, så det er tydeligt, hvordan disse bidrager til opfyldelsen af Roadmap.

8.2. Udvalgelse af projekter

- 8.2.1. Partnerskabet skal udvælge Projekter, der skal modtage finansiering fra Fondens investering, ud fra en faglig bedømmelse af modtagne projektforslag i åben konkurrence på baggrund af offentliggjorte opslag i overensstemmelse med bilag 1.
- 8.2.2. Alle opslag om projektforslag skal beskrive Partnerskabets vurderingskriterier, og Partnerskabets bedømmelser af projektforslagene skal følge disse kriterier.
- 8.2.3. Processen for udvælgelse af projekter skal følge beskrivelsen i bilag 3, som offentligøres sammen med Partnerskabets opslag.
- 8.2.4. Partnerskabet skal i sin bedømmelse af projektforslag og administration af projekter i øvrigt overholde forvaltningslovens regler om habilitet og partshøring samt de grundlæggende forvaltningsretlige principper om ligebehandling og krav til saglige afgørelser.
- 8.2.5. Alle afgørelser skal fremsendes til ansøgere, og begrundelser for tilsagn eller afslag skal være baseret på de vurderingskriterier, som har været defineret i opslaget.
- 8.2.6. Projektforslag skal vurderes af mindst én anerkendt forsker¹, hvis de omfatter forskningsaktiviteter.

¹ For yderligere oplysninger om anerkendte forskere, se: [LBK nr. 1660 af 12/08/2021, Bekendtgørelse af lov om Danmarks Innovationsfond](#)

8.2.7. Op til 1% af Fondens investering afsat til Partnerskabets videreformidling kan anvendes af Partnerskabet til honorering af eksterne eksperter, som kan assistere Partnerskabet i vurdering af projektforslag. Alle vurderinger af eksterne eksperter skal partshøres hos Projektpartnerne inden det kan indgå i den samlede vurdering af projektforslaget.

8.2.8. Senest 14 dage inden Partnerskabet meddeler tilsagn til et konkret Projekt, skal Fonden have modtaget projektbeskrivelse og projektbudget for det pågældende Projekt. Fonden kontrollerer ved modtagelse, at Projektpartnerne er relevante for det pågældende Projekt, at Projektet falder inden for det respektive tema beskrevet i bilag 1, at Projektet bidrager til opfyldelsen af målene i Roadmap, og at statsstøttere reglerne er overholdt. Fonden kan gøre indsigelse mod udvælgelsen af et konkret projekt, hvis det ikke opfylder ovenstående betingelser. I tilfælde af Fondens indsigelse, kan Partnerskabet ikke meddele tilsagn til det pågældende Projekt.

8.3. Projektaftale

8.3.1. For hver tildeling af midler til et Projekt skal Partnerskabet lave en Projektaftale med Projektpartnerne. Projektaftalen kan være i form af en "Projektskrivelse", hvor vilkår og betingelser for finansieringen fremgår. Der skal gives en skriftligt accept fra projektets kontaktperson af aftalens indhold, inden projektet kan påbegynde.

8.3.2. Projektaftalen skal fastlægge vilkår og betingelser for finansieringen, fastlægge Projektpartnerens opgaver og forpligtelser i Projektet, den skal fastlægge milepæle for Projektet, og den skal fastlægge et budget for Projektet. Omfatter Projektet mere end én Projektpartner, skal Projektaftalen derudover fastlægge vilkår for obligatorisk nedsættelse af en Styregruppe for Projektet og udnævnelse af en projektleder. Partnerskabet kan derudover vælge at fastlægge vilkår for den fortsatte finansiering af Projektet afhængig af Projektets præstation, såsom en stage-gate proces eller lignende.

8.4. Krav til Partnerskabets bestyrelse

8.4.1. Partnerskabets bestyrelse har ansvaret for, at videreformidlingen af Fondens investering sker til Projekter, som understøtter opfyldelse af Partnerskabets mål og milepæle i overensstemmelse med Roadmap i bilag 4 og beskrivelse af temaer i bilag 1.

8.4.2. Afgørelser om tilsagn og afslag til konkrete Projekter træffes af Partnerskabets bestyrelse.

8.4.3. Ændringer i et igangværende Projekt, herunder budget eller partnersammensætning, kan alene ske med udtrykkelig godkendelse fra Partnerskabets bestyrelse og Fondens efterfølgende godkendelse af overholdelse af statsstøttere reglerne.

8.4.4. Partnerskabets bestyrelse skal løbende følge op på fremdrift i igangværende Projekter og tage stilling til Projekternes berettigelse til fortsat finansiering.

8.5. Krav til Projektpartner

8.5.1. Omfatter et Projekt mere end én Projektpartner, skal en samarbejdsaftale om det konkrete Projekt mellem Projektpartnerne være indgået og underskrevet, inden Partnerskabet kan udbetale midler til Projektpartnerne. Samarbejdsaftalen skal fastlægge vilkår for ejerskab, udnyttelse og formidling af Projektets resultater og deraf afledte immaterielle rettigheder. Partnerskabet skal ikke være part i samarbejdsaftalen, eller påtage sig noget ansvar i relation dertil.

8.6. Krav til Partnerskabet i Investeringsaftalen

8.6.1. Som led i sædvanlig projektopfølgning og kontrol med udbetalte midler er Partnerskabet forpligtet til at undersøge berettiget mistanke om bedrag eller svig i Projekter. Partnerskabet er forpligtet til at foretage retslig forfølgelse af eventuelle krav afledt af en Projektpartners misligholdelse, såfremt der er tale om bedrag og svig.

8.6.2. Som fastlagt i Budgettet i bilag 2 kan Partnerskabet hvert år anvende en begrænset del af Fondens investering for det pågældende år til indenretlig forfølgelse af tilbagebetalingskrav rettet mod en Projektpartner som følge af Projektpartnerens misligholdelse af en Projektaftale eller uretmæssig udbetaling af midler. Fonden skal altid orienteres, hvis der rettes tilbagebetalingskrav imod Projektpartnere.

8.7. Indsigelse til Fonden for projektansøgere

Partnerskabets meddelelsesbreve om afgørelser i relation til projektforslag skal omfatte en henvisning til Fonden for indsigelser rettet mod Partnerskabets manglende efterlevelse af kravene om habilitet, ligebehandling, partshøring og saglig vurdering. Ved modtagelse af sådanne indsigelser vil Fonden kontrollere forholdene omkring udvælgelsen og påtale eventuelle afvigelser. I gentagne eller ved særligt grove tilfælde af afvigelser, kan Fonden ophæve Investeringsaftalen.

9. Udbetaling

9.1. Fondens udbetaling af investeringen til Administrator sker bagudrettet på baggrund af indsendte Udbetalingsanmodninger, hvor afholdte udgifter fra de konkrete Projekters regnskab og administration af Partnerskabet fremgår.

- 9.2.** Partnerskabet kan i forbindelse med indgåelse af Investeringsaftalen anmode Fonden om en forudbetaling til Administrator på 20% af midlerne. En eventuel forudbetaling vil blive modregnet i 2. sidste udbetaling i Investeringsperioden.
- 9.3.** Fonden er berettiget til permanent at stoppe al udbetaling af midler, såfremt Fonden på baggrund af Annual Investment Review, tilsynsmøder eller andet review mv. finder, at der ikke er tilstrækkelig fremdrift i Partnerskabets opfyldelse af Roadmap, at Bevillingsgrundlaget ikke er overholdt, eller at referater fra bestyrelsesmøder eller Årsrapporter ikke er modtaget til tiden, eller såfremt nævnte referater eller rapporter ikke er udarbejdet i overensstemmelse med de gældende regler og retningslinjer. Fonden kan vælge, men er ikke forpligtet til, midlertidigt at standse udbetaling af midler helt eller delvist, til sådanne forhold er bragt på plads.
- 9.4.** 10% af Fondens investering er afsat som Slutbeløb. Udbetaling af Slutbeløb sker, når og såfremt Fonden har modtaget og godkendt rettidig Afslutningsrapport udarbejdet i overensstemmelse med de gældende regler og retningslinjer. Endvidere forudsætter udbetaling af Slutbeløbet, at Fonden har modtaget og godkendt den sidste Årsrapport og Årsregnskab for Partnerskabet.
- 9.5.** Fonden forbeholder sig ret til at kræve ikke forbrugte beløb tilbagebetalt, og ikke forbrugte beløb skal altid tilbagebetales til Fonden efter udløb af Investeringsperioden. Fonden retter et eventuelt tilbagebetalingskrav mod Administrator på det ikke forbrugte beløb.
- 9.6.** Partnerskabet skal påse, at aktiviteter finansieret eller medfinansieret med Fondens investering ikke samtidig finansieres eller medfinansieres af offentlige myndigheder eller offentlige støtteordninger, og Fondens investering kan ikke indgå som medfinansiering til andre offentlige støtteordninger.

10. Opfølgning og tilsyn

10.1. Opfølgning og tilsyn

- 10.1.1.** Fonden foretager kontrol af Partnerskabet som led i sædvanlig faglig og økonomisk opfølgning på Fondens investering. Som led heri monitorerer Fonden løbende Partnerskabets fremdrift, effekt og værdiskabelse (impact), som vurderes i henhold til Partnership Plan og Investeringsaftalens Bilag 1, 2 og 4. Som hovedregel vil Fonden udføre sin opfølgning gennem møder med Partnerskabet bestyrelse, sekretariat og Administrator, og igennem Partnerskabets afrapporteringer til Fonden.
- 10.1.2.** Møder i Partnerskabsbestyrelsen
- 10.1.2.1.** Fonden deltager som observatør i Partnerskabsbestyrelsen, og Fonden deltager i Partnerskabsbestyrelsens møder.

10.1.2.2. Fonden skal modtage bestyrelsesmødemateriale inden det enkelte bestyrelsesmøde og skal modtage referat af bestyrelsesmødet efter bestyrelsesmødets afholdelse. Frister for materialet følger Partnerskabs egne frister for udsendelse til Partnerskabets bestyrelse.

10.1.3. Dialogmøder

10.1.3.1.

Fonden afholder et årligt dialogmøde, såkaldt Annual Investment Review (AIR), med Partnerskabet. I et AIR kan Fonden vælge at inddrage fagkyndige til at bistå Fondens. Annual Investment Review udføres efter Fondens nærmere anvisninger og omfatter gennemgang og vurdering af investeringens status og forventelige udvikling, både ud fra et fagligt, herunder resultatmæssigt, et økonomisk/budgetmæssigt, et tidsmæssigt og et administrativt/organisatorisk synspunkt. Annual Investment Review baserer sig på input fra Partnerskabet, Partnerskabsdirektøren, Koordinator og Administrator, samt eventuel yderligere information, som Fonden måtte kræve.

10.1.3.2.

Fonden skal modtage AIR rapport fra Partnerskabsdirektøren senest fjorten (14) dage forud for Annual Investment Review dialogmødet. Afrapportering skal udarbejdes på baggrund af skabelon, som fremsendes af Fonden forud for udarbejdelsen.

10.1.3.3.

Forud for Annual Investment Review fremsender Fonden dagsorden og deltagerliste. Efter Annual Investment Review udsender Fonden en opsamling på reviewet, inkl. eventuelle anbefalinger og krav til Partnerskabet.

10.1.4. Tilsynsmøder

10.1.4.1.

Fonden afholder et årligt tilsynsmøde med Partnerskabet, der – i kombination med de øvrige opfølgningsaktiviteter – har til formål at sætte Fonden i stand til at vurdere, om Fondens investering anvendes i henhold til Bevillingsgrundlaget og Aftalen og under økonomisk forsvarlig forvaltning. Fonden kan til brug for sit tilsyn inddrage en eller flere eksterne, uafhængige vurderingspersoner i tilsynsmøderne.

10.1.4.2.

Der udføres i forbindelse med tilsynsmøderne stikprøvekontrol på sager udvalgt af Fonden. Hver af de udvalgte sager gennemgås af Fondens repræsentanter, hvor Administrators og Sekretariats rolle er at fremlægge relevant dokumentation og besvare spørgsmål. Fonden kan på og i forbindelse med et tilsynsmøde kræve enhver sådan dokumentation og information, som Fonden anser for nødvendig for at udføre Fondens tilsynsopgave.

10.1.4.3. Fondens bemærkninger efter et tilsyn vedrørende de udvalgte sagers efterlevelse af eventuelt udpegede fokusområder, afvigelser, styrker, konklusion og eventuelle forbedringsforslag, samt eventuelle øvrige bemærkninger vedrørende sagsbehandlingen, noteres i en tilsynsrapport og sendes til Partnerskabets Bestyrelse.

10.1.4.4. Fonden sender Partnerskabet en kopi af tilsynsrapporten, hvor eventuelle mangelfulde forhold til udbedring vil fremgå sammen med Fondens angivelse af fristen herfor.

10.1.4.5. Tilsynsmøder afholdes på Fondens foranledning, og Fonden sender Partnerskabet en dagsorden for et kommende tilsynsmøde samt orientering om eventuelle fokusområder senest én (1) uge forud for tilsynsmødet.

10.1.5. Årlig afrapportering

10.1.5.1.

Fonden skal årligt modtage afrapportering fra Administrator og Sekretariat på vegne af Partnerskabet af:

økonomi i form af et årsregnskab for Projekter og aktiviteter støttet med midler fra Fondens investering, og specifikation af eventuelt ikke-allokerede midler fra investeringen. Regnskabsåret følger kalenderåret. Afrapporteringen skal indeholde en opgørelse af de Projekter og Aktiviteter, der modtager finansiering gennem denne investering, herunder deres budget og samlede forbrug i perioden. Regnskabet skal tydeligt skelne mellem udgifter til administration af Partnerskabet, såsom sekretariats funktioner, og midler til Projekter. Den økonomiske afrapportering skal udarbejdes på baggrund af skabeloner, der er tilgængelige i e-grant, eller som fremsendes af Fonden forud for udarbejdelsen. Afrapporteringen for et givent regnskabsår skal være Fonden i hænde senest seks (6) måneder efter endt regnskabsperiode og skal forud for fremsendelse til Fonden være godkendt af Partnerskabets bestyrelse.

10.1.5.2.

Fonden skal årligt modtage afrapportering fra Partnerskabet af:

faglig status og fremdrift, herunder med beskrivelse af og dokumentation for opnåede resultater og status i forhold til overholdelse af de for Projekterne fastsatte milepæle og Projekternes status i forhold til de opstillede mål og opfyldelse af partnerskabets Roadmap. Den faglige rapportering skal udarbejdes på baggrund af skabeloner, der er tilgængelige i e-grant eller som fremsendes af Fonden forud for udarbejdelsen.

10.1.5.3.

Fonden kan bede om, at den faglige afrapportering indgår i en samlet rapport sammen med faglige rapporter fra andre investeringer fra Fonden til Partnerskabet.

10.1.6. Slutrapportering

I umiddelbar forlængelse af investeringens afslutning og senest seks (6) måneder efter Investeringsperiodens udløb afleverer Partnerskabsdirektøren en skriftlig Afslutningsrapport for samtlige Projekter og aktiviteter støttet af Fondens investering beskrevet i Aftalen. Afslutningsrapporten skal udarbejdes efter en skabelon, som Fonden udleverer inden investeringsafslutning. Alle Projekterne skal udarbejde deres egen afslutningsrapport, som kan vedlægges Partnerskabets afslutningsrapport som bilag.

Der skal ydermere laves et samlet regnskab for hele investeringsperioden, hvor det fremgår hvor meget de enkelte Aktiviteter har fået finansieret, og alle endelige projektbudgetter skal vedlægges som bilag.

10.1.7. Rapportering om fremdrift i investeringen

Fonden kan til enhver tid anmode Partnerskabet om at aflægge en detaljeret afrapportering om specifikke elementer af investeringens fremdrift. Fristen for Partnerskabets besvarelse af en sådan anmodning er tyve (20) hverdage fra anmodningen.

11. Formidling og offentliggørelse

11.1. Partnerskabet skal sikre, at det ved offentliggørelse af resultater fra et Projekt eller en Projektpartner eller et medlem af Partnerskabets offentlige omtale af et Projekt tydeligt fremgår, at der er tale om et Projekt støttet af Fonden.

11.2. Enhver publikation, beretning eller andet materiale, der offentliggøres af Projektpartnerne, og som indeholder en omtale af Projektet og/eller resultater opnået i forbindelse med Projektet, skal angive, at Projektet er støttet af Fonden, og Fondens logo skal fremgå af materialet. Dog kan Fondens logo undtages i videnskabelige publikationer m.v. i det omfang, der ikke er kutyme for anvendelse af logo.

11.3. Partnerskabet skal i Investeringsperioden en gang årligt og en gang i det første kalenderår efter Investeringsperiodens afslutning efter Fondens nærmere anvisning bistå Fonden med udarbejdelse af en kort beskrivelse af investeringen og de finansierede Projekters status og resultater, ligesom Partnerskabet skal stille billedmateriale til rådighed til brug for Fondens offentliggørelse af årsberetning, Fondens hjemmeside, m.v. Materialet skal af Partnerskabet stilles til rådighed på dansk og engelsk. Fristen for indlevering af materialet fastsættes af Fonden, og det er Partnerskabets bestyrelse og Partnerskabsdirektøren, der på vegne af Partnerskabet har ansvaret for, at Fonden modtager materialet rettidigt.

11.4. Projektpartnerne samtykker til, at Fonden kan offentliggøre navnene på Projektpartnerne, Projektets titel og varighed, og nøgletal fra investeringen, herunder investeringens størrelse, i Den Danske Forskningsdatabase

(www.forskningsdatabasen.dk), på Fondens hjemmeside (www.innovationsfonden.dk) og i Fondens publikationer.

12. Ikrafttræden, løbetid, ophør og opsigelse

- 12.1.** Investeringssaftalen træder i kraft ved Koordinator og Fondens underskrifter.
- 12.2.** Investeringsperioden begynder 01-01-2025. Investeringsperioden er 3 år og 5,5 måneder. Der kan ikke afholdes omkostninger på investeringssagen efter denne dato.
- 12.3.** Partnerskabet kan anmode om forlængelse af investeringsperioden gennem re-budgettering foretaget i e-grant seneste 3 måneder inden udløbet af denne investeringsskifte.
- 12.4.** Fonden kan skriftligt opsig Investeringssaftalen med fem (5) måneders skriftligt varsel til udgangen af en måned, såfremt Fonden efter sin frie vurdering, herunder faglige vurdering, finder,
- I. på baggrund af et review, (A) at Partnerskabets Aktiviteter ikke opfylder et eller flere af Fondens Investeringskriterier, eller (B) at der ikke er tilstrækkelig fremdrift i Projekterne, hvilket kan være, men ikke er begrænset til situationer, hvor der generelt ikke er den tilstrækkelige fremdrift i Projekterne, eller situationer, hvor de grundlæggende antagelser for temaerne viser sig ikke længere at være til stede, eller
 - II. at Partnerskabet ikke opfylder de formål, som er beskrevet i beskrivelsen af temaerne og/eller Budgettet.
- 12.5.** Partnerskabet og Fonden kan hver hæve Investeringssaftalen i tilfælde af den andens væsentlige misligholdelse.
- 12.6.** Partnerskabet kan opsig investeringssaftalen, hvis Partnerskabets Generalforsamling beslutter dette, som følge af mangel på den fornødne kapacitet eller opbakning til at opfylde formål med aftalen, som er beskrevet i beskrivelsen af temaerne og/eller budget.
- 12.7.** I tilfælde af opsigelse eller hævelse af Investeringssaftalen skal Partnerskabet efter opsigelsesperiodens udløb udarbejde et afsluttende regnskab for Investeringen, som indeholder en oversigt over modtagne midler fra Fonden og eventuelt tilgodehavende til Projektdeltagerne fra Administrator. Administrator skal udarbejde det afsluttende regnskab på vegne af Partnerskabet og forelægge det til Fondens godkendelse inden for en af Fonden fastsat frist. Regnskabet skal være godkendt af Partnerskabets bestyrelse, inden det forelægges Fonden. Godkendes regnskabet af Fonden, udbetaler eller opkræver Fonden differencebeløbet.

12.8. Skriftlig varslng

Fonden kan udstede et skriftligt påkrav til Partnerskabet om udbedring af et eller flere forhold, der kan danne grundlag for en opsigelse, med en angivelse af en frist for udbedring af de mangelfulde forhold. Såfremt Partnerskabet inden for fristen foretager udbedring som anvist, kan de udbedrede forhold ikke danne grundlag for opsigelse.

12.9. Opfyldelse af økonomiske forpligtelser over for projekterne

Hvis Fonden opsiger Aftalen, forpligter Fonden sig til at fortsætte finansieringen af ph.d.-forløb i allerede igangsatte Projekter med uændret støtteintensitet.

12.10. Hvis Fonden eller Partnerskabet opsiger Aftalen, skal Partnerskabet fortsætte sit arbejde indtil udløbet af opsigelsesperioden.

13. Forrang, ændringer og lovgrundlag

13.1.1.

Investeringsaftalen har forrang frem for andre dokumenter og aftaler, herunder Partnerskabsaftalen.

13.1.2.

Tilføjelser eller ændringer til Investeringsaftalen skal være skriftlige. Ændringer skal godkendes af begge parter i aftalen, og af Partnerskabets bestyrelse inden de træder i kraft.

13.1.3.

Meddelelser i henhold til Investeringsaftalen kan sendes per e-mail. Meddelelse om opsigelse eller hævelse skal dog sendes som e-mail med bekræftet modtagelse eller som anbefalet brev.

13.1.4.

Denne investeringsaftale med Innovationsfonden er udarbejdet med hjemmel i § 18, stk. 1, 1. pkt. i lov nr. 306 af 29. marts 2014 om Danmarks Innovationsfond, som senest er ændret ved lov nr. 1660 af 12. august 2021, og bekendtgørelse nr. 1150 af 25. oktober 2017 om bevillingsfunktionen m.v. under Danmarks Innovationsfond. Investeringsaftalen er ydermere udarbejdet med hjemmel i Aftale om fordeling af forskningsreserve mv. i 2023.

13.2. Vi gør bevillingshaver opmærksom på, at Innovationsfonden tilslutter sig retningslinjerne for international forskning og innovation (URIS). Læs mere her:

<https://ufm.dk/publikationer/2022/afrapportering-udvalg-om-retningslinjer-for-internationalt-forsknings-og-innovationssamarbejde>.

Bevillingshaveren indestår for, at modtagelse og anvendelse af investeringen fra Innovationsfonden ikke strider mod gældende nationale eller internationale sanktioner, herunder sanktioner om indefrysning af midler eller forbud mod direkte og indirekte tilrådgivningsstillelse.

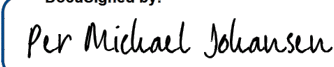
Bevillingshaveren er opmærksom på, at EU i forbindelse med konflikten mellem Rusland og Ukraine i betydelig grad har begrænset adgangen til at stille pengemidler og økonomiske ressourcer til rådighed for bestemte fysiske eller juridiske personer, enheder eller organer i medfør af EU-forordning 269/2014 "om restriktive foranstaltninger over for tiltag, der underminerer eller truer Ukraines territoriale integritet, suverænitet og uafhængighed", og bevillingshaveren indestår for, at modtagelse og anvendelse af bevillingen fra Innovationsfonden ikke strider mod denne forordning. En konsolideret liste over aktører omfattet af EU-sanktioner er tilgængelig online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02014R0269-20220604>.

14. Lovvalg

Investeringsaftalen er underlagt dansk ret, og alle tvister, som ikke kan løses i mindelighed, skal afgøres af Retten i Aarhus i første instans.

15. Underskrifter

For AAU

DocuSigned by:

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Rektor

30.01.2025 | 07:13 CET

For Innovationsfonden



Søren Asp Mikkelsen,
Vicedirektør - Missioner & Partnerskaber
17.02.2025

Bilag 1

Beskrivelse af temaer under investeringen inkl. mål og milepæle for anvendelse af investeringen samt indfrielsen af mål i Partnerskabets Roadmap, Bilag 4

MissionGreenFuels

Nedenstående elementer gentages for hvert tema for investeringen. Der tages udgangspunkt i beskrivelserne fra ansøgningen.

Tema 1: Sustainability and system integration

Beskriv det overordnede formål med temaet

Integration of PtX with the energy system plays a significant role in the MGF roadmap and was the top-priority theme from the MGF partnership and BoD workshops in August 2023.

The crucial part is to realise a sustainable transformation of the energy system sector by building on the strengths of the individual systems and components and efficiently integrate exiting and nascent sectors. Although the Danish energy system is highly developed and well-integrated, it comes with different challenges (and opportunities) of technical, market, systemic and regulatory character. There are several gaps in the current energy systems which leads to suboptimal integration of alternative fuel production, distribution, storage, and consumption, which must be solved.

Denmark is internationally known for its integration of electricity and heat in combined power and heat plants along with identifying, developing and deploying Danish cost-effective solutions across sectors and disciplines. Denmark can leverage on acquired knowledge and experiences to mature competitive system integration solutions in a national and international perspectives given Denmark's close ties to Europe concerning trade and exchange of gas and electricity.

Realising this potential requires research, development and demonstration of solutions across sectors, technologies etc. thereby, opening this theme for a range of new stakeholders and partners in MGF. Furthermore, we expect to see projects testing new solutions in existing assets to optimize and achieve synergies.

This theme relates strongly to one of the objectives in the Governments PtX strategy "The integration between Power-to-X and the Danish energy system must be improved".

With a budget of 18 mio dkk, this theme can contribute to realizing the flexibility potential of PtX in Denmark, thereby accelerating the green transition. The solutions can make global impact by sharing knowledge and best practices, inspiring other countries to adopt them.

Beskrivelse af plan for tema med angivelse af milepæle

Process milestones:

- Call published M8, 2024
- Applications evaluated and selected/rejected M3, 2025
- Project agreements signed, M8, 2025
- Projects kicked off, M10, 2025

Roadmap milestones:

- Enhanced system flexibility, sustainability and energy efficiency in PtX plants.

Success criteria:

- Smooth and efficient process with funding for projects with highest impact for green fuels in Denmark.
- Collaborative national and international research and innovation projects.

Tema 2: Cost down and competitiveness 2030

Beskriv det overordnede formål med temaet

The MGF partnership and roadmap is set to deliver beyond the lifetime of MGF. In order to deliver on the climate targets, the partnership will build the foundations for value creation for current and new partners in the longer perspective with new innovative ideas and solutions that might not have an obvious impact within the original MGF lifetime (June 2027).

Green fuels must be bankable and competitive towards fossil alternatives before the world can become climate neutral. It is therefore paramount to reduce cost of green fuels in parallel with creating market structures and frameworks to profoundly enhance the demand for green fuels and support the urgent for decarbonisation.

With this theme we expect to see new ideas that are not yet fully mature or economically viable. This gives the opportunity to test and support the next generation of potential solutions, and for potential new spinouts and business. Examples hereof are: more effective cleaning of water, as impurity destroys the expensive equipment, increase efficiency and viability of electrolysis and catalysis for rapid ramp-up and ramp-down, to improve the business plan, new methods for green fuels production, like pyrolysis oils etc. and direct connection between wind/solar and electrolysis, thereby saving AC/DC conversion and expensive electricity grid expansions.

Denmark is a pioneer in the green sector especially in wind energy and system integration/optimization, and excels in creating new ideas, collaboration between industry and research. Therefore, solutions aimed at 2030 and beyond hold the potential to become the next Danish strongholds and export opportunities. This relates strongly to one of the objectives in the Governments PtX strategy "Denmark must be able to export PtX products and technologies".

With a budget of 8 mio dkk the theme enables further development and maturation of innovative solutions, fostering a skilled workforce in advanced technologies and enhancing Denmark's global standing.

Beskrivelse af aktiviteter

Process milestones:

- Call published M8, 2024
- Applications evaluated and selected/rejected M3, 2025
- Project agreements signed, M8, 2025
- Projects kicked off, M10, 2025

Roadmap milestones:

- Improvement in overall cost for green fuels

Success criteria:

- Smooth and efficient process with funding for projects with high impact for green fuels in Denmark.
- Collaborative national and international research and innovation projects.
-

Tema 3: Cost down and competitiveness 2030 booster

Beskriv det overordnede formål med temaet

Reducing the overall cost of green fuels to make them more competitive in the market is a key element within the MGF roadmap in order to reach the climate targets. In addition to the partnership goals on climate, there is a clear focus on involving new partners within the green fuels value chain, including SMEs, and further contributing to Danish export potentials and job creating.

This theme will focus specifically on the uptake of SMEs and/or startups in MGF with the aim of fostering their participating, and in turn expanding the MGF partnership with new SMEs keen on applying for funding.

On one hand, SMEs often have limited capital, may lack specialized knowledge and expertise in-house, might encounter scaling up of production challenges and limited access to testing facilities. On the other hand, SMEs play a significant role in Denmark's future competitiveness, economic growth and job creation - both nationally and regionally.

Creating synergies to other MGF projects along with its partners can allow the solutions to be taken to the next level by providing SMEs with access to resources and expertise that they may not have in-house, such as equipment, facilities, and technical expertise. This collaborative approach can help them to accelerate the development and commercialization of their products and services. Moreover, the MGF partnership can help the SMEs to reach new markets and increase their visibility. In doing so, it enhances their opportunities for growth and sustainability.

With 5 mio dkk this theme can fund at least 2 SMEs or start-up projects that show great potential for scale-up, has a clear goal and can attract large investments in a short timeframe. This will help secure economic growth, create jobs and long-term competitiveness of Denmark.

Beskrivelse af aktiviteter

Process milestones:

- Call published M8, 2024
- Applications evaluated and selected/rejected M3, 2025
- Project agreements signed, M8, 2025
- Projects kicked off, M10, 2025

Roadmap milestones:

- Ideas from SMEs or start-up companies, with significant risk and innovative value tested or taken to the next level.

Success criteria

- Smooth and efficient process with funding for projects with high impact for green fuels in Denmark.

Tema 4: Safety and regulations

Beskriv det overordnede formål med temaet

There are several challenges in the MGF roadmap within safety and regulation, that currently impede the widespread adoption of green fuels. The purpose of this theme is:

- Developing robust certification protocols for green fuels, ensuring high-quality production and usage standards.

- Establishing comprehensive industry standards that guarantee consistency and reliability across the green fuel sector.
- Exploring innovative pricing models for both CO2 emissions and green fuels, making them economically viable alternatives.
- Creating monitoring initiatives and standards compared to purity of feedstocks to ensure market development.
- From production to storage and usage, addressing the challenges of handling green fuels, ensuring safety and efficiency throughout the process.
- Navigating the evolving landscape of regulatory frameworks, including CO2 taxes, subsidies, and requirements in cap-and-trade systems, to foster seamless integration of green fuels into existing energy ecosystems.

Currently, industries and investors are waiting for industry standards, and decisions from the government before investing in new PtX plants and large-scale productions. The projects in this theme will call for engagement with relevant regulatory bodies and/or the industry as the challenge owner (end-user, production, transportation, handling, storage etc of green fuels). Furthermore, the international level must be considered to ensure the most impact on EU and global level.

This theme relates strongly to one of the objectives in the Governments PtX strategy “The regulatory framework and infrastructure must be in place for Denmark to utilise its strengths and allow PtX to perform on market terms in the long run”.

With a budget of 6 mio dkk, the theme can contribute to address challenges hindering the effective implementation and use of green fuels. It can offer guidance to policymakers on regulations that stimulate CO2 reductions and make green fuels attractive to investors and end-users.

As is stated in the [call text](#), this theme supports solutions related to safety and regulations **in a research and innovation context**.

Beskrivelse af aktiviteter

Process milestones:

- Call published M8, 2024
- Applications evaluated and selected/rejected M3, 2025
- Project agreements signed, M8, 2025
- Projects kicked off, M10, 2025

Roadmap milestones:

- New solutions related to safety and regulations for green fuels.

Success criteria:

- Smooth and efficient process with funding for projects with high impact for green fuels in Denmark.
- Collaborative research and innovation projects that fit within the EU and international legal framework.

Tema 5: Cost down and competitiveness 2050

Beskriv det overordnede formål med temaet

As a mission-driven partnership with goals and a roadmap looking all the way to 2050, we have the responsibility and possibility to look ahead. The solutions of 2050 will take many years to invent, test, upscale and put it into production. Denmark is strong in early-stage inventions, entrepreneur/startups at universities, and in MGF we want to build the foundations for value creation in the longer perspective.

Denmark has a number of current and potential strengths in the area of green fuels, including a strong research and development base, collaborative culture across the value chains and an ability and experience of reducing costs in the renewable energy sector. The theme can help to leverage these strengths to make Denmark a global leader in the development and deployment of new cost-saving technologies and solutions for green fuels.

With this theme we look for new ideas that we as a partnership can help in its early stage. The MGF partnership can provide knowledge, competences and other resources like testing facilities to speed up the development of the idea.

With a budget of 8 mio dkk we here have the opportunity to contribute to long-term impact on nation and international level by supporting the development and deployment of new cost-saving technologies and solutions that can help make green fuels more competitive in the market by 2050. These solutions will contribute to the future Danish export potentials, job creation and Denmark's international standing.

Beskrivelse af aktiviteter

Process milestones:

- Call published M8, 2024
- Applications evaluated and selected/rejected M3, 2025
- Project agreements signed, M8, 2025
- Projects kicked off, M10, 2025

Roadmap milestones:

- Innovative and promising solution(s) tested

Success criteria:

- Smooth and efficient process with funding for projects with high impact for green fuels in Denmark.
- Collaborative national and international research and innovation projects.

Tema 6: Usage of Green Fuels

Beskriv det overordnede formål med temaet

By developing innovative ideas and solutions to address the challenges of using green fuels in engines, the theme can help to achieve the climate goals of 2030 and 2050.

For 2030 we need engines retrofitted for intermediate greener fuels, that allow existing vehicles/fleets to lower CO₂ emission for a period, as it should not be replaced before its end-of-life. For the 2050, we need engines for the future green fuels, like CH₃OH and NH₃ for aviation or ships.

There are strong Danish competences e.g. Ballard, Advent Technologies, Blue World Technology within fuel cell development. None of these are currently part of the pool 1 or 2 projects. In the

MGF partnership we are open to more partners with expertise on fuel cells and new off-takers/end-users of green fuels with specific requirements/challenges to be solved that has a significant impact of decarbonizing the transport and industry sectors (e.g. Danish Defence).

With a budget of 12 mio dkk, this theme can contribute to solutions hindering the current adoption and usage of green fuels, both intermediate and future green fuels. The solutions can improve Denmark's international standing by sharing of Danish knowledge and export of Danish solutions.

Beskrivelse af aktiviteter

Process milestones:

- Call published M8, 2024
- Applications evaluated and selected/rejected M3, 2025
- Project agreements signed, M8, 2025
- Projects kicked off, M10, 2025

Roadmap milestones:


- Solutions that help the adoption and usage of green fuels
- New partner(s) with expertise on fuels cells and/or new off-takers/end-users of green fuels

Success criteria:

- Smooth and efficient process with funding for projects with high impact for green fuels in Denmark.
- Collaborative national and international research and innovation projects.

Konsolideret milepælsplan

See next page.

| Innovation 2022 - Budget template | | Section 4 - Budget overview | |
|--|---|---|----------------|
| Docusign Envelope ID: 59276688-7915-4C19-99F2-5C1131CD8C80 | | | |
| <p>Step-by-step instruction on how to fill in this sheet</p> <p>This budget template is structured around four sections that all need to be filled in. All numbers/values are in DKK.</p> <p>Section 1: Basic information - please fill in all relevant information.</p> <p>Section 2: Budget total - All information is automatically transferred from section 4.</p> <p>Section 3: Budget signing - the budget must be signed by the chairperson of the partnership.</p> <p>Section 4: Budget overview - please specify in detail the theme and Administration title requested from Innovation Fund Denmark.</p> <p>Support: Questions regarding the budget template can be addressed to the Innovation Fund Denmark.</p> | | Themes (Specify name) | Budget |
| | | Sustainability and system integration | 18.000.000 kr. |
| | | Cost down and competitiveness 2030 | 8.000.000 kr. |
| | | Cost down and competitiveness 2030 booster | 5.000.000 kr. |
| | | Safety and regulation | 6.000.000 kr. |
| | | Cost down and competitiveness 2050 | 8.000.000 kr. |
| | | Usage of green fuels | 12.000.000 kr. |
| | | | |
| | | | |
| Section 1 - Basic information | | | |
| Innomission Partnership | MissionGreenFuels | Administration (Specify name) | Budget |
| Contact Person | Carina Jensen, cje@adm.aau.dk | Evaluators | 150.000 kr. |
| Investment start date (dd-mm-yyyy) | 01-01-2025 | Buffer for potential prosecution | 493.750 kr. |
| Investment end date (dd-mm-yyyy) | 14-06-2028 | | |
| Investment duration | 41 months,13 days | | |
| | | | |
| Section 2 - Budget total | | | |
| Total | 57.643.750,00 kr. | | |
| Section 3 - Budget signing | | | |
| 22.01.2025 13:58 CET | | Signed by:  5D00E90AD5CA441... | |
| Date | Signature: Chairperson of the Partnership | | |

Bilag 3

Governance for udvælgelse af projekter

MissionGreenFuels

Der skal forelægge en beskrivelse af governance for hvert tema. Dog kan man samle temaer i en beskrivelse, hvis de følger samme governance

Temaer:

- 1: Sustainability and system integration
- 2: Cost down and competitiveness 2030
- 3: Cost down and competitiveness 2050
- 4: Safety and regulations
- 5: Usage of green fuels

Rammer for Projekter

All information kan findes her: <https://missiongreenfuels.dk/pool-3-solutions-call/>

Projects should include at least one organization which is part of the MissionGreenFuels partnership. Eligible organizations are research institutions or private/public institutions in or outside Denmark, directly involved in the project activities.

Any Danish or international legal entity, directly involved in the project activities, is eligible to apply to participate in and receive funding. The legal entity acting as main applicant should have a Danish CVR number.

To receive funding from MissionGreenFuels you must be a partner in the partnership.

Total budget for this call is minimum 52 mio. DKK conditioned by sufficient quality within the field of applications. Investment per project ranges from 2-8 mio. DKK, see details for each theme.

MissionGreenFuels covers a maximum of 75% of the total project cost. Applicants must ensure that each partner follow the rules for maximum investment rates as detailed in the guidelines for InnoMission projects ([see guidelines here](#)).

The MissionGreenFuels partnership does not accept applications where a successful outcome is dependent on receiving additional funding for further research and development (e.g. projects that involve financing in multiple phases).

The same project **cannot apply** for funding in both this call and pool 2.5.

Co-financing of salaries and other expenses that are directly linked to the implementation of the project can be included in the budget.

Evalueringskriterier:

All applications will be evaluated on:

1. Quality of the idea – the quality of the research and innovation
2. Impact – value creation during and after the project
3. Quality of execution – efficiency in the project execution and the implementation of the results

A detailed description of these criteria can be found in the assessment criteria document. International peers will evaluate these criteria.

4. Strategic fit to the MissionGreenFuels vision and roadmap

Applications will be evaluated by the MissionGreenFuels Board of Directors regarding the strategic fit to the MissionGreenFuels' vision and roadmap (please make sure to address this in the application in section 4 "Strategic fit to MissionGreenFuels vision and roadmap").

Criteria 4 includes (but is not limited to) that the project:

- clearly contributes to creating societal value and value for the MissionGreenFuels partnership
- describes clearly the direction towards the Danish 2030 and/or 2050 climate goals, i.e. total time horizon and investment need for the potential CO2 reduction and long-term plan for the proposed solution
- contributes to maturing the entire Danish value chain
- clearly describes how the project fits into the EU legal framework
- can be scaled internationally
- contributes to CO2 reduction, job creation in Denmark and export potential
- contribute to lowering overall system costs in the production, distribution, and utilization of green fuels.

Evalueringsproces:

Applications must be submitted via "**Filkassen**". The call opens in August, 2024.

Criteria 1-3 will be evaluated by at least two international external experts. Criteria 4 will be evaluated by the Partnership Board of Directors. Please notice that criteria 4 is crucial for the evaluation and poor evaluation of this section alone can decide whether the applicant will receive funding or not.

Before proposals are subjected to review by external experts, the Partnership Director will ensure that the proposals comply with the formal requirements described in the call text. Applications which do not comply with the requirements will receive administrative rejection before subjected to external review.

Projects with the highest total score from the international peer reviews, will be evaluated by the MissionGreenFuels Board of Directors. If there are 30 applications or more, a number of applications that fits 3x the size of pool 3 (3x52 mio DKK) will be evaluated by the Board of Directors, however, at least five applications from each theme will be evaluated, if possible. If fewer than 30 applications are received, all will be evaluated by the MissionGreenFuels Board of Directors.

The members of the Board of Directors can be found [here](#). Applicants are asked to indicate whether they see any conflict of interest with any of these.

It is expected that the project applications will receive either invitation for investment negotiations or a rejection of the application in December 2024, after which the investment negotiations can be initiated with an expected project start in Q2 of 2025.

Tema:

6: Cost down and competitiveness 2030 - Booster

Rammer for Projekter

All information can be found here: <https://missiongreenfuels.dk/pool-3-booster-call/>

Only SME's and startups are eligible to apply.

Total budget for this call is minimum 5 mio. DKK, conditioned by sufficient quality within the field of applications. Investment per project ranges from 1.5-5 mio. DKK and the partnership will cover a maximum of 35% of the project's total cost.

Applicants must follow the Innovation Fund Denmark InnoBooster Guidelines in regard to – section 1.2, 1.4, 1.5 and 6 ([link](#)). Please note that there are specific requirements related to the financial status of the company acting as the applicant.

The following types of expenses may be covered by the Booster investment:

- Actual labour costs calculated from hours worked by new or existing employees employed directly by the company and engaged in specific activities in the project. Working hours for both the company's employees and owners may be included.
- Expenses for public and private knowledge providers, both Danish and foreign (e.g. universities, GTS institutes, contract research institutes, private knowledge companies and specialist companies).
- Expenses for purchase of materials, experimental equipment, equipment rental as well as depreciation costs on new equipment corresponding to the extent and the time it is used within the project. Such expenses must amount to at least DKK 10,000 per invoice to be included in the budget and the financial accounts

All expenses should relate to the well-defined Booster project that you describe in the application that should clearly state how significant development is still needed for the solution to be fully developed and ready for market implementation. Expenses and costs that are not specifically justified in the application, cannot be included in the budget or the financial accounts.

MissionGreenFuels does not fund projects with a fully developed solution ready for market implementation, with the remaining activities dealing mainly with sales, marketing, testing, documentation and commercial production. If the solution is already available on the market, and the project deals mainly with optimisation, further development, verification and documentation, the project is probably too far in its development to receive booster funding.

Evalueringskriterier:

All applications will be evaluated on:

1. Quality of the idea – the quality of the research and innovation
2. Impact – value creation during and after the project
3. Quality of execution – efficiency in the project execution and the implementation of the results
4. Strategic fit to the MissionGreenFuels vision and Roadmap

Criteria 4 includes (but is not limited to) that the project:

- clearly contributes to creating societal value and value for the MissionGreenFuels partnership
- describes clearly the direction towards the Danish 2030 and/or 2050 climate goals, i.e. total time horizon and investment need for the potential CO2 reduction and long-term plan for the proposed solution
- contributes to maturing the entire Danish value chain
- clearly describes how the project fits into the EU legal framework
- can be scaled internationally
- contributes to CO2 reduction, job creation in Denmark and export potential
- contribute to lowering overall system costs in the production, distribution, and utilization of green fuels.

All criteria are included in the assessment and contribute to the overall assessment.

Evalueringsproces:

Applications must be submitted via “**Filkassen**”.

Criteria 1-3 will be evaluated by external reviewers, see details on the criteria in the guidelines section 3.3 ([link](#)). Criteria 4 will be evaluated by the Partnership Board of Directors. Please notice that criteria

4 is crucial for the evaluation and poor evaluation of this section alone can decide whether the applicant will receive funding or not.

Each proposal will be evaluated by at least two external reviewers.

Before proposals are subjected to external review by experts, the Partnership Director will ensure that the proposals comply with the formal requirements described in the call text. Applications which do not comply with the requirements will receive administrative rejection and will not be subjected to external review.

The 20 applications with the highest total score from the external expert reviews, will be evaluated by the MissionGreenFuels Board of Directors. If fewer than 20 applications are received, all will be evaluated by the MissionGreenFuels Board of Directors.

The members of the Board of Directors can be found [here](#). Applicants are asked to indicate whether they see any conflict of interest with any of these.

Roadmap for Green Fuels in Transport and Industry

Danish Roadmap 2024



MISSION
GREEN FUELS

About this publication:

The Roadmap for Green Fuels in Transport and Industry is developed and published by MissionGreenFuels in collaboration with Ramboll. MissionGreenFuels is one of four state-initiated mission-driven green research and innovation partnerships supported by the Innovation Fund Denmark and Next Generation EU.

MissionGreenFuels
www.missiongreenfuels.dk

MissionGreenFuels has received funding from The Innovation Fund Denmark – 1150-00001B and Next Generation EU.

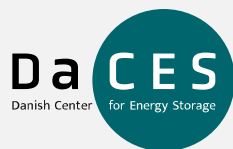
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The partnership



Secretariat

The MissionGreenFuels secretariat consists of Aalborg University (Lead), Energy Cluster Denmark and Danish Center for Energy Storage



+ Additional input from Danish business lighthouses “erhvervsfyrtårn”

GESEK
Fyrtårn Sydjylland

Baltic Energy Island
Fyrtårn Bornholm

CO2Vision
Fyrtårn Nordjylland

Water Technology
Fyrtårn Midtjylland

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List of Abbreviations

| | | | |
|------------------------|---|-----------------------|---|
| AEC | Alkaline Electrolysis Cells | LCA | Life Cycle Assessment |
| AF | DEA Analysis assumptions for Energinet | LCOE | Levelized Cost of Energy |
| ASTM | American Society for Testing and Materials | LCOH | Levelized Cost of Hydrogen |
| AtJ | Alcohol-to-Jet | LHV | Lower Heating Value |
| BAU | Business as usual | LNG | Liquified natural gas |
| BOP | Balance of Plant | LOHC | liquid Organic Hydrogen Carrier |
| CAGR | Compound Annual Growth Rate | LPG | Liquified Petroleum Gas |
| CCS | Carbon capture and storage | LSFO | Low Sulphur Fuel Oil |
| CCU | Carbon capture and utilization | MDO | Marine Diesel Oil |
| CCUS | Carbon capture, utilisation, and storage | MeOH | Methanol |
| CH₄ | Methane | MGF | MissionGreenFuels |
| CO₂ | Carbon Dioxide | MSW | Municipal Solid Waste |
| CO₂e | Carbon Dioxide Equivalent | Mt | Megatonne |
| CORSIA | Carbon Offsetting and Reduction Scheme for International Aviation | MWh | Megawatt-hour |
| CRI | Commercial Readiness Index | NG | Natural Gas |
| DAC | Direct Air Capture | NH₃ | Ammonia |
| DH | District Heating | NO_x | Nitrogen Oxides |
| DME | Dimethyl ether | NZIA | Net Zero industry Act |
| EC | European Commission | OEM | Original Equipment Manufacturer |
| EJ | Exajoule | OFMSW | Organic Fraction of Municipal Solid Waste |
| ETS | Emissions Trading System | OFW | Offshore Wind |
| FAME | Fatty Acid Methyl Ester | PEM | Proton Exchange Membrane |
| FCEV | Fuel Cell Electric Vehicle | PPA | Power Purchase Agreement |
| FEED | Front End Engineering Design | PS | Point source (CO ₂ capture) |
| FID | Final Investment Decision | PtG | Power-to-gas |
| FOG | Fats, Oils, and Greases | PtL | Power-to-liquids |
| FT | Fischer-Tropsch | PtX | Power-to-X |
| G/FT | Gasification/Fischer-Tropsch | PV | Photovoltaic |
| GDP | Gross Domestic Product | R&D | Research and Development |
| Gt | Gigatonne | RES | Renewable Energy Sources |
| GW | Gigawatt | RWGS | Reverse Water Gas Shift |
| H₂ | Hydrogen | SAF | Sustainable Aviation Fuel |
| HEFA | Hydroprocessed Esters and Fatty Acids | SNG | Synthetic Natural Gas |
| HFO | Heavy Fuel Oil | SOEC | Solid Oxide Electrolyzer Cell |
| HHV | Higher Heating Value | SOFC | Solid Oxide Fuel Cell |
| HTL | Hydrothermal Liquefaction | SPK | Synthetic Paraffinic Kerosene |
| HVO | Hydrogenated Vegetable Oil | STEM | Science, Technology, Engineering, and Mathematics |
| ICAO | International Civil Aviation Organization | TRL | Technology Readiness Level |
| ICE | Internal Combustion Engine | TTW | Tank-to-Wake |
| IEA | International Energy Agency | TW | Terawatt |
| IMO | International Maritime Organization | TWh | Terawatt-hour |
| IPCEI | Important Projects of Common European Interest | WTT | Well-to-tank |
| KEFM | Danish Ministry of Climate, Energy and Utilities | WTW | Well-to-wake |

Foreword

Green fuels represent one of the key levers to decarbonize our energy system, alongside renewables, electrification, and energy efficiency measures. In “hard to abate” industries like heavy transport, shipping, and aviation, where fossil fuels have long been dominant, green fuels offer a path forward. Derived from green hydrogen or bio-resources, these fuels are poised to play a central role in overcoming the complex challenges of the global energy transition. However, the journey to fully integrate these fuels into our existing energy systems is not without its hurdles. Scaling green fuels production, integrating them into our current infrastructure, and lowering the cost requires innovation, collaboration, and coordinated action.

For Denmark, green fuels present a strategic opportunity beyond national-level decarbonization efforts. By advancing innovation and development in areas like electrolysis and efuel synthesis, systems integration, carbon capture technologies, and sustainable biofuel production, Denmark can position itself as a global leader in green fuel technology. This leadership could boost energy exports, create thousands of clean jobs, and strengthen Denmark's economic competitiveness. Moreover, by exporting its technology and expertise, Denmark can help other nations accelerate their shift to green fuels, contributing to a more rapid and coordinated global transition to low-carbon energy systems.

This roadmap is designed to guide Denmark towards these goals, aligning with the government's ambitious targets of reducing carbon emissions by 70% by 2030 and reaching full decarbonization by 2050. Originally introduced in 2021, the roadmap has been updated to reflect the latest national and global developments, ensuring it remains a relevant and tool for researchers,

policymakers, and other central stakeholders.

The roadmap, developed by MissionGreenFuels in collaboration with key partners, provides a comprehensive framework to address technical, commercial, regulatory, social, and sustainability challenges that impede the widespread adoption of green fuels. The document identifies critical activities across these domains, with a focus on advancing technology readiness, scaling production capabilities, and improving market competitiveness of green fuels.

This document explores the following dimensions:

- **Technical innovations:** Advancing production, storage, distribution, and offtake technologies to enhance efficiency and scalability.
- **Commercial strategies:** Lowering costs and improving market competitiveness to ensure economic viability vis-à-vis conventional fossil-based fuels.
- **Regulatory frameworks:** Supportive policies that incentivize the growth and integration of green fuels into the broader energy system.
- **Social considerations:** Public perception, community engagement, and workforce development to foster broad societal support and a social license to operate.

By taking a holistic approach, this roadmap outlines clear priorities and actionable steps for green fuels stakeholders. It aims to drive immediate actions and guide long-term strategies to position Denmark as a leader in green fuels, supporting both national and global climate goals.

Executive Summary

Roadmap for Green Fuels in Transport and Industry 2024

Green fuels are critical in meeting climate targets

Green fuels **will significantly contribute** to the Danish climate goals and the global ambitions of a green transition.

Green fuels offer a substantial opportunity for **Danish technologies and exports to support other countries in achieving their climate goals**. This could be via export of Danish-born innovation and technologies, or export of fuels to neighbouring countries.

MissionGreenFuels drives the development of the green fuels value chain by supporting R&D projects that address key needs such as technological innovation, systems integration, cost reduction, and processes optimization.

MissionGreenFuels also emphasizes **research on social, sustainability, safety, and market aspects** related to green fuels.

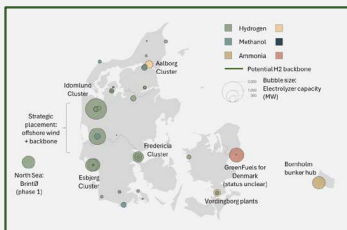
The Danish roadmap for green fuels guides the way

The **roadmap highlights the necessary pathways** to advance the adoption of green fuels in Denmark's transport and industrial sectors.

The roadmap examines several important topics:

- **R&D in production, user, and distribution technologies** to enhance efficiency and scalability of green fuels technologies
- **Strategies for reducing costs and improving market competitiveness**
- **Policies and frameworks necessary** to support the growth and integration of green fuels into the energy system.
- **Public perception, community engagement, and workforce development** to foster broad societal support.

Reading Guide



Introduction and Context

New to green fuels? Start here for an introduction to green fuels and an overlook of recent national strategies, projects, and infrastructure plans.

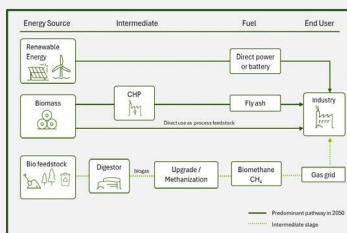
Green Fuels Introduction

Danish potential

Innovation Ecosystem

Systems Integration

Social and Sustainability



Sector Pathways

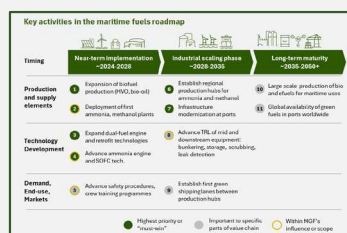
How will green fuels assist in transitioning certain sectors? For a look at sectoral level decarbonization pathways for industry, road transport, and the aviation and maritime sectors, please refer to Chapter 7.

Industry

Road Transport

Maritime

Aviation



Fuel Roadmaps

How do we get there? For a look at the key short- and long-term activities to advance green fuels, as identified by MGF stakeholders, please refer to chapter 8.

Green Hydrogen

Intermediary Fuels

Maritime Fuels

Aviation Fuels

Insights from the Green Fuels roadmap

In the roadmap, key activities in the short-and-long term are identified across various themes including technical, commercial, regulatory, and financial, and social elements. Timing of when activities will happen is informed by the latest developments in industry and policy. Key takeaways are shown below:



Availability of sufficient quantities of green power is identified as the most important prerequisite for developing H₂-based green fuels. Without it, the sector will fail to launch.



Infrastructure development should be prioritized: Integration with existing and future energy systems, including electricity grids, district heating networks, gas/H₂ pipelines, and CO₂ supply chains, is critical for the success of green fuels.



Advancement of low-TRL technologies in biofuel and efuel production is essential for new synthesis pathways that use advanced/sustainable feedstocks.



The energy transition requires efuels, but its success hinges on the successful deployment of other technologies that are still nascent and expensive, such as green hydrogen and carbon capture technologies.



First movers and reference projects are needed: Companies that take risks and innovate can set a strategic direction quickest and can position themselves to capture the most attractive elements of the value chain and take those learnings forward.



From CCS to CCU: Utilization, not storage, of biogenic CO₂ will be needed long-term to provide carbon feedstock for efuels production. Long-term direct air capture (DAC) will likely be needed as sources of biogenic CO₂ will be tapped.



Research and innovation is cornerstone: Denmark's strong innovation ecosystem, supported by government, industry, and academia, is fundamental to driving the commercialization of green fuels and maintaining Denmark's leadership position.



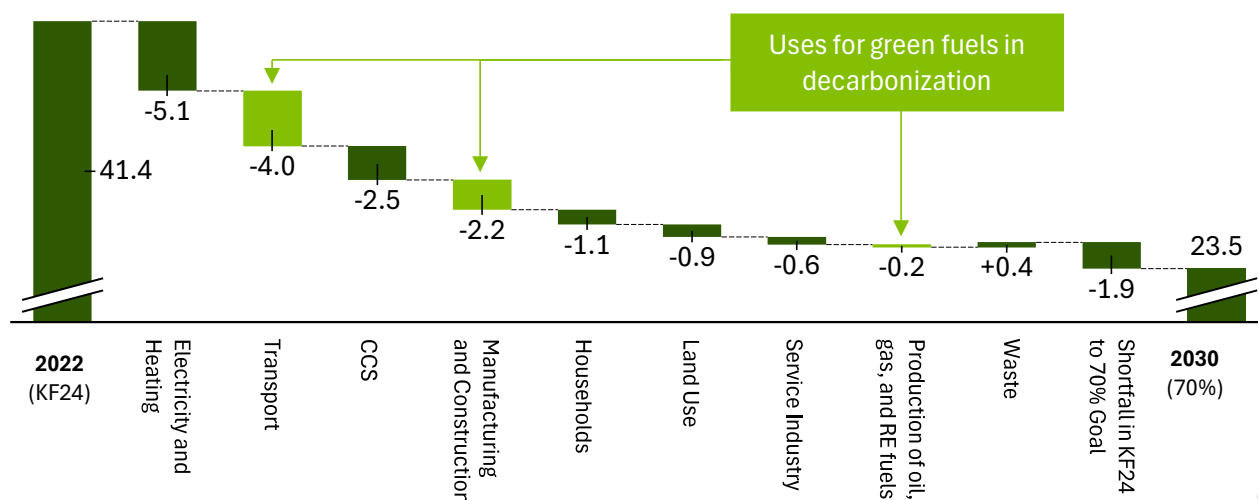
Social aspects should not be overlooked: Ensuring the social license to operate is critical. This requires community engagement, transparency, and broad stakeholder involvement.

Green fuels important contribution to emission reductions in the short and long term

Short term: Emissions reductions via green fuels will primarily come from fuel switching (biomethane injection, fossil-to-bio drop-in replacement, renewable biodiesel fuel blending) and niche applications of green hydrogen in transport and industrial uses.

Long term: Build-out of methanol, ammonia, and sustainable aviation fuel (SAF) production facilities with their usage in decarbonizing the maritime and aviation sectors, both domestically and for international routes.

Danish GHG reduction measures 2022-2030, Mt CO₂e (KF24)



Driving Denmark's green future: MissionGreenFuels' Roadmap to green fuels leadership

This roadmap provides a structured and urgent call to **action for advancing the adoption of green fuels in Denmark's transport and industrial sectors**, guiding stakeholders through key milestones from now until 2050.

The roadmap is **developed through extensive collaboration with Danish stakeholders** and emphasizes the importance of coordinated action and the necessity to support demonstration and upscaling activities immediately to meet both national and international climate goals.

MissionGreenFuels plays a central role in developing and driving the implementation of the roadmap for green fuels in Denmark. As a state-initiated, mission-driven partnership supported by Innovation Fund Denmark, **MissionGreenFuels brings together key stakeholders across research organizations, industry, and government** to address the challenges and opportunities associated with green fuels in transport and industry.

The roadmap serves as a **strategic guide, developed by MissionGreenFuels in collaboration with experts and stakeholders, to align research and innovation efforts with Denmark's ambitious climate targets**. It outlines clear pathways for technological advancement, infrastructure development, and policy

support, all of which are crucial for scaling up the production and use of green fuels.

MissionGreenFuels uses the roadmap to identify critical inflection points, set priorities, and coordinate actions across the value chain, ensuring that Denmark remains at the forefront of the global green energy transition.

Through this roadmap, MissionGreenFuels aims to reduce uncertainties, support large-scale demonstrations, and drive the commercialization of green fuel technologies, ultimately contributing to Denmark's 2030 and 2050 climate goals.

Denmark's ability to attract private investments will be crucial, requiring a clear strategy that highlights the country's strengths in renewable energy and leadership in clean energy technologies.

There needs to be a focus on green fuels and PtX technologies, aiming to **make PtX the next "wind adventure"**. This would involve significant investment in innovation, infrastructure, and partnerships, both within the EU and globally.

Denmark could not only sustain its leadership in renewable energy but also **become a pioneer in the next generation of green technologies**, securing long-term economic and environmental benefits.

The roadmap is strategically designed to align research, development, funding, and policy initiatives with Denmark's ambitious climate goals for 2030 and 2050

Guiding funding and investments: It identifies key areas where investment is needed, such as infrastructure development, technological innovation, and scaling of green fuel production. By highlighting these areas, it helps direct both public and private sector investments to projects that will have the most significant impact on achieving Denmark's climate targets.

Shaping research and development: The roadmap outlines technological pathways and innovation needs. It serves as a framework for researchers and industry partners to focus their efforts on overcoming the technical challenges associated with green fuel production, storage, and distribution.

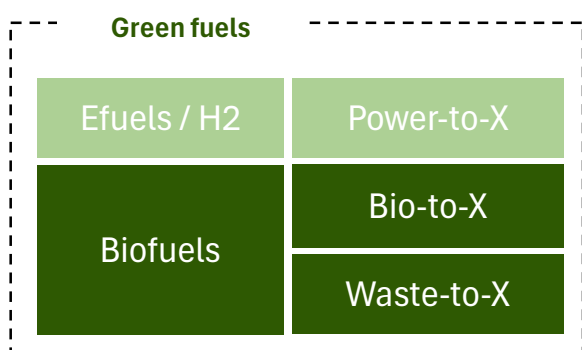
Informing policy development: Policymakers can use the roadmap to design regulations and incentives that support the green fuel industry. It provides a clear understanding of the regulatory needs and the types of policies that could accelerate the deployment of green fuels, ensuring they are integrated effectively within Denmark's broader energy system.

Strategic planning for infrastructure: The document emphasizes the importance of infrastructure integration, such as the development of hydrogen backbones and connections to renewable energy, water, CO₂, and district heating systems.



1. Introduction to Green Fuels

Green fuels, also known as renewable or sustainable fuels, are produced using renewable or low-carbon energy sources and can serve as a substitute for fossil fuels. Depending on their production pathway, they can be carbon-neutral or even carbon-free. The input renewable energy can for example be wind and solar energy or organic material (biomass). Broadly, they are split into two categories: biofuels, based on biogenic sources, and synthetic fuels (efuels), based on low-carbon hydrogen derived from the electrolysis of water using renewable electricity. This combined process is commonly referred to as Power-to-X (PtX) where the “X” could be hydrogen, or a hydrogen derivative used for fuel, mobility, heat, or storage applications. Sometimes, hydrogen and efuels are also referred to as “indirect electrification”, wherein electricity can be stored in chemical bonds of these molecules and used later for energy purposes. This differs from direct electrification where electricity is used directly, without any conversion steps.



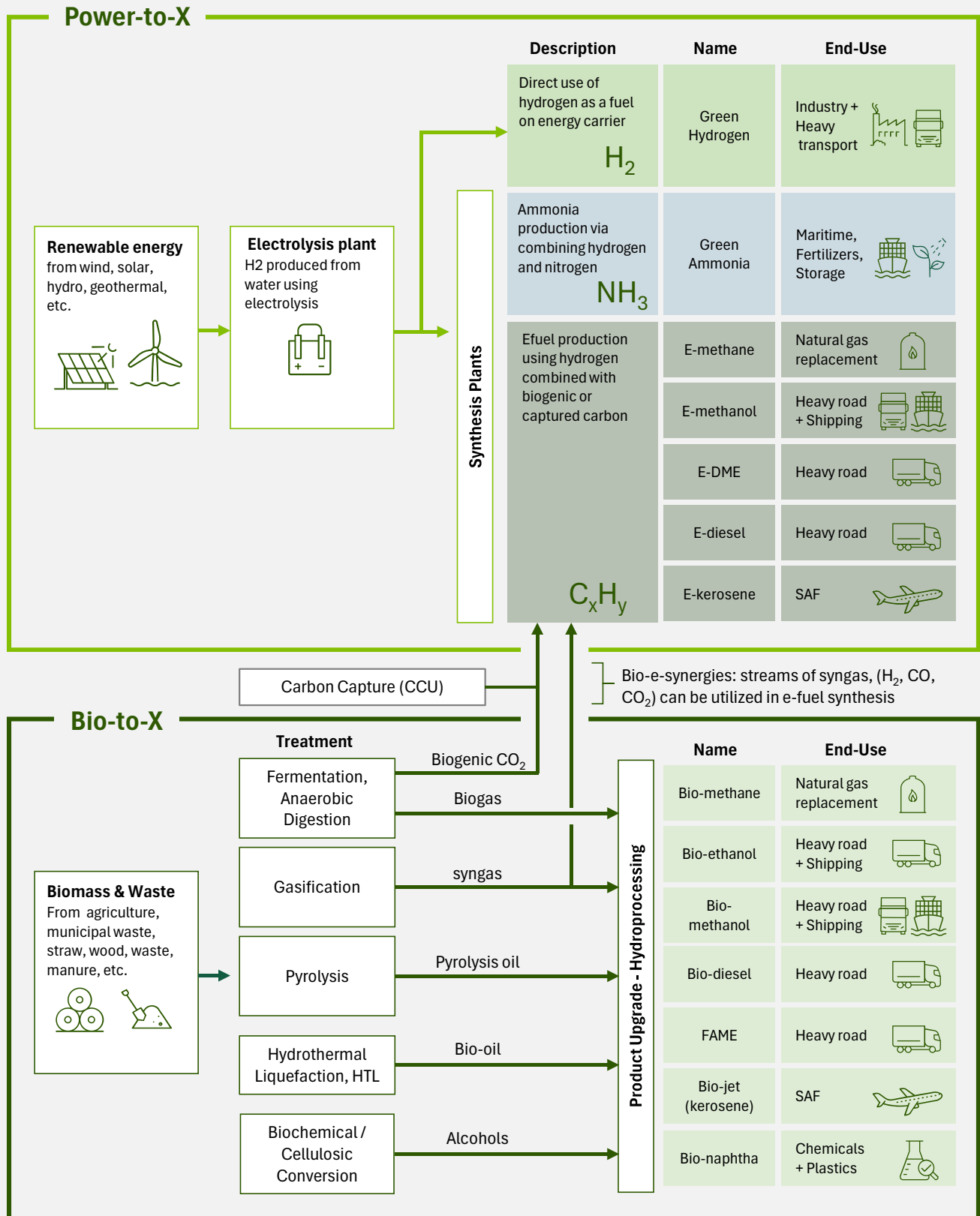
Each fuel, either liquid or gaseous, will have properties that make them technical replacements for conventional fuel sources. Depending on their energy densities, transport and handling properties, carbon inputs, combustion characteristics, existing infrastructure, some fuels are more attractive than others in certain applications. For example, biogas upgraded to biomethane can be directly injected into the existing gas grid and used in industry, however ammonia cannot be used in existing maritime engines

and would require specialized engines, or fuel cells, that can use this type of fuel. These facts influence the timing of when green fuels can ultimately replace their conventional counterparts due to the fuel requirements of existing fleets or trucks, ships, or airplanes.

Other terminology used

- **Intermediary fuels:** serve as transitional fuels that facilitate the integration and utilization of renewable energy within the existing energy infrastructure and vehicle fleets (MeOH/DME and bio-oil, for example)
- **Drop-In fuels:** Renewable fuels compatible with existing infrastructure and engines without requiring modification
- **Bio-to-X:** Process of converting biomass into various forms of fuels or chemicals, such as biofuels, biogas, or biochemicals.
- **Waste-to-X:** Process of converting waste materials (e.g. plastics, OFMSW) into useful products like fuels or chemicals

There is lively debate between energy experts and policymakers about the extent that green fuels will play in future energy systems in both 2030 and 2050. Projections for hydrogen demand in 2050 differ greatly between various publications (based on key assumptions on end-use viability and adoption rates), however it is generally accepted that H₂ will amount to 10%¹ to 26%² of primary energy in 2050. Regardless, both the low-end and high-end of these projections result in massive investment and scaling needs.³ The levers that will impact this involve electrification, how much hydrogen is used for derivative applications such as sustainable aviation fuels (SAF) and maritime fuels, availability of sustainable biomass feedstocks, and how quickly price parity can be reached with conventional fuels, alongside demand-side, behavioral, and social aspects.

Figure 1.1: Green fuel production and end-use

Note: This is a non-exhaustive list and a simplification of often complex multi-step production processes. There are other lower TRL technologies and pathways not shown in the above diagram.

Source: Adaption of Green Power Denmark's "Recommendations for a Danish Power-to-X Strategy"⁴, Ramboll analysis

Intermediary fuels

In the original roadmap, the term intermediate or intermediary fuel was used to denote certain fuels that will serve a transitional or interim purpose. These are fuels that can be used in existing vehicle packages such as internal combustion cars or marine engines with minimal to no modification. The reason that they are intermediate is A) the transition to road transport electrification will not be quick enough based on current trajectories and existing asset lifetimes of for example lorries, vans, etc and an “intermediate” fossil fuel replacement is needed B) developing methanol, DME, or bio-oil production now for uses in existing engines allows the production and technology to scale to aviation fuels in the long term wherein carbon based fuels must be diverted to aviation purposes because of biomass/biogenic CO₂ constraints. This is covered in greater detail in Chapter 7. The term intermediate fuel will also be adopted in this roadmap.

RFNBOs: Renewable Fuels of Non-Biological Origin

The EU refers to RFNBOs as liquid or gaseous fuels utilized in the transport and industrial sectors. These fuels differ from biofuels or biogas because their energy content is derived exclusively from renewable sources other than biomass.

Production pathways for green fuels

For both PtX based efuels and biofuels the feedstocks must be sustainable for these solutions to be truly green. For PtX, renewable energy is the input and for Denmark this is primarily onshore and offshore wind and solar. For biofuels, the feedstocks typically consist of organic fraction of municipal solid waste (OFMSW), manure, agricultural residues (straw, husks, etc), wood wastes, waste oils and fats. It is important to note that to be considered sustainable, the bio-feedstocks must align with the EU RED III rules for “advanced” feedstocks and must not include energy crops or crops grown for food.

The main technology for PtX is electrolysis used to produce green hydrogen. Further synthesis steps such as the Haber-Bosch Fischer-Tropsch process can combine hydrogen with various carbon and nitrogen streams to produce ammonia or other longer chained hydrocarbons. For biofuels, the main technologies are anaerobic digestion, fermentation, gasification, pyrolysis, and hydrothermal liquefaction (HTL). Each fuel production process can have either one of several synthesis steps, each adding complexity, cost, or inefficiencies (thermal losses) into the conversion process.. A simplified production and end-use diagram is shown in Figure 1.1 with the main green fuels shown

with the production steps and potential end-uses.

The technology readiness levels (TRLs) of the key green fuels technologies and additional detail on the main challenges and opportunities are covered in Chapter 8 and Appendix 1.

The best use of green fuels

Electrification will play a major role in decarbonizing large portions of the transport and industrial sector. In the Danish government’s PtX strategy⁵, it is assessed that the majority of national transport can be directly electrified in the long run, particularly light road or heavy transport traveling shorter distances. Hydrogen, efuels, and biofuels, should be reserved for cases in which electrification is not viable due to technical or economic requirements. This means that hydrogen and its derivatives will be utilized mostly in heavy transport, shipping, and aviation.

Identifying the correct use cases for green fuels is crucial. It is known today that battery technologies are advancing at a rapid pace, have experienced fast cost reductions on the learning curve, and are seeing mass adoption as the consumer EV market becomes mature. Therefore, it would be incorrect to apply green hydrogen for light mobility and place it in the roadmap. Similarly, if we know that heat pumps for residential and commercial low-temperature heating are seeing successful adoption, it would be incorrect to label hydrogen as the heating fuel of the future. There are of course exceptions to each of these examples, but generally speaking, green fuels will see little practical use in light-mobility or low-temperature heating.

Scarcely renewable energy resources should be used wisely as the more green energy is needed for green fuels, the more land or ocean resources must be exploited. This results in more environmental impact, more raw material use in PV panels and wind turbines, and additional negative impacts on terrestrial and marine biodiversity. For more on sustainability aspects, see chapter 5.

Green fuels in the energy trilemma

Green fuels are central in addressing the energy trilemma by enhancing energy security and sustainability. They reduce dependency on imported fossil fuels by utilizing local renewable resources like biomass, wind, and solar power, thus bolstering energy security. Sustainability is a key advantage, as green fuels significantly reduce greenhouse gas emissions and can support the circular economy by utilizing waste streams. Technologies like PtX enable the production of hydrogen and synthetic fuels using renewable electricity, achieving zero or near-zero emissions.

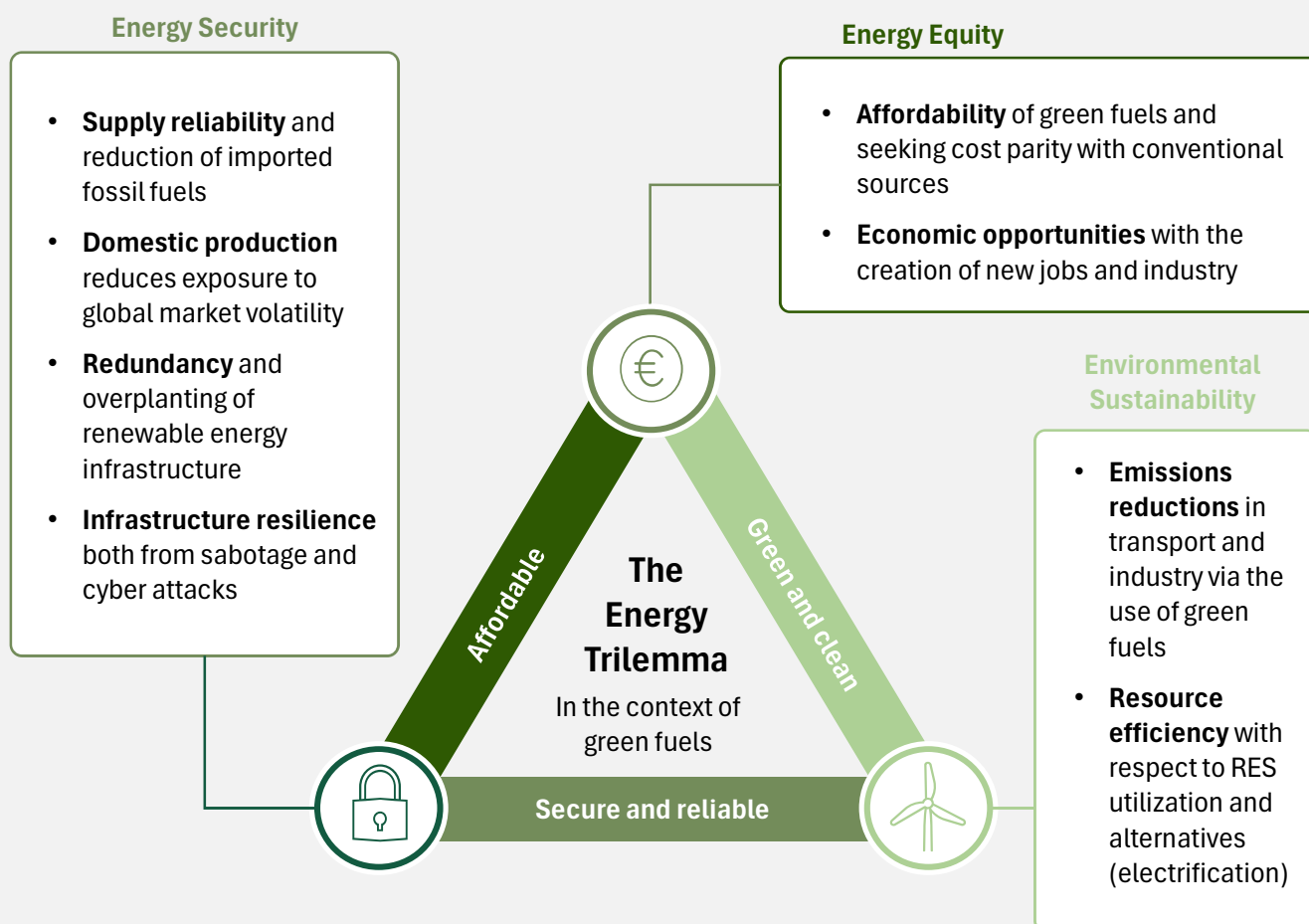
However, green fuels currently lack affordability. Initial production costs are higher compared to conventional fossil fuels, mainly due to feedstock costs, the nascent stage of technologies and infrastructure development, and relative cheapness of fossil fuels. Despite this, technological advancements and economies of scale are expected to reduce costs over time, making green fuels more economically competitive. If, or when, parity is met depends on various factors. Currently, green fuels are poised to meet two out of the three pillars of the energy trilemma—energy security and sustainability—but affordability remains a challenge that will likely be addressed with continued innovation and supportive policies. Achieving affordability will be imperative to accelerate market uptake of green fuels and will be a key focus in the coming chapters.

The security of supply angle

The adoption of green fuels enhances Denmark's energy security by providing an alternative to imported fossil fuels, thus reducing vulnerability to geopolitical risks. The Russian war against Ukraine has highlighted the importance of energy independence, as European countries seek to decrease their reliance on Russian natural gas. Denmark's strategy, in alignment with the EU's REPowerEU plan, focuses on increasing biomethane production and expanding renewable energy sources, aiming to replace imported energy supplies with domestically produced, sustainable alternatives.⁶

Additionally, by enabling the storage and conversion of renewable energy into storable and transportable fuels as gases and liquids, green hydrogen provides a flexible energy reserve that can be tapped into during periods of low renewable energy production.

Figure 1.2: The Energy Trilemma



This flexibility helps to stabilize the grid and ensure a consistent energy supply, even when wind and solar outputs fluctuate. Curtailment and grid surplus (high generation but low consumption) issues can be addressed by allowing electrolyzers to provide flexible offtake solution for green power produced. The ramp rate and dynamics of the electrolyzer are important considerations here.

The integration of green hydrogen into the national grid also supports the continuous build-out of renewable energy infrastructure when the grid cannot handle the added generation capacities, one of the identified bottlenecks of mass build out of renewables, This is covered more in Chapter 4: Systems Integration.

Cost Elements

Green fuels are more expensive than conventional fuels and will be so until production costs come down or conventional fuels are penalized (e.g. pollution costs are internalized). Green fuel production can be considered a conversion process whereas fossil fuel production is an extraction process – wherein the conversion has already taken place geologically over millions of years of pressure and heat. These dynamics make it inherently more challenging for green fuels to compete on cost. The production of green fuels involves multiple energy-intensive steps. These include the generation of renewable energy (e.g., wind, solar), the conversion of that energy into a usable form (e.g.,

electrolysis for hydrogen), and further processing or refinement to produce efuels. Each of these steps introduces inefficiencies, cost, and complexity. Moreover, the infrastructure required for the production, distribution, and storage of green fuels is still underdeveloped and requires significant capital investment. In contrast, the existing infrastructure for fossil fuels is well-established, further compounding the cost and disadvantage for green fuels.

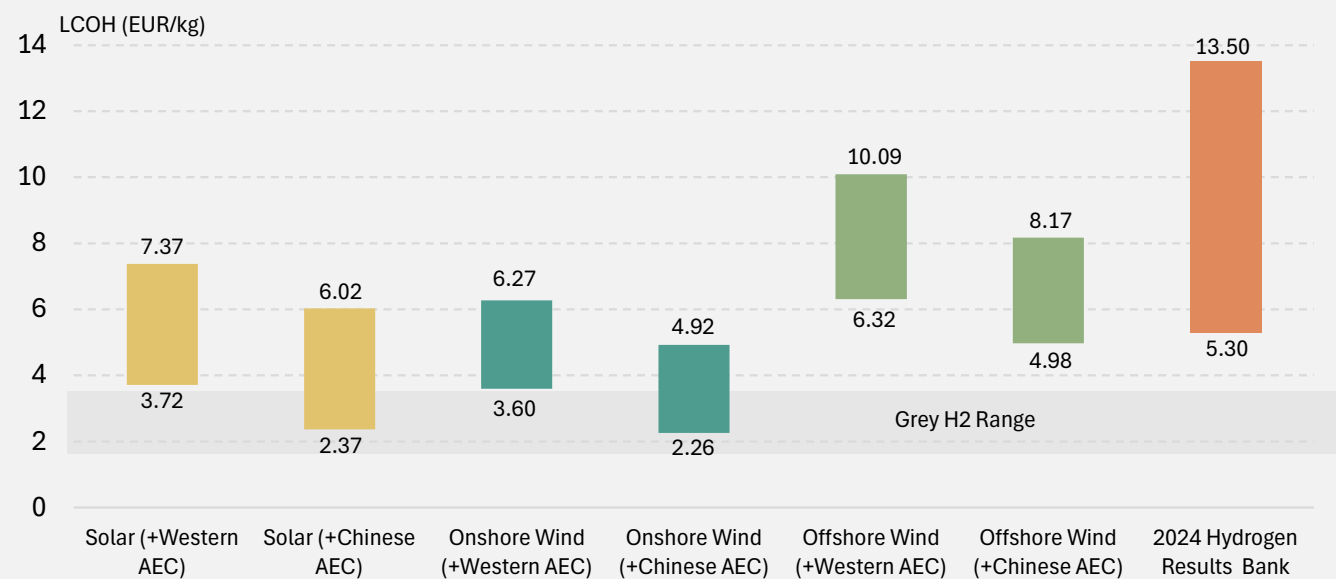
Hydrogen costs

The main price element for most hydrogen is electricity cost which can make up 50-80% of the levelized cost of hydrogen (LCOH). Therefore, the cost of energy (e.g. solar vs wind) is extremely important for cost competitive hydrogen (and derivatives) production. Cheaper electricity means cheaper hydrogen which means cheaper efuels. Cost reductions, particularly offshore wind, will be critical for Denmark to compete on hydrogen price. Electrolyzer plant capex is also important. Currently, alkaline electrolyzers plants (includes stack, EPC, BOP) range in the costs of ~800-1000EUR/kW in the west and about a third of that cost in China.⁹ CAPEX costs for electrolyzer plant typically make up around 30% of the cost of hydrogen.

Many analysts predict that cheap electricity + cheaper electrolyzers can make hydrogen cost competitive with grey hydrogen in the near-future (e.g. 2-3EUR/kg hydrogen). China is already producing at 2.50/EUR.¹¹

Figure 1.3: Levelized Cost of Hydrogen (LCOH) Estimates, 2023

Different renewable technologies shown with Western and Chinese Alkaline Electrolyzers (AEC)



Notes: Low end and high end LCOE estimates for solar (utility scale), onshore, and offshore wind from Lazard LCOE+ Western alkaline electrolyzers assumed capex of 850EUR/kW. Chinese Alkaline assumed capex of 270EUR/kW
Other assumptions: 7% discount rate, 30-year lifetime, 55kWh/ kg H2, 4000 FLH, LCOH does not include sale of heat or O2
Source: Lazard LCOE+ June 2024⁷, Agora Energiewende LCOH Calculator⁸, BloombergNEF⁹, EC H2 Bank Results¹⁰, Ramboll Analysis

Ongoing biogas/biofuels projects:

There are over 150 operational biogas upgrading facilities in DK of which livestock waste (slurry, manure) constitutes around 75 pct. of the biomass input.¹² Many of these sites are biomethane upgrading facilities that can inject methane into the national grid. Within Denmark, the company Emmelev A/S produces 1st generation biodiesel using rapeseed oil while the company Daka ecoMotion A/S FAME biodiesel using animal fat and other residual products. Overall, domestic production of liquid biofuels is limited.

Ongoing PtX projects in DK

Currently, there are over 40 active PtX projects in Denmark, the majority of them located in Western Jylland.¹³ Most of the planned gigawatt scale sites are pure hydrogen production (feed-to-pipeline), but there are several examples of PtX plans to include production of derivatives including:

Ammonia:

- Skovgaard Energy REDDAP: "Renewable Dynamic Distributed Ammonia Plant, Lemvig (operational)
- Bornholm Bunker Hub, Rønne (concept)

- CIP Høst, Esbjerg (Hydrogen and Ammonia). (FEED)

Methanol:

- European Energy, Kassø facility (construction)
- Green2X, Vordingborg Biofuel (under approval)
- Greengo energy, Megaton Phase 1 (concept)

Sustainable Aviation Fuels:

- Arcadia efuels, Vordingborg (under approval)
- MeSAF, Aalborg to be integrated with existing Power2Met facility (feasibility study completed)
- CIP Fjord PtX, Aalborg (concept)

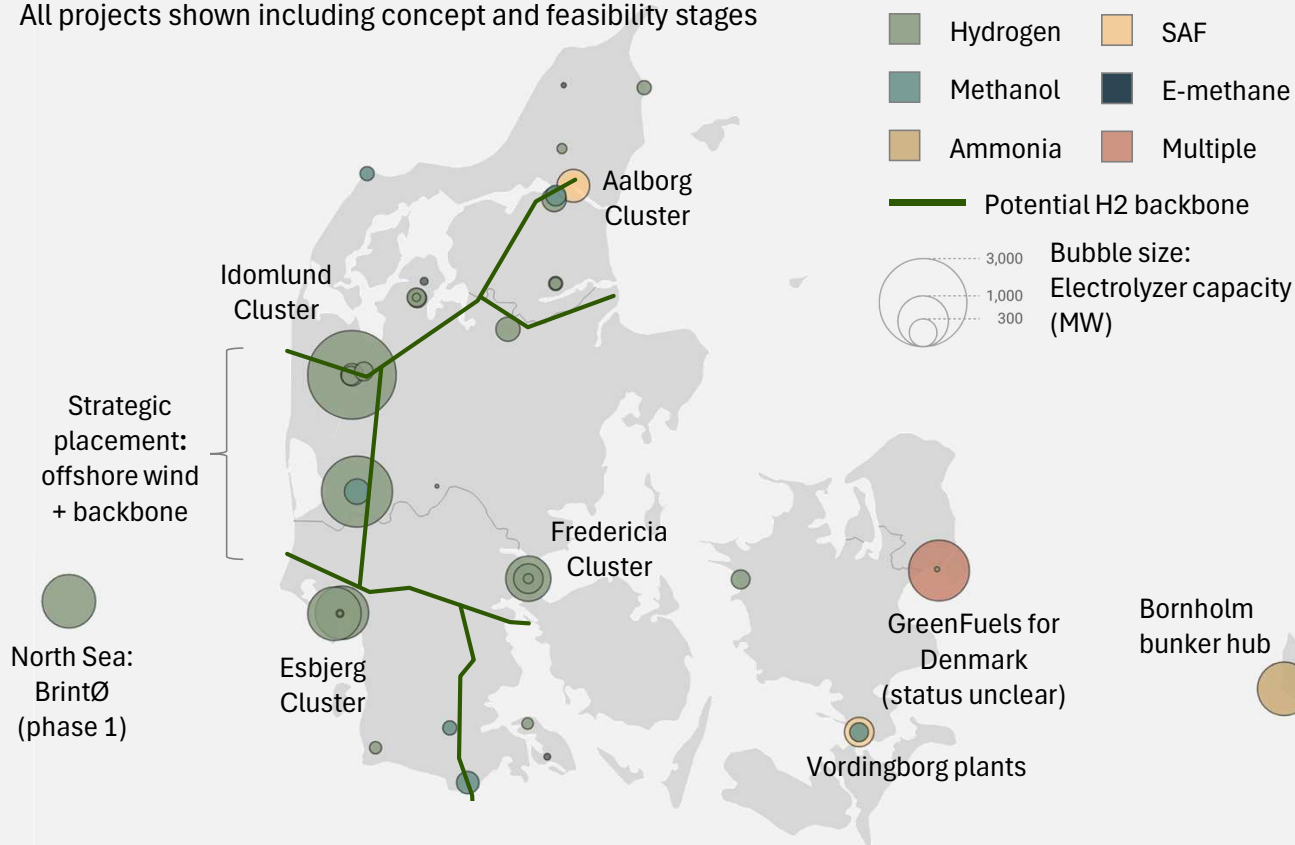
E-methane:

- Andel and Nature Energy (Shell) Biogas +PtX Glansager (operational)
- Electrochaea P2G-Biocat, Roslev (under approval)
- = First of a kind in DK (operational or soon-to-be)

Note: the above lists are not exhaustive

Figure 1.4 PtX projects in Denmark

All projects shown including concept and feasibility stages



Source: Brintbranchen "Brint i Tal"¹³, Rystad Energy, Guidehouse European Hydrogen Backbone¹⁴, Ramboll Analysis

Planned infrastructure: hydrogen backbone

Much of the ongoing discussion related to hydrogen in Denmark surrounds the development of the hydrogen backbone to Germany. The pipeline, likely to be built in phases, would stretch from the southern border, and up through Western Jylland, where it eventually would connect to a hydrogen storage facility in Lille Torup. The first section of the backbone would consist of a repurposed natural gas pipeline. The final routing and connections points are still being studied and will be influenced by current knowledge of hydrogen projects and expectations about the landing of offshore wind power connected to the ongoing North Sea offshore wind auctions.

Energinet has entered a cooperation agreement with German Gasunie, who is responsible for developing the German part of the backbone (“hyperlink 3”).¹⁵ Such a pipeline would allow for hydrogen produced in Denmark, to be delivered to Germany, where it would be used in the German industrial and transport sector (substantially more existing demand than Denmark).

The pipeline is still undergoing user studies, route selection studies, FEED studies with additional clarity expected in end of 2024. Final investment decision (FID) is expected in Q1 2025 based on the latest information.¹⁶ The concrete investment decision for establishing the hydrogen infrastructure is made by Energinet who requires approval from the Ministry of Climate, Energy, and Utilities, which depends on demonstrating sufficient demand and positive socio-economic benefit. If FID is made, tendering, environmental studies, and further engineering work would commence in 2025. Construction would take place in 2027-2028 with the first gas exports to Germany ready in 2028. Storage in the North to Lille Torup would be connected in 2030.

Outside of the main backbone, hydrogen pipeline branching infrastructure will also be needed. This includes connections between small scale producers and users of hydrogen, not directly connected to the main backbone. Evida is responsible for developing this part of the Danish hydrogen network.

Many proponents of the backbone point to the following benefits:

- Increased load factors for PtX plants significantly improving the business case for producers
- Socioeconomic benefits of 30-75 billion DKK by 2060 compared to a BAU scenario (highly dependent on assumed price levels of offtake)¹⁷
- Infrastructure provides incentives to invest in PtX capacity (and offshore wind overplanting capacity)

and gives a route-to-market for producers

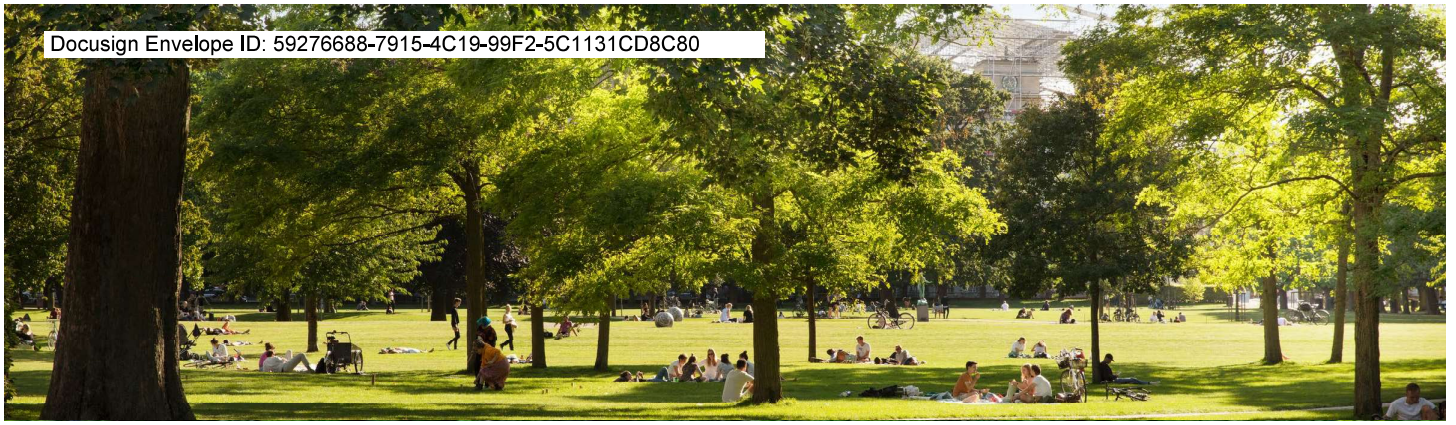
- Increases demand for Danish hydrogen and helps Denmark become a net exporter of green energy.

When commercial market participants were surveyed by Energinet, they found that 96% of respondents stated the need for hydrogen infrastructure and 97% of production from H₂-only producers is expected to be destined partly or wholly for export.¹⁷ This underscores the crucial need for hydrogen infrastructure to the overall PtX project landscape. Without it, most large-scale hydrogen plants will undoubtedly never move out of the concept and feasibility stages and reach FID. Transporting those volumes of hydrogen via truck would be impractical and uneconomical.

Figure 1.5: Proposed backbone routing



Source: Energinet, Information package June 2024¹⁶



2. Danish Potential

Danish climate goals

Denmark aims to reduce its carbon emissions by 70% by 2030 and achieve climate neutrality by 2050. The latest KF24 analysis places Denmark's current emissions at 41.4 MtCO₂e.¹⁸ The 2030 goal, over 1990 levels is 23.5 MtCO₂e, meaning that around 18.2Mt will have to be reduced in the next six years. The main reductions are projected to come from electricity and heating, transport, CCS, and manufacturing, respectively. The expected reductions between now and 2030 are shown in Figure 2.1.

Danish Energy Agency assessment of PtX potential

In 2021, the DEA assessed the “robust potential” of PtX and efuels to contribute to climate reduction targets for 2030 and 2050.¹⁹ Robust potentials is defined as areas of application where direct electrification is not possible or expected to be more expensive than

adopting PtX fuels. For some applications, there is an “indeterminate extent” or “uncertain potential” for the effectiveness of PtX and efuels for sectors or applications which include significant adoption of electrification as being the most practical or cost-effective solution. Some transitional solutions, like blending methanol or efuels into gasoline and diesel are deemed possible in the short term but likely not long-term cost-effective solutions. The expectation is that they will not be competitive compared to 2nd or 3rd generation biofuels in the long run. Overall, the DEA estimates PtX can contribute 1.3 - 5.1 MtCO₂e of which 0.5 - 1.9 MtCO₂e would contribute to the domestic 70% target for 2030. For 2050, the estimate is a potential of 4.1 – 8.2 MtCO₂e of which 1.1 – 3.5 MtCO₂e would contribute to national targets. The majority of reductions would come from shipping and aviation or other “hard to abate” sectors. See Table 2.1 for a breakdown of PtX reduction estimates.

Figure 2.1: Danish GHG reduction measures 2022-2030, Mt CO₂e

Source: Danish Energy Agency KF24¹⁸

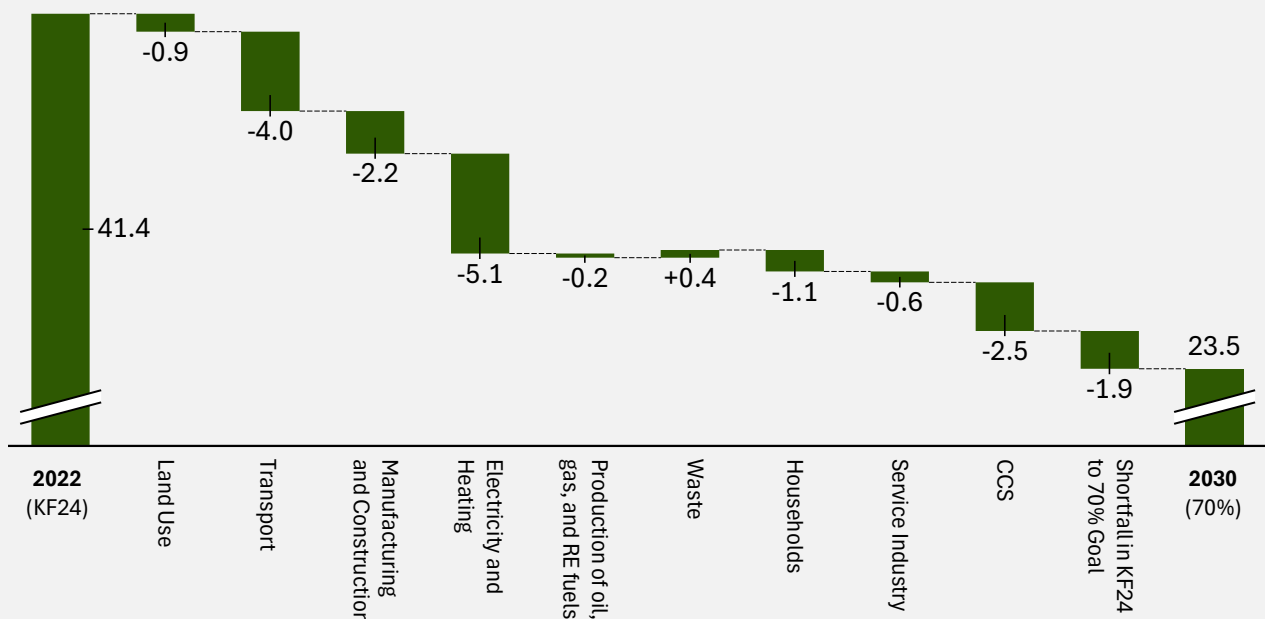


Table 2.1: DEA estimates for the use of PtX fuels in emissions reduction, Mt CO₂eSource: Danish Energy Agency “Demand for Power-to-X products”, 2021¹⁹**PtX Strategy**

| | 2030 | 2050 |
|--|------------------|------------------|
| Robust potentials | | |
| PtX to maritime | 0.6 - 1.2 | 1.9 - 2.6 |
| -of which domestic maritime | 0.1 - 0.4 | 0.4 - 0.7 |
| PtX for aviation | 0.3 - 2.5 | 1.5 - 3.0 |
| -of which domestic aviation | 0.02 - 0.13 | 0.08 - 0.15 |
| Robust potentials of indeterminate extent | | |
| H2 to road transport (vans, trucks, and buses) | 0.02 - 0.5 | 0.4 - 1.6 |
| H2 to industry, direct use | 0.0 - 0.1 | 0.0 - 0.5 |
| H2 or e-diesel to industry, internal transport | 0.0 - 0.2 | 0.2 - 0.5 |
| Efuels for defence/military (aircraft, ships, vehicles) | unknown | unknown |
| H2 to biogas production (refineries) | unknown | unknown |
| Production of chemicals (fertilizers, plastics) | unknown | unknown |
| Uncertain potential for transitional solutions that are not deemed cost-effective | | |
| Methanol blended into gasoline | 0.03 - 0.05 | 0.00 - 0.01 |
| Efuels blended into diesel/gasoline | 0.3 - 0.5 | 0.0 - 0.1 |
| Total estimated potential | 1.3 - 5.1 | 4.1 - 8.2 |
| Of which contributes to the 70 percent target | 0.5 - 1.9 | 1.1 - 3.5 |

Danish PtX Strategy

On March 15th, 2022, the Danish government entered into a political agreement (“The PtX Agreement”)²⁰ on the development and promotion of hydrogen and other green fuels. Building on the earlier 2021 PtX strategy which envisioned 4-6GW of electrolyzer capacity, the new PtX Agreement also dedicated funding to support production of PtX in Denmark and dedicated PtX taskforce, among other overarching measures shown in Table 2.2. The agreement aims to position Denmark as a leading force in Northern Europe for the production and export of green energy and fuels, while also establishing the country as a frontrunner in the development of PtX technology.








The agreement outlines several key initiatives, including the establishment of national hydrogen infrastructure, which will enable the production, storage, and distribution of green hydrogen across the country. Furthermore, the agreement emphasizes the importance of international collaboration, particularly with neighbouring countries like Germany, to create a robust market for green hydrogen. This collaboration is seen as vital for securing long-term offtake agreements and ensuring that Denmark can maintain its competitive edge.

A PtX taskforce²¹ was appointed that will run through 2026. The main goals are coordination between state and municipal authorities focusing on approval and permitting processes for PtX projects as well as

identifying barriers to sector development. Additional focus themes for the committee include infrastructure, permitting, water supply, grid flexibility, use of excess heat, and location siting for PtX projects.

Table 2.2: Danish PtX strategy measures

Source: KEFM, 2022

| Measure | Status |
|--|---|
| Denmark to target 4-6 GW of electrolysis capacity in 2030 |  |
| Dedicate 1.25 billion DKK to support production of PtX in Denmark |  |
| Enable direct lines, geographically differentiated tariffs, and local collective tariff structures |  |
| Enable the build-out of infrastructure for hydrogen in Denmark |  |
| Appoint of PtX task force to support developing a market for hydrogen and infrastructure for hydrogen in Denmark |  |
|  Complete  In progress | |

Danish Green Gas Strategy

The Danish Green Gas Strategy²², published in 2021, aims to transition Denmark's gas system to fully green by 2035, aligning with the broader goal of reducing greenhouse gas emissions by 70% by 2030. The strategy envisions a complete phase-out of natural gas, replacing it with biogas and other green gases like hydrogen and e-methane, with biogas expected to make up 70% of gas consumption by 2030. By 2035, the goal is to achieve 100% green gas consumption. The Green Gas Strategy presents nine interlinked objectives that represent the green gas while remaining competitive. The main strategic objectives for the strategy are listed below in Table 2.3.

The gas strategy outlines several hurdles to overcome. A significant challenge is modifying the existing gas infrastructure to handle an increasing share of biogas and new green gases like hydrogen, which requires substantial upgrades and potential repurposing of pipelines. Integrating PtX technologies into the gas system (hydrogen, e-methane, etc) also demands careful planning as ensuring the compatibility of various green gases within the current system, including managing different gas qualities and compositions. Developing reliable and scalable storage solutions for green gases to manage supply and demand fluctuations is additionally key for the strategy's success.

Success of biogas

The Danish gas strategy seems to be well on track. In 2023, biogas in the form of upgraded biomethane already made up nearly 40% of the domestic supply.²³ The latest AF23 projections²⁴ expect biogas to supply 100% of domestic demand by as early as 2030. This is driven partly by lowered gas usage, specifically for households, and the further integration of biogas upgrading plants connected to the gas grid. Domestic supply may even outpace demand, meaning there could be a potential export market for biomethane (depending on the gas quality requirements for neighbouring countries).

Figure 2.2: Danish Biogas (GJ) 1990-2030

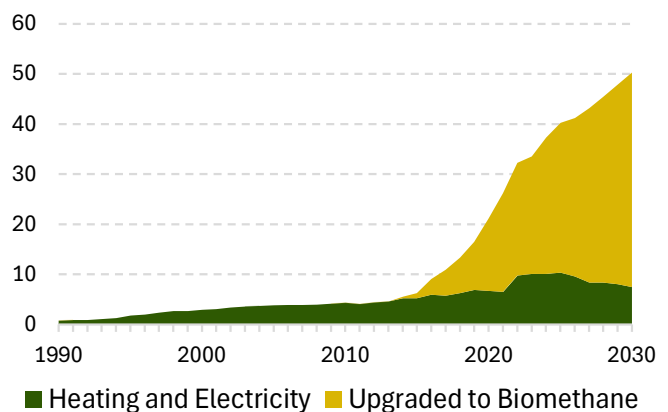


Table 2.3: Danish Green Gas Strategy objectives

| | |
|---|---|
| 1 | Green gases must supplement electrification and be used where it has the greatest value |
| 2 | Green gas in industry must support jobs in Denmark and provide economic growth and employment opportunities |
| 3 | The transition to green gas must occur with consideration for competitive tariffs and on commercial terms |
| 4 | Green gas must eventually be able to compete on market terms |
| 5 | Green gases must be produced sustainably |
| 6 | The development of green gas production and gas infrastructure must include a high level of public involvement and take into account biodiversity and the environment |
| 7 | The gas system must support and be used for the green gases of the future |
| 8 | The gas system needs to be adapted to efficiently support Denmark's future energy system, contributing flexibility and security of supply |
| 9 | Denmark must help further the development of a well-functioning European market for green gases |

● Consumption ● Production ● Future System

| Plan | By 2024 | | By 2030 | |
|-----------------------------|---------------------------------|--|--|--|
| EU Hydrogen Strategy | Install 6GW of H2 electrolyzers | Produce up to 1 million tonnes of renewable H2 | Install 40GW of H2 electrolyzers | Produce up to 10 million tonnes of renewable H2 |
| REPowerEU plan | | | Produce 10 million tonnes renewable H2 | Import 10 million tonnes renewable H2 |
| | | | | Biomethane production to 35 bcm ⁱ by 2030 |

i. bcm = billion cubic meters. 2022 EU production was 4.2 bcm of biomethane

Denmark within a European context






Denmark's green fuels goals sit within a greater overarching EU strategy regarding hydrogen and renewable fuels. In July 2020, the European Commission (EC) published a communication outlining the EU Hydrogen Strategy, setting the course for renewable hydrogen in the EU.²⁵ The strategy focuses on obtaining, distributing, and scaling up the use of renewable hydrogen, with non-binding quantifiable targets for the EU's production. It also acknowledges the need for support for low-carbon hydrogen during a transitional phase. In 2022, following Russia's war against Ukraine, the EC issued its REPowerEU communication, which included more ambitious production targets than those in the Hydrogen Strategy and set import targets for the first time.⁶ The two main strategies are shown in Figure 2.3.

On a per capita basis, Denmark's PtX plans are by far the most ambitious. The goal of 4-6GW of electrolyzer capacity amounts to 0.68 to 1.02 GW of electrolyzer capacity per million inhabitants, which is over three times the Dutch amount and over five times the amount Germany targets per person.

An export driven strategy

Estimates place the electrolyzer capacity required to serve domestic needs (for 2030 measures) at around 1.8 to 2.7 GW.²⁶ Achieving the 4-6 GW target means that the residual capacity will go to exports in neighbouring markets. This approach is core to the Danish PtX strategy wherein Danish production would meet potential supply gaps in export markets and gain revenues from the sale of hydrogen, or other hydrogen based efuels.

Table 2.4: Country level hydrogen strategy comparison

| Country | 2030 goal for electrolysis (GW) | Govt. allocated funds (mio. EUR) | Electrolysis goal (GW/mio. People) |
|---|---------------------------------|----------------------------------|------------------------------------|
|  Denmark | 4 – 6 | 167 | 0.68 - 1.02 |
|  France | 6.5 | 4,000 | 0.10 |
|  Germany | 10 | 4,600 | 0.12 |
|  Spain | 4 | 900 | 0.09 |
|  Netherlands | 3 – 4 | 7,500 | 0.17 – 0.23 |
|  Portugal | 2 – 2.5 | 140 | 0.20 – 0.25 |
|  UK | 5 | 480 | 0.08 |

Access to green energy



- High penetration of RES. Planned build out of 6+ GW offshore wind by 2030
- Grid projected to hit >90% renewable by 2027

First movers (end-use)



- Global companies willing to take risks and innovate on new technologies (e.g. Maersk, MAN, etc)

Supply of biogenic CO2



- High amount of biomass CHP and biomethane upgrading with potential capture points
- Import strategy and creating CO2 infrastructure

Equipment manufacturing



- Home base to world-class electrolyzer OEMs and auxiliary equipment manufacturers
- Innovators in 2nd gen electrolyzers (SOEC)

Advanced infrastructure integration



- Resilient electricity grid with EU leading TSO
- District heating network offers integration with PtX and possible revenue streams
- Testbed for sector-coupling / integration tech.

Geographic placement



- German market access with future connection to backbone for cross-border H2 exports
- Closer to German offtake compared to Scandinavian neighbors

Strong innovation ecosystem



- World leading technology and engineering companies, industry organizations, and universities
- Strong history of industry partnerships

Government support



- Strong government commitment to the green transition with proactive policy measures
- Financial funding (PtX tender) and innovation fund targeting new clean technologies

Danish strengths

Denmark is a leader in energy technologies and benefits from strong government support and world-class technology companies. The country's established reputation in renewable energy, particularly wind power, provides a solid foundation for expanding into hydrogen and PtX technologies. Denmark's innovation ecosystem, with leading universities and research institutions, drives cutting-edge research and benefits from collaboration between academia, industry, and government. Collaborative projects between research institutions and industry players are accelerating the commercialization of PtX technologies, positioning Denmark as a global innovation hub within green fuels. The key strengths are shown above in Figure 2.4.

Key limitations and hurdles

Denmark's strategy heavily relies on access to large amounts of renewable electricity, particularly from offshore wind. Any delays or shortfalls in renewable energy expansion could constrain hydrogen production capacity and hamstring ongoing PtX projects in the concept and feasibility stage. Limited renewable feedstock in the near-term will make green hydrogen less competitive (both relative to conventional fuels, and other producer nations), potentially causing investments to move to countries with cheaper input costs (e.g. Southern Europe, or hydropower countries).

Lack of domestic demand is another near-term hurdle. Unlike Germany, Denmark does not currently have many industrial processes that could offtake hydrogen and use it to decarbonize. There are no steel plants, no existing grey ammonia fertilizer plants, no large-scale chemical plants where an easy switch can be made. Existing Danish demand is 96% concentrated in refining use.²⁷ Germany has over 68x the existing hydrogen demand of Denmark (0.025Mt versus 1.74 Mt) with ongoing plans to stimulate demand in its Kraftwerksstrategie²⁸ via subsidization of the roll-out of a wave of hydrogen-fired power plants.

The assumption that there will be future demand for hydrogen, particularly in transport sectors such as long-haul aviation and shipping, but the timeline and scale of this transition are uncertain. Additionally, the market for green fuels, especially in new applications like transport, is still nascent, creating uncertainty about future demand and fuel cost.

There are limited immediate use cases and the impact for PtX on the 2030 targets is relatively limited compared to other government priorities in electrification, energy efficiency, and carbon capture and storage, which could be seen as more impactful (with regards to national emissions accounting) in the near-term with a business case featuring less risk.

A further challenge is the extensive infrastructure development required to support large-scale hydrogen production, storage, and distribution. Denmark's existing infrastructure is not fully equipped for the widespread use of hydrogen, necessitating significant investments in pipelines, storage facilities, and end-use infrastructure such as fuelling stations. Convincing policymakers and the public of the socioeconomic benefits of this investment may be difficult, particularly when considering the "bang-for-buck" in terms of near-term decarbonization impact. Prioritizing which projects to fund—whether immediate, high-impact decarbonization initiatives (e.g. 2030 goals) or long-term strategic PtX infrastructure—will be a complex decision-making process for Danish policymakers and investors.

International developments:

Since the last roadmap was developed in 2021, there have been significant global developments in the green fuels space. This is largely driven by government climate legislation, supply aspects related to energy security and geopolitical leverage, and strategies that emphasize the importance of securing a leading position in energy technology manufacturing (jobs, exports, etc).

In the US, the Inflation Reduction Act (IRA) and the CHIPS and Science Act were passed in 2022 and are the two cornerstone pieces of legislation of the Biden administration's climate and economic plan. The IRA includes provisions for tax credits, grants, and other financial incentives aimed at accelerating the development of hydrogen production, infrastructure, and associated technologies.²⁹ The Chips Act will invest billions into accelerating zero-emissions technologies such as energy storage, hydrogen, and CCUS technologies. It also includes funding for bolstering STEM education and workforce development within high-tech and green jobs.³⁰

China has also made strides in the green fuel sector, focusing heavily on scaling up its hydrogen production capabilities. The Chinese government has outlined ambitious targets for hydrogen development in its latest Five-Year Plan, emphasizing the role of hydrogen in decarbonizing its vast industrial sector and reducing reliance on imported fossil fuels. Additionally, China is subsidizing and investing heavily in electrolyzer manufacturing, positioning itself as a key supplier in the global hydrogen supply chain. A similar strategy that has been utilized in PV solar manufacturing.

Outside of the U.S. and China, other countries are also making significant moves in the green hydrogen space. For example, Saudi Arabia is developing one of the world's largest green hydrogen projects as part of its NEOM megacity, aiming to become a global hub for

hydrogen production and export. Additionally, Australia is rapidly advancing its hydrogen industry, with a focus on exporting green hydrogen to energy-hungry regions such as Japan and South Korea.

These developments indicate a rapidly evolving global landscape where nations are competing to secure leadership positions in hydrogen and other renewable energy technologies.

Tariffs and potential implications

The EU followed the US's lead and recently introduced 17 to 38 % import duties³¹ on Chinese manufactured EV's in response to concerns over unfair competition.

These tariffs, designed to protect the European automotive industry from what is perceived as subsidized, below-cost competition from Chinese manufacturers, underscore the growing tensions between major economic blocs over control of the emerging green economy. As EVs are a critical component of the transition to decarbonized transport, the imposition of tariffs may have cascading effects on related technologies and industries (e.g. electrolyzers, fuel cells, critical materials).

Denmark, as part of the EU, will need to navigate these challenges carefully. The country's leadership in green hydrogen and renewable energy could be bolstered by the EU's protectionist measures, provided they are coupled with strong domestic policies that encourage innovation and investment. However, Denmark must also be wary of the potential for increased costs and reduced access to critical technologies if global trade tensions continue to rise.

Competition for funding

Competing with other nations that are also investing heavily in green fuels technologies could impact Denmark's ability to secure necessary resources, such as EU-level financing and private investments, and maintain its position in the global market.

Denmark's ambition to be a leader is challenged by the sheer scale of investments and subsidies being rolled out by other countries, particularly China and the United States. The aggressive expansion of electrolyzer manufacturing in China, backed by substantial investments, puts pressure on Danish manufacturers to remain competitive. Moreover, the U.S. has implemented the Inflation Reduction Act and other policies that provide substantial financial incentives to local industries, potentially attracting investments that might otherwise have flowed to Europe, including Denmark. Denmark's ability to attract private investments will be crucial, requiring a clear strategy that highlights the country's strengths in renewable energy and leadership in clean energy technologies.

Danish trajectory – where should the ambition lie?

Denmark's trajectory in green fuels is at a critical juncture. Given the nation's established strengths in renewable energy, particularly wind power, and the increasing global competition in green hydrogen and PtX technologies, Denmark must carefully consider its next steps. The key question is: where should Denmark's ambition lie?

On one hand, Denmark could choose to maintain its current level of ambition, leveraging its existing expertise in renewable energy to solidify its position in the emerging green hydrogen market. However, simply maintaining the status quo might not be enough in an increasingly competitive global landscape where other nations are scaling up and investing more heavily in their efforts.

Alternatively, Denmark could scale down its ambitions, focusing on niche areas within the green fuels sector where it has the strongest competitive advantage. This approach might reduce risk but could also limit Denmark's potential to lead in a rapidly growing global market.

The most ambitious path would be to double-down on the focus on green fuels and PtX technologies, aiming to make PtX the next "wind adventure". This would involve significant investment in innovation, infrastructure, and partnerships, both within the EU and globally. By doing so, Denmark could not only sustain its leadership in renewable energy but also become a pioneer in the next generation of green technologies, securing long-term economic and environmental benefits.

One critical question is whether Denmark can produce offshore wind energy at a cost low enough to make its hydrogen production globally competitive. The ability to generate hydrogen economically will be crucial in establishing Denmark as producer and exporter of hydrogen and other efuels. Continued advancements and cost reductions in offshore wind are crucial, especially in the face of rising inflation and material costs.

Another concern is whether delays in renewable capacity additions (potentially unbankable wind projects at current support levels³², prolonged permitting and approval processes, etc) could hinder the near-term scalability of PtX projects. The scalability of PtX technologies is directly linked to the availability of abundant, cheap renewable energy. If the expansion of offshore wind or other renewable resources lags, it could significantly impact the viability and timing of PtX projects, potentially causing Denmark to miss critical

market opportunities. Projects could sit for years in the concept phase before decisions are made whether to proceed.

Furthermore, A key consideration is whether there will be a sufficiently robust offtake market in neighbouring countries, particularly Germany, that is willing to pay a premium for imported green hydrogen. Germany's energy transition strategy places a significant emphasis on hydrogen, but the extent to which it will rely on domestic production versus potentially more cost-effective imports versus Danish imports will directly influence Denmark's export prospects. Securing and understanding this offtake market is essential for the long-term viability of Denmark's green hydrogen strategy, as the success of both countries in meeting their climate targets is closely intertwined. Germany's demand could serve as a critical driver for Denmark's hydrogen economy, but only if pricing, supply stability, and strategic alignment are effectively managed.

What the market thinks

Ramboll conducted surveys in 2022 and 2023 with over 100 key developers and investors in PtX and green fuels to assess Denmark's role in producing and exporting green fuels.^{33,34} The key conclusions from these surveys are summarized below:

- The majority (62%) believe Denmark should both produce and export green hydrogen and green fuels. Meanwhile, 18% prefer a focus solely on hydrogen, 11% on green fuels alone, and 9% suggested other priorities.
- The two biggest barriers identified were the availability of sufficient competitively priced green electricity and the development of necessary infrastructure for export and transport. These are seen as both the greatest challenges and the most crucial prerequisites for establishing a robust market for green fuels.
- The industry sees Denmark's trajectory as that of a green fuel producer and exporter but stresses the need for improved regulatory conditions. Ensuring this is primarily the responsibility of Danish and EU policymakers.
- Politicians can support companies by simplifying and accelerating regulatory approvals, setting CO₂ reduction requirements in the transport sector (such as green fuel blending mandates), and providing funding for essential infrastructure like port facilities and hydrogen refuelling stations.



3. Innovation Ecosystem

Research and development underpin all aspects of green fuels development, and the ecosystem that allow ideas to evolve into demonstrations projects and eventually to large-scale commercialization is crucial to highlight. One of Denmark's main strengths, relative to its small size, is its high innovation output. Denmark consistently ranks among the top countries in global innovation rankings³⁵, demonstrating its leadership in clean energy technology. The government understands the importance of funding innovation in energy technologies, not only from a climate perspective, but from a national welfare and jobs perspective. This leadership is often said to have formed Denmark's success in wind and other energy technologies, that are now exported globally.

However, it is essential to recreate and sustain this innovative environment for green fuels to ensure Denmark remains competitive. By building an ecosystem that includes government support, funding entities, universities, small firms, start-ups, large firms, and industry associations, Denmark can and will

continue to lead in the energy transition. Ensuring continued collaboration and investment in research and development will be key to maintaining Denmark's position at the forefront of green fuel technologies and the broader clean energy sector.

The ecosystem for green fuel development is a dynamic network of stakeholders including research institutions, private companies, industry associations, and policymakers. Together, these entities drive technological advancements, policy frameworks, and market mechanisms to accelerate the development of green fuels. Linking these entities are uni or bi-directional flows of funding, knowledge sharing, intellectual property, and trained people that culminate in new innovations that can reach commercialization and contribute to the development of a green fuels industry domestically, and exports of Danish technology abroad. This ultimately results in national socioeconomic benefit and welfare. The figure below shows a simplified way of how various stakeholders interface with each other.

Figure 3.1: Innovation ecosystem

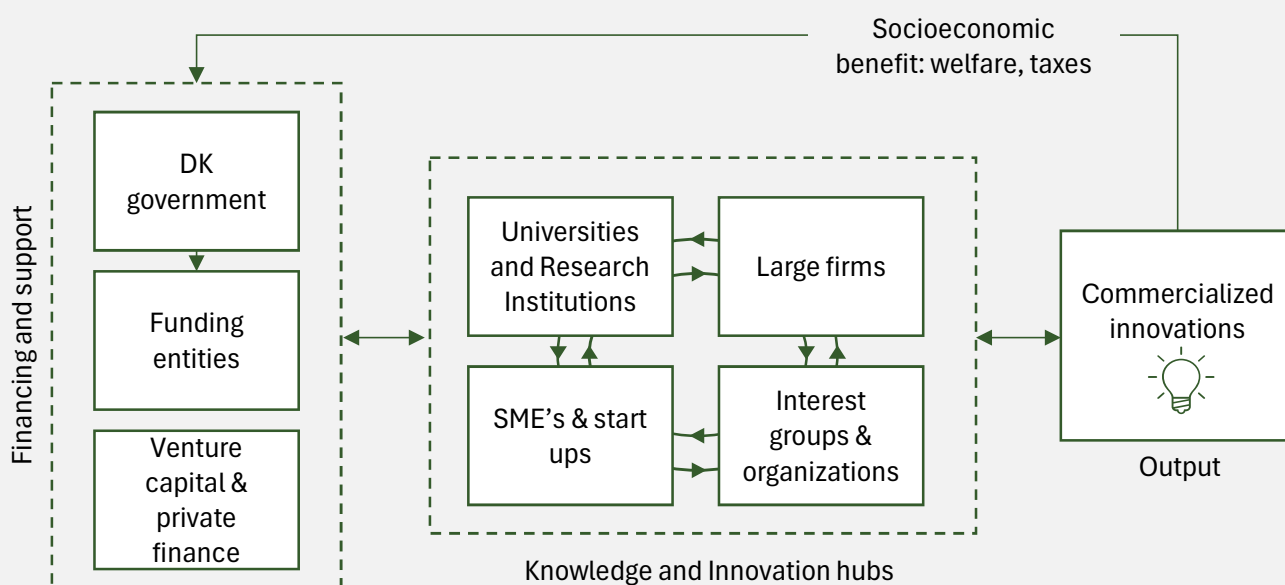



Table 3.1: Innovation ecosystem for green fuels development

| Entity | Role in innovation ecosystem | Examples of pro-innovation measures for green fuels | Main levers |
|---|---|--|---|
| Government | Designs regulatory frameworks, sets policies, and funding support levels. Creates incentives and sets long-term goals for green transition and climate targets. | <ul style="list-style-type: none"> Creation of energy parks (zones) for fast-track permitting World's first Power-to-X tender awarding 1.25 billion DKK Danish-German joint declaration on H2 infrastructure | <ul style="list-style-type: none"> Legislation and mandates Funding and support International agreements |
| Public funding entities | Entities such as the Innovation Fund, EIFO, etc. distribute funds to research projects, missions, and startups. Supports early-stage development of green fuel technologies. | <ul style="list-style-type: none"> Funding of Innomissions such as MissionGreenFuels Green accelerator programmes for innovative ideas Funding of "lighthouses" for Danish municipalities³⁷ | <ul style="list-style-type: none"> Grants Strategic funding Knowledge hubs |
| Universities & research institutions | Conducts fundamental and applied research. Bridges gap between theoretical and practical applications of green fuels. Facilitates knowledge transfer to industry and a trained workforce. | <ul style="list-style-type: none"> DTU "Risø Gateway" project to create test facilities for PtX and green fuels DTU/AAU CAPEX – PtX laboratory for advanced materials research AAU's collaboration project with Port of Aalborg | <ul style="list-style-type: none"> Education and knowledge transfer Strategic research areas |
| Private capital | Provides investment needed for scaling up technologies. Engages in venture capital and private equity funding for innovative projects. | <ul style="list-style-type: none"> CIP's Energy Transition Fund and Advanced Bioenergy fund allocating over 3 billion EUR ESG aligned investment funds by banks, pension funds | <ul style="list-style-type: none"> Investment funds Venture capital Private equity |
| Large companies | Implements and scales up innovative technologies. Invests in R&D and collaborates with research institutions. | <ul style="list-style-type: none"> Company backing of pilot projects such as Green Fuels for Denmark, Green Hydrogen Hub Innovation and industrialization of new electrolyzer technology | <ul style="list-style-type: none"> R&D funding Partnerships Corporate investment |
| Small and medium enterprises | Innovate rapidly and adapt new technologies. Acts as a key player in early-stage development and niche markets. | <ul style="list-style-type: none"> Arcadia efuels SAF facility in Vordingborg (first in DK) Electrochaeta's biocatalyst technology for synthetic methane production | <ul style="list-style-type: none"> Collab. with universities Niche focus and risk-taking ability |
| Industry groups | Advocates for policy direction and industry standards. Facilitates collaboration among companies and with government agencies. | <ul style="list-style-type: none"> Green Power Denmark publications for policymakers regarding H2 infrastructure Brintbranchen's "hydrogen Academy" to disseminate industry knowledge | <ul style="list-style-type: none"> Advocacy Standards networking events lobbying |
|  | Supports the development and market introduction of green fuels technologies via the funding of research and innovation projects | <ul style="list-style-type: none"> Support for more than 20 projects (~280 million DKK) for green fuels research and technology development | <ul style="list-style-type: none"> Strategic funding Stakeholder coordination Roadmaps |



4. Systems Integration

At its core, PtX is a sector coupling technology that builds bridges between different energy systems; converting green electrons into various sustainable gases and fuels. Large scale electrolyser plants will need considerable integration with new or existing infrastructure. This includes electricity generation infrastructure, district heating networks, water and wastewater infrastructure, as well as future CO₂ infrastructure. PtX plants consume substantial power to produce hydrogen, generating significant surplus heat and oxygen in the process. Additionally, the electrical interfaces of gigawatt scale PtX have considerable impacts on grid capacity, flexibility, and planned build out. This chapter explores how the production of green fuels will integrate with current and future energy systems.

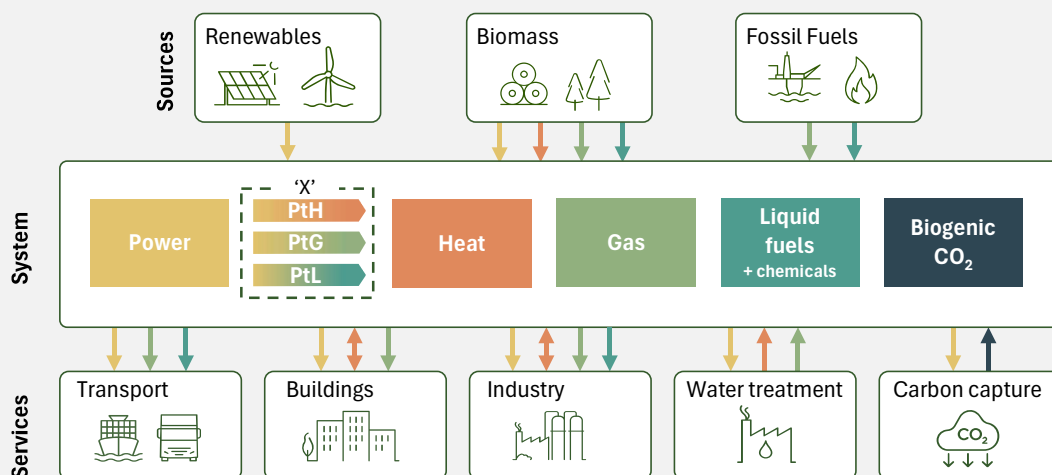
Integration with electricity net

Gigawatt scale PtX plants and the associated wind and solar build-out have significant implications on the energy system. As such, their integration with the collective grid must be considered carefully. Various connection models for large scale PtX can be considered depending on the scale of the electrolyzer plant, geography, local grid capacity, tariff design, and

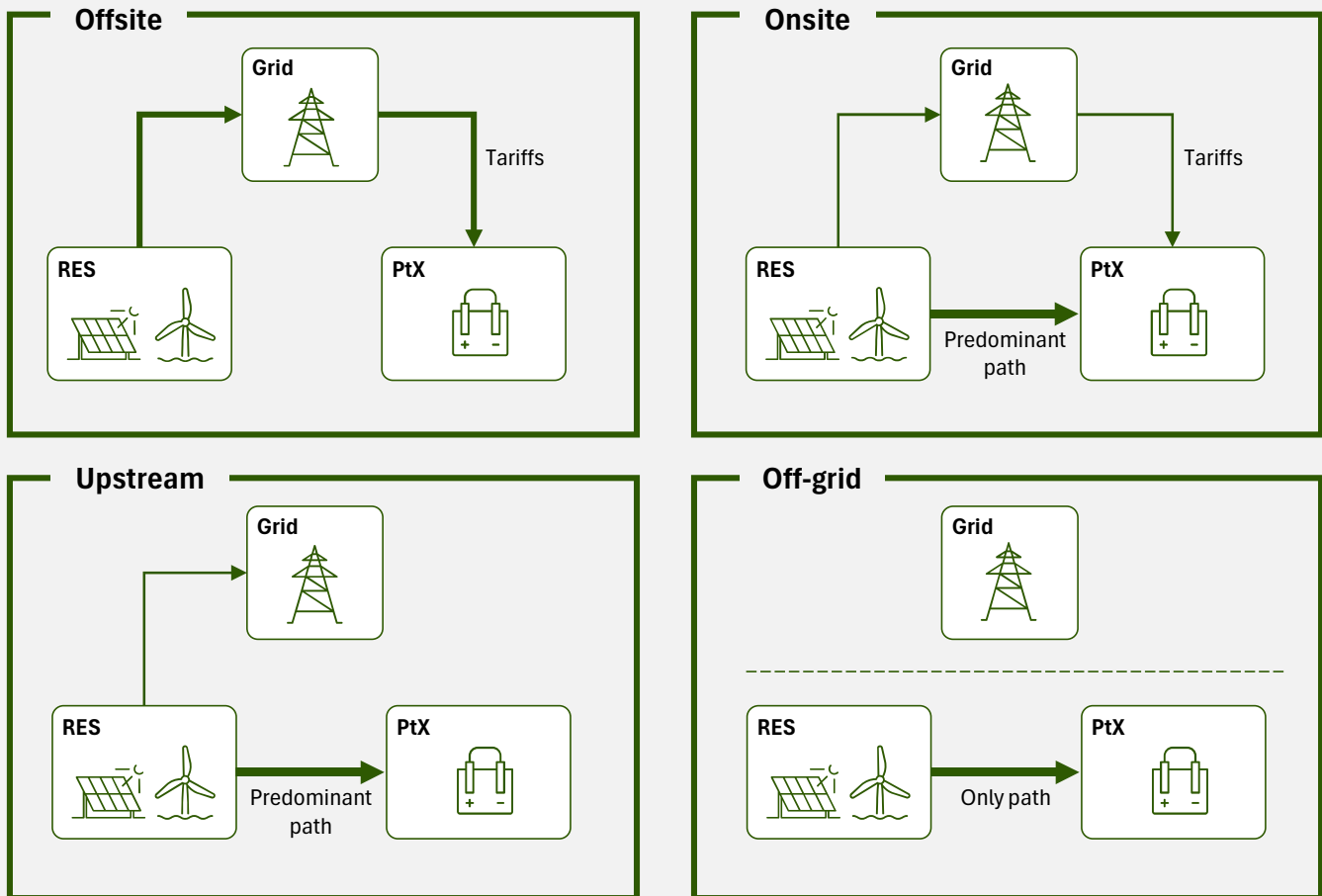
profit model. Green electrons can flow from RES either through the grid to the PtX facility, or directly to the electrolyzer plant, or a combination of both, where optimization and price hedging can occur.

In 2023 a draft bill allowing “direct lines” where a high voltage lines directly connect production and consumptions points is to be implemented in the Danish Electricity Supply Act.³⁶ Direct lines allow for the coupling of large-scale offshore wind projects in the gigawatt+ scale allowing for offtake of green electrons without overloading the grid with excessive power influx. This could potentially mean less upgrades are needed to the existing electricity grid and less curtailment of offshore wind power, when supply exceeds demand. The changes allow for A) establishment of a direct line with approval from the Danish Energy Agency B) direct lines both onshore and offshore C) up to four different consumptions plants (PtX sites) D) electricity supplied to be subjected to taxes and duties. This is an important development for the viability of large scale PtX due to reduced transmission bottlenecks and grid stability. It may also improve the economic viability of projects, depending on the tariff model and grid connection fees.

Figure 4.1: Sector coupling



Source:
Adaption from
DTU's Sector
Development
Report,³⁷ 2020

Figure 4.2: PtX connection models

Source: Adaption from Energinet's "Potential for PtX in Denmark in the near term from a systems perspective" 2019.³⁸

Connection Models

The four main connection models for PtX are shown in Figure 4.2 above. Each model comes with its own set of advantages and disadvantages.

The offsite connection model has no direct connection to the electrolyzer plant and all power generated from renewables passes through the collective grid. This is an option if the renewable sources and PtX plant are located geographically distant. In theory, this is the most macroeconomic efficient connection model and may be the desired long-term end state once the grid is sufficiently renewable.

The onsite and upstream models are systems that are connected to the grid and to the PtX facility and offer greater flexibility and potentially higher revenue streams, in the case of high electricity prices where sell-to-grid would offer the highest price. In addition, having the electrolyzer connected to the grid allows for potential supplementation of grid-sourced electricity during periods of lower renewables production, making it easier to produce hydrogen at a steady rate and avoiding major system ramping. However, this may

introduce complication in green certification if the grid mix is not 90% or greater renewable.

Off-grid production is relevant for a decentralized or remote models such as energy islands where connection to a grid is not technically or economically feasible or where hydrogen itself will be the energy carrier onshore. For such models, the owner may experience additional costs from overplanting of RES or needing to supplement the system with energy storage during periods of low power output.

Ancillary Services

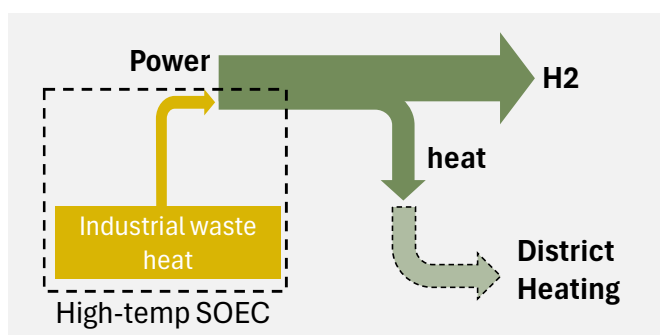
Power-to-X can also offer ancillary services to the grid in the form of frequency response (FCR). During periods of excess electricity supply, electrolyzers can increase their power consumption to absorb surplus energy, thus helping to balance the grid frequency. The speed of this ramping depends on the type of electrolyzer and plant design. Conversely, they can reduce their consumption or temporarily shut down during power shortages, aiding in demand response effort. This flexibility in operation allows electrolyzers to offer valuable balancing services.

In theory, hydrogen can provide a form of grid services via combustion in a hydrogen peaker plant or used in a hydrogen fuel cell power plant to provide for peak load periods. This would allow hydrogen to be used as a grid stabilizing energy source during periods of low intermittent power if the hydrogen is taken from a storage facility or via line packing (storing compressed H₂ in a pipeline network) to be later used for power applications. However, this suffers from low round trip efficiency and would likely be better suited for large scale battery energy storage or another form of storage.

Integration with heating systems

A by-product of low-temperature electrolysis is heat, typically ranging between 50 and 80 °C, which can be recovered and utilized in district heating networks. For Alkaline Electrolysis Cells (AEC), approximately 27% of the energy input can be recovered as heat, while Proton Exchange Membrane (PEM) electrolysis has an estimated heat recovery potential of 33%.⁴⁰ The amount of recoverable heat depends on several factors, including the efficiency of the electrolysis process, operating parameters, current density, and stack design.

In contrast, high-temperature Solid Oxide Electrolysis Cells (SOEC) use heat as an input, with around 20% of the energy required for electrolysis supplied by high-temperature steam, reaching up to 600 °C. This characteristic makes SOECs particularly suitable for integration with industrial waste heat sources, maximizing cost efficiency. Sector coupling in this scenario occurs at the front-end of the system, where the placement of SOEC plants adjacent to high-temperature heat sources, such as those found in industrial processes, facilitates industrial symbiosis and enhances overall system efficiency.



According to COWI and Dansk Fjernvarme analysis⁴², selling heat for district heating uses can improve revenues by 5 to 15%, based on the operating hours of the PtX plant. This could provide a competitive

advantage to hydrogen produced in Denmark, making the LCOH more competitive compared to PtX not integrated with district heating systems. However, if PtX plants were to be placed offshore or geographically remote, the benefits of system coupling with heat would be lost. However, there could be potential uses for some of the heat in optimizing the auxiliary processes connected to the system.

On a Danish level, analyses estimate that a build out of 6 GW of PtX could potentially provide enough heat to meet 20% of district heating needs.⁴²

Integration with gas infrastructure

Utilizing existing infrastructure will be critical to lower to overall socioeconomic costs of transitioning to sustainable fuels. Re-using existing infrastructure, such as gas pipeline distribution networks, will be important and potentially preferred from a cost and carbon standpoint. Transmission system operators assume the costs for retrofitting to be at around 10-15% of new construction.⁴³ Upgraded biomethane can easily be injected into the existing gas grid and is done so extensively already.

Hydrogen can be blended into the existing gas grid at varying levels, but typically no more than 20% without major retrofitting, hazards, or compatibility issues with end-uses (e.g. gas appliances, furnaces). However, hydrogen carries only about one-third as much energy per unit of volume as does methane, which means that a 20 percent blend of hydrogen will only reduce the emissions impact of its use by 6 to 7 percent.⁴⁴ As such, pipeline blending of H₂ at high levels is not likely to be a viable path forward or a significant contributor to emissions reduction. Retrofitting existing gas networks to be 100% hydrogen and used in the planned European hydrogen backbones is a likelier scenario.

In a ten-year testing period, FORCE Technologies tested hydrogen in steel and plastic pipes⁴⁵ (the same used in the existing gas grid) to investigate whether the existing gas transmission network can distribute hydrogen without fatigue-induced cracking or degradation. The results showed that long-term exposure to hydrogen had “no impact on the steel or plastic pipes” meaning that it is expected that the existing Danish gas system would be able to handle a full transition to hydrogen gas without major issues. However, upgrades may be needed for seals, valves, and compressors to handle the different properties of hydrogen, including its higher diffusivity and lower energy density compared to natural gas.

Integration with carbon supply

Effective integration of PtX plants with carbon supply is needed for producing efuels. PtX plants can utilize CO₂ captured from industrial processes, power plants, or direct air capture technologies. Integrating carbon capture infrastructure with PtX facilities allows for a steady supply of CO₂, essential for synthesizing fuels like e-methanol, e-methane, and other e-hydrocarbons. Additionally, transporting CO₂ via pipelines to PtX plants or situating PtX plants near CO₂ sources can minimize transportation costs and logistical challenges. Biogenic CO₂ or syngas produced from processes such as anaerobic digestion or gasification can be used for efuel production. Co-locating “bio-e” generation infrastructure can be done strategically to optimize the various feedstock and waste streams and maximize cost-effectiveness.

Integration of biorefineries

Integration of biorefineries into existing energy systems supports the circular economy by utilizing waste and by-products from agriculture, forestry, and keeping waste food out of landfills. Similar to PtX, biorefineries can enhance energy system resilience and flexibility. Bio feedstocks can be stored and processed as needed. By producing biodiesel, biogas, or other bio derivatives, biorefineries provide fuels that can be blended with or substitute conventional fuels. This integration is facilitated by existing fuel infrastructure, such as pipelines and refineries, which can often accommodate biofuels with minimal modifications.

Upstream, effective integration of biorefineries with feedstock systems and waste sorting is vital. Incorporating agricultural residues and the organic fraction of municipal solid waste (OFMSW) with biorefineries requires coordinated efforts across multiple sectors. This includes developing infrastructure for collecting, transporting, and processing diverse feedstocks, as well as creating supportive policies and incentives to encourage participation from farmers, municipalities, and industries.

For the agricultural sector and biogas plants, the collection area, or geographic radius from which the plant collects its feedstock is an important factor for successful integration. The radius of the collection area typically ranges from 20 to 50 kilometers, depending on the plant's capacity and local infrastructure.⁴⁶ A smaller radius minimizes transportation costs and associated greenhouse gas emissions, enhancing the overall environmental benefits of the biogas plant. However, a larger radius may be necessary in sparsely populated or rural areas to gather sufficient feedstock.

For urban environments, the integration of OFMSW collection programs with biorefineries supports urban sustainability goals by closing the loop on waste and energy cycles. Copenhagen has a goal of recycling 70% of residents' waste by 2024 and has engaged in an ambitious marketing and awareness campaign to encourage residents to place biowaste into the appropriate collection bins.⁴⁷ In Copenhagen, food waste is taken to a biogas plant in Solrød, where it is upgraded to biomethane and used in the gas network.

Integration with water systems

Producing large amounts of hydrogen requires significant volumes of water. Denmark's water infrastructure must ensure adequate water availability, treatment, and recycling systems to support the increased demand from PtX plants while maintaining the balance and sustainability of water resources. The ideal location for a PtX facility is where there is a reliable excess water supply that is not subject to competitive use from households and agricultural activities.

PtX plants can potentially utilize treated wastewater or greywater for their processes. This approach not only conserves freshwater resources but also aligns with Denmark's goals for sustainable water management. Collaborations with municipal water treatment facilities will be essential to establish pipelines and infrastructure capable of delivering treated wastewater to PtX plants.

MISSION GREEN FUELS

Systems integration and sector coupling are a key focus of MissionGreenFuels' strategic initiatives. Ongoing projects include:

- **PtX Sector Coupling and LCA:** This project involves evaluating optimal plant locations by considering grid capabilities, market forecasts, and resource availability. It also explores sector coupling and co-optimizing gas, electricity, hydrogen, and district heating.
- **PtX Infrastructure:** Focused on assessing hydrogen and CO₂ infrastructure needs for a future integrated energy system, this project aims to shift from siloed approaches to holistic energy systems.
- **HyFueling HD:** This project validates hydrogen refuelling technologies linked to the HySynergy production site, including multi-ton storage buffers for use in heavy-duty fuel cell vehicles.



5. Social and Sustainability

Sustainability

Sustainability issues surrounding green fuel production involve environmental, economic, and social dimensions. Environmentally, the production of green fuels, necessitates careful consideration of resource use and ecological impacts. Land use change, water consumption, and biodiversity loss (in regard to the mass build-out of wind and solar parks) are critical concerns, especially for biofuels, which can lead to indirect land-use change and habitat destruction if not managed responsibly. Furthermore, the production processes themselves must minimize emissions and waste to truly contribute to sustainability goals.

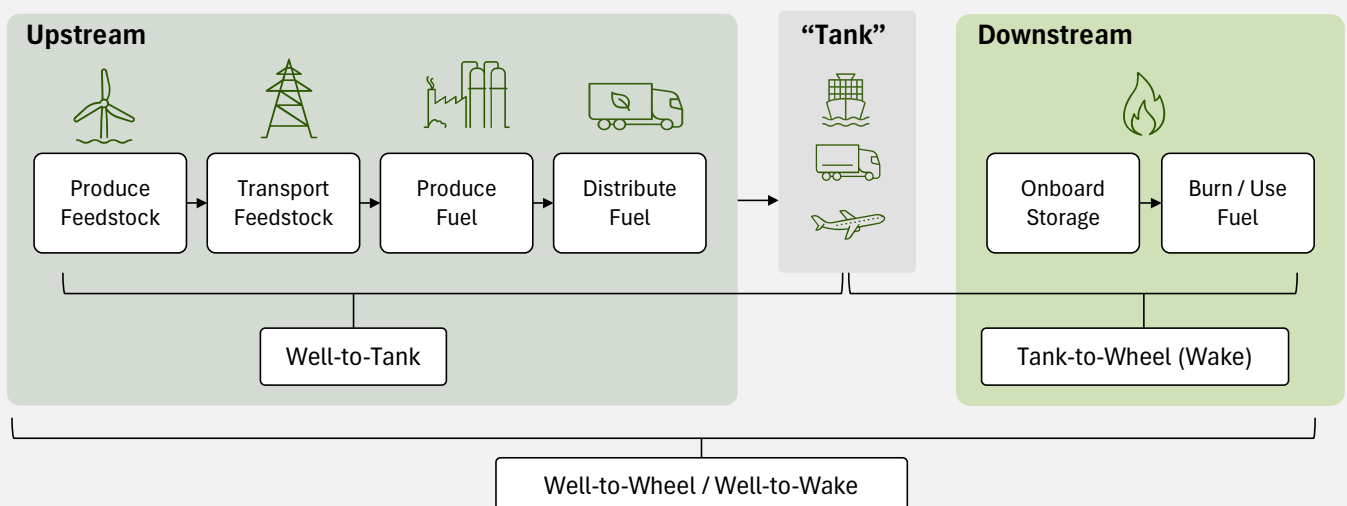
As such, Life Cycle Assessment (LCA) should be used as a tool to evaluate the environmental performance of green fuels. LCA examines the entire life cycle of a fuel, from raw material extraction to production, distribution, use, and disposal. This approach ensures that all potential environmental impacts are accounted for, including greenhouse gas emissions, energy use, water use, and pollutants. By identifying hotspots and inefficiencies in the production chain, LCA helps in optimizing processes and guiding policy decisions

towards more sustainable practices.

Within transport fuels, the production, transport, and distribution emissions are commonly referred to as Well-to-Tank (WTT) while operational emissions during fuel usage are referred to as Tank-to-Wheel or Tank-to-Wake (TTW) depending on the type of transport (road vs maritime or aviation). The sum of emissions from both stages is used to evaluate a fuel's carbon intensity, or emissions per unit of delivered energy (e.g. gCO₂e/MJ). The full lifecycle emissions are referred to as Well-to-Wheel or Well-to-Wake (WTW) and can be compared across different transport fuels. The potential sources for WTW of emissions are shown below.

Emissions related to green fuel production are a significant focus of LCA. Different production pathways have varying emission profiles; for instance, biofuels can sequester carbon during feedstock growth but may also release methane (via leakage) and nitrous oxide during production. Synthetic fuels, made through CCU, can potentially close the carbon loop but require substantial energy inputs and are highly inefficient compared to direct electrification. These aspects should be accounted for when assessing green fuels.

Figure 5.1: Life cycle stages of a green fuel



The embodied carbon of building several GW of renewable energy to support the production of efuels must also be taken into account. Thus, LCA provides a framework to compare these pathways and identify the most sustainable options, ensuring that the pursuit of green fuels does not inadvertently lead to adverse or unforeseen environmental impacts.

Social and community aspects

Large-scale energy projects require wide social acceptance to be carried out. Lacking a “social license to operate”⁴⁸ puts clean energy projects at risk and in the past has led to costly disputes, additional surveying and impact studies, project pauses, regulatory restrictions and difficulties in obtaining legal permits. Social acceptance is therefore critical to the success of green fuel advancement and the associated build out of renewable energy. If stakeholders’ interests and expectations are not aligned, formal procedures and

issuance of permits can be significantly delayed, or not given. Therefore, the social acceptance by local communities is as important as the technical and economic feasibility of the project.

As such, early two-way community engagement is needed to communicate the local benefits of large scale PtX projects. There is a high risk that projects are rejected by local communities if the project benefits are not clear at the start of project development. The idea of benefit sharing recognizes that the placement of large-scale industrial energy projects leads to significant changes in the local landscape and community dynamics. Benefits for local communities, and ways to create trust and credibility to increase the “social license to operate”, are listed below in Table 5.1.

Table 5.1: Potential community impacts and benefits of green fuels development

| Negative impact | Description of impact | Strategy to mitigate |
|-----------------------------------|--|--|
| Land use and visual impact | <ul style="list-style-type: none"> Alters local landscapes Large scale land-use for projects (e.g. solar farms, onshore wind) | <ul style="list-style-type: none"> Strategic site selection to minimize aesthetic impacts Visual impact simulations |
| Disturbance and noise | <ul style="list-style-type: none"> Noise, increased traffic during construction and operation phase Impact quality of life for neighbors | <ul style="list-style-type: none"> Noise mitigation measures, construction schedules Communication channels for complaints |
| Resource competition | <ul style="list-style-type: none"> Increased demand for water, or other resources, potentially competing with local needs | <ul style="list-style-type: none"> Measures not to compete with local water or energy needs by using treated wastewater and own power |

| Positive benefit | Description of benefit | Strategy to implement |
|----------------------------------|---|---|
| Job creation | <ul style="list-style-type: none"> Employment opportunities in construction, operation, maintenance Local economy boost | <ul style="list-style-type: none"> Source local labour (if possible) and highlight job postings |
| Economic development | <ul style="list-style-type: none"> Local economic activities through project-related investments local spending and business opportunities (hotels, restaurants, etc) | <ul style="list-style-type: none"> Estimate economic impact via studies, communicate results Estimate tax generation for municipalities |
| Infrastructure investment | <ul style="list-style-type: none"> Upgrades and modernization in local infrastructure such as roads and utilities Improvement in local facilities | <ul style="list-style-type: none"> Communicate planned infrastructure improvements to local community |

Strategies to increase social buy-in

During the planning and development phase of PtX projects, analysis should be undertaken to quantify benefits to local communities such as permanent job creation, the types of jobs, economic activity, and local procurement of services or materials.

Outside of direct economic impacts, other strategies can be used to incentivise local support and increase community buy-in.⁴⁹ These strategies are meant to foster co-ownership and community involvement into the projects and have been used for onshore wind and solar development projects in Denmark in the past.

- **Co-ownership model:** Allowing communities to purchase shares in part of the project (e.g. 20% of the installed capacity) to take a financial stake in the success of the project. This has been successful for onshore wind.
- **Green pool / green fund schemes:** Project developers pay local municipalities a one-time sum of money per MW of capacity built which is then earmarked for community improvement projects such as bike lanes, playgrounds, parks, or infrastructure improvements.
- **Proximity bonus:** local community members within a certain radius of a project site, and the ones most likely impacted by disturbance, are given a pay-out-based production of site.
- **Property value guarantee:** financial compensation mechanisms to protect property owners from value loss due to siting of facility.

Implementing these strategies not only helps in gaining social acceptance but also ensures that the local communities see tangible (financial and non-financial) benefits from the projects.

However, there are many challenges associated with community engagement that must be overcome including limited municipal resources and skills for effective engagement (e.g. surplus of renewable energy projects and limited resources to effectively administer civic engagements), civic meetings that are often one-directional with limited or under-representative stakeholder engagement, or low levels of public awareness of understanding of green fuel technologies leading to misunderstanding.

Research into the most effective and democratic ways of civic engagement should be conducted to ensure that concerns are properly addressed and green fuel infrastructure is built in an equitable and fair way for local communities. Innovative community buy-in

methods, such as the ones used historically in Danish wind development, should be studied for PtX and other green fuel infrastructure projects.

Safety aspects:

One of the main community concerns around PtX surrounds safety aspects with fuels such as hydrogen which is explosive and ammonia and methanol which are toxic at varying levels. The concerns around an accidental spill or explosion in local communities should be addressed early in the development of a project and communicated clearly. This could include descriptions of leak detection and monitoring systems, fire and explosion protection, safety distances used during project siting, emergency response plans, and so on. It is important for project developers to communicate transparently about the safety measures in place, emergency response plans, and the statistical likelihood of incidents, to alleviate public fears.

Future workforce needs

Skilling the future workforce or reskilling the existing workforce for the energy transition is one of the most critical needs identified by MissionGreenFuels stakeholders. There will be no energy transition if there are no workers to carry it out. Developing green fuels and the associated renewable energy feedstock will take an enormous amount of technical know-how, skilled labour, technicians, and other support roles. The list below lists strategies and examples of how to approach skills development for the green fuels sector:

Skilling the future workforce

Young people approaching higher education today should be targeted with STEM programmes that feature curriculums in green fuels, electrochemistry, energy storage and conversion, etc. Similarly, persons entering potential vocational education programmes (VET) should be encouraged to apply for programmes relevant for the energy transition: automation, electrical work, welding, controls, among others. See Table 5.2 for more occupational profiles and the relevant skills needed for green jobs.

Strategies: Embed green fuels and PtX education into standard engineering coursework across chemical, mechanical, and electrical disciplines. Expand the programmes offering tangible skills in green fuels technologies. VET jobs in automation, electrician should feature hands-on training with PtX technologies. Encourage apprenticeships during construction and operation phases of PtX facilities to skill the entering workforce with real-world experience.

Examples:

- DTU offers over 25 courses specifically relevant for green fuels and PtX in courses such as “Electrochemical energy technologies”, “Industrial Reaction Engineering”, and more. Other universities offer similar courses.⁵⁰
- In June 2024, the Danish government allocated over 200 million DKK to vocational schools to invest in up-to-date equipment and training within the green transition and created frameworks to attract more young people to technical vocational educations, based on the expected shortage of skilled workers.⁵¹

Upskilling the existing workforce

The existing workforce in traditional engineering and trades fields (non-green fuels related) can be targeted via continuing education programmes (non-degree career training, professional continuing education, modules, etc).

Strategies: Offer topic specific training courses that build on existing competencies. For example, existing workers within shipping may need upskilling in the safety and handling procedures for ammonia, an area that builds on existing competencies for other fuels or materials handling.

Examples:

- Green Skills for Hydrogen Project (GreenSkillsforH2) has a core objective of addressing the hydrogen skills gap by providing training to industry. The alliance offers a suite of training material for competencies relevant for PtX.⁵²

- Flexible Masters in Power-to-X offered by a collaboration between AAU, AU, DTU, and SDU that caters to working professionals.⁵³

Reskilling the fossil fuel workforce

PtX plants (essentially chemical plants at their core), will share many crossover skills with traditional roles in the petrochemical industry. This includes workers with tangible skills in refinery operation, pipeline infrastructure, fuel-logistics, etc. Fossil fuel workers should be able to fill emerging green jobs with only minimal reskilling.

Strategies: Top-down corporate strategy to reskill parts of existing workforce to transition to green fuels. Offer compensation and re-qualification to existing workforce during fossil fuel phase-out.

Examples:

- RePowerEU strategy includes the Pact for skills partnership in which the EU aims to reskill several million workers for careers within the green jobs sector.⁵⁴
- Danish companies phasing out or selling off oil and gas parts of their business and focusing on offshore wind and emerging green fuels sector.

Recruitment and integration of skilled foreign workers should also be considered to fill the projected skills gap.

In the box below, ongoing MissionGreenFuels projects that focus on social and sustainability aspects of green fuels are listed.

**Focus areas and projects within social & sustainability**

MGF is strategically positioned to drive innovation within social and sustainability topic area related to green fuels, particularly within:

- Developing frameworks for effective citizen engagement and social buy-in
- LCA and sustainability assessments of green fuels feedstocks and production processes
- Disseminating safety guidelines to advance public acceptance

Examples of past or ongoing MGF projects include:

→ **Safer and Faster PtX**

- Assessment of safety, risks, and mitigation in relation for social acceptance of PtX
- A guideline to safer PtX will be developed



→ **COMON:** Engaging communities in the green fuels transition

- Catalogue with best practices and promising venues for citizen engagement and acceptance
- Scenarios and design guidelines for tackling barriers to development of green fuels

→ **DEEP:** Designing community collaboration for sustainable energy parks

- Provide a platform for designing holistic energy parks, which includes both citizen needs and considerations for improving local nature and biodiversity.
- Strategy for community collaboration, including principles and processes for involvement and dialogue

Table 5.2: Potential occupational profiles in the green fuels sector

| Occupational profiles | Relevant educational development / skills |
|--|---|
|  <p>Engineers</p> <ul style="list-style-type: none"> • Chemical engineers • Civil engineers • Electrical engineers • Mechanical engineers • Marine engineers • Power and grid engineers • Process engineers | <ul style="list-style-type: none"> • Deep understanding of electrochemical energy technologies (production, storage, use) • Understanding of energy systems integration, energy systems analysis, design, and optimization • Understanding of various fuel production methods (e.g., electrolysis, pyrolysis, biomass gasification). • Skills in data analysis, statistical modelling, and predictive analytics |
|  <p>Tradespersons and technicians</p> <ul style="list-style-type: none"> • Process control technician • Automation technician • Electrical fitter • Electrician • Welder • Gas fitter | <ul style="list-style-type: none"> • Certifications in electrical safety, welding, or automation technologies • Hands-on experience with electrolyzers, synthesis equipment, and balance of plant equipment • Maintenance and troubleshooting skills for plant equipment and infrastructure |
|  <p>Safety and Quality Control</p> <ul style="list-style-type: none"> • Health and safety officer • Quality assurance technician • Inspector • Emergency response coordinator | <ul style="list-style-type: none"> • Training in emergency response and hazardous materials handling .e.g. ammonia leakage • Skills in risk assessment, incident investigation, and reporting • Knowledge of safety standards and regulations specific to green fuel production and storage |
|  <p>Specialists</p> <ul style="list-style-type: none"> • Plant operator • Water treatment plant operator • Integration specialist • Fuel cell and electrolyzer testing technician | <ul style="list-style-type: none"> • Specialized training in water treatment, electrolyzer technologies, or integration of renewable energy systems • Proficiency in laboratory techniques for testing fuel cells and electrolyzers • Experience in process optimization and systems integration for green fuels production |
|  <p>Logistics</p> <ul style="list-style-type: none"> • Machinery operator • Heavy vehicle operator • Warehouse manager • Marine operator • Stevedore | <ul style="list-style-type: none"> • Understanding of regulations and safety requirements for transporting hydrogen and other green fuels • Knowledge of green fuel supply chain logistics, including transportation and storage • Skilling in the latest handling and safety requirements e.g. ammonia bunkering |
|  <p>Management</p> <ul style="list-style-type: none"> • Operations manager • Maintenance manager • Planner and scheduler • R&D manager • Engineering manager | <ul style="list-style-type: none"> • Strategic planning and decision-making skills with a focus on sustainability and innovation • Leadership skills and experience in managing teams within the energy sector • Project management for complex infrastructure projects • Local stakeholder management (engagement) |

Source: Adaption from PwC “Skills and Training to Support the Hydrogen Economy”, 2022.⁵⁵



6. Resource Potentials

Production of green fuels will require a substantial amount of renewable energy, water, and biomass resources. This section describes the potential needs and availability of these feedstocks needed to produce green fuels.

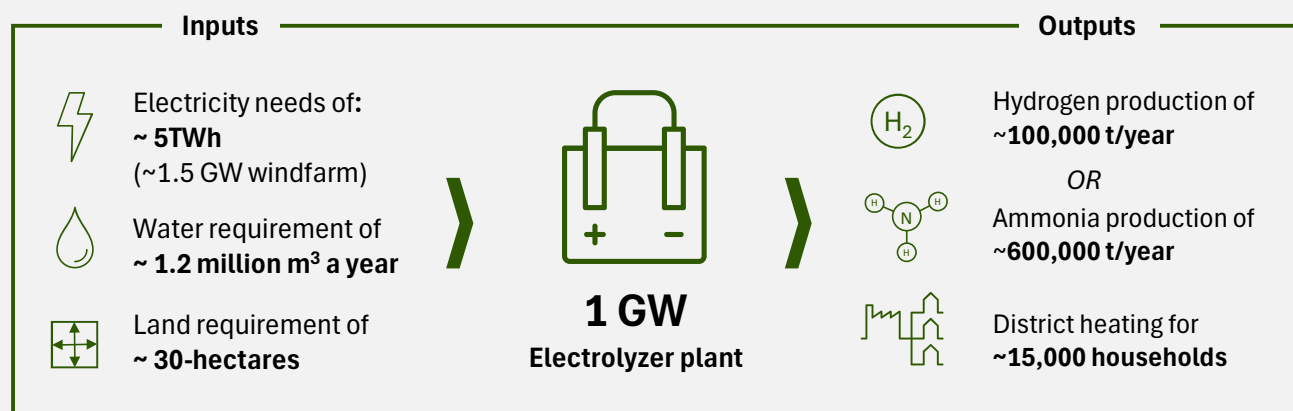
Renewable electricity availability

To reach the government's target of 4-6 GW would require an estimated 20-30TWh of electricity, assuming 5,000 full load hours for the electrolyzer. For context, total Danish electricity consumption in 2023 was approximately 37 TWh, of which 30TWh was supplied by low carbon sources such as wind and solar. An additional 4-6GW would mean approximately 6-15 GW of additional renewable energy capacity would need to be dedicated to hydrogen production. The amount depends on the technology, its capacity factor, production profile, and the potential integration of energy storage. In essence, hitting the 4-6GW electrolyzer target would mean a doubling of Danish wind and solar by 2030, which stands at around 12GW in 2023.⁵⁶ To put the resource needs into context, the

requirements for a generic 1GW electrolyzer plant is shown in Figure 6.1. As shown, A 1GW electrolyzer plant would need an equal or (likely) greater amount of additional renewable energy to power it, but this depends on the load profiles of both the RES source and the operational philosophy of the electrolyzer plant.

To meet this resource requirement, the Danish government is set to tender out large amounts of offshore wind capacity in the North and Baltic sea by 2030, amounting to a minimum of 9GW of capacity, with the potential for more via overplanting.⁵⁷ Energy islands in Bornholm and the North Sea are expected to provide 3GW and 10GW respectively are slated to come online in the mid 2030's.⁵⁸ Additionally, utility scale solar is expected to rise significantly, driven by the low levelized cost of power and the affordability of high efficiency panels. Most new additions will come from offshore wind and solar. Onshore wind will provide some marginal capacity addition in the near-term but is projected to remain fairly stable towards 2050, as shown in Figure 6.3.

Figure 6.1: Estimated needs of a generic 1 GW electrolysis plant



Assumptions

Electrolyzer running 5,000 hours a year at full-load with energy efficiency estimated at 64%

Windfarm operating at ~40% capacity factor

Land requirements, production outputs, district heating numbers are based on project HØST in Esbjerg.⁵⁹

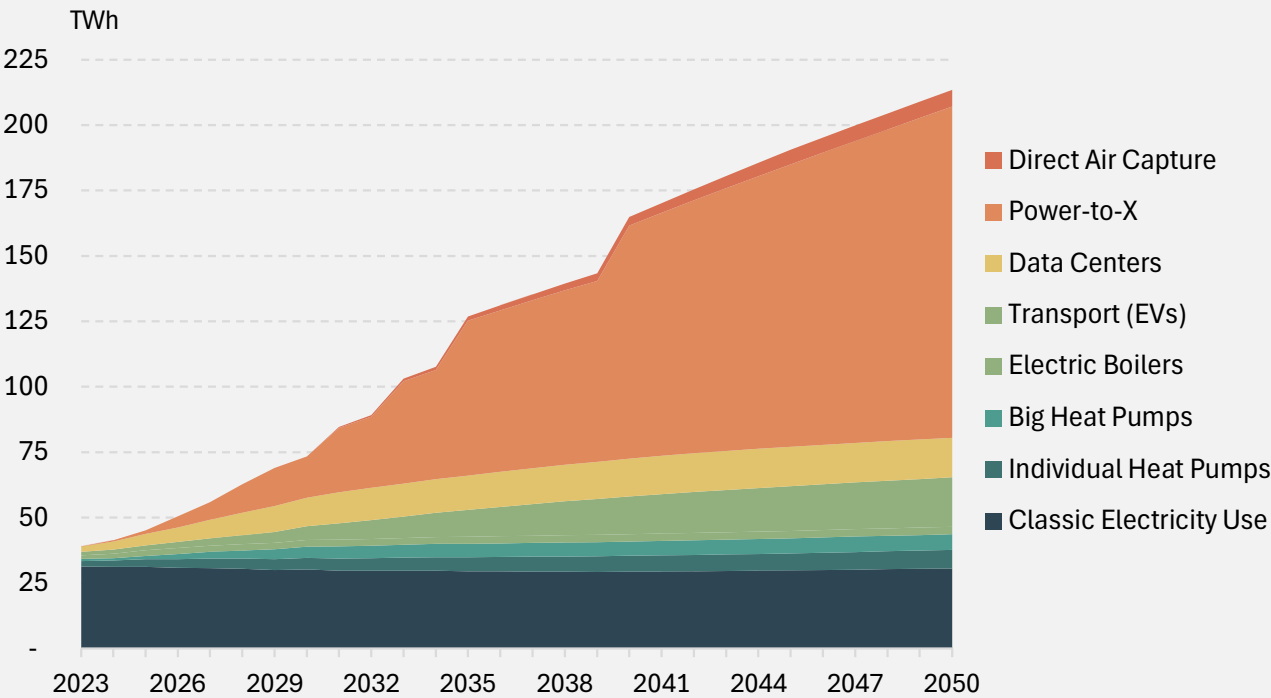
Massive electricity needs projected

When looking longer term, the latest AF23 analysis²⁴ projects that total Danish electricity use will reach 73TWh by 2030, of which more than 20% will be used for PtX. This is projected to reach 213TWh by 2050, of which almost 60% will be devoted to PtX and the production of green fuels. This energy consumption dwarfs the future needs of electrification technologies. Without PtX, total electricity consumption in 2050 would be projected to stand at 87 TWh, of which transport (EVs), heat pumps, and data centres drive most of the growth over baseline levels. The growth in electricity use is shown in Figure 6.2.

Data centres: a potential near-term competitor for renewable capacity additions

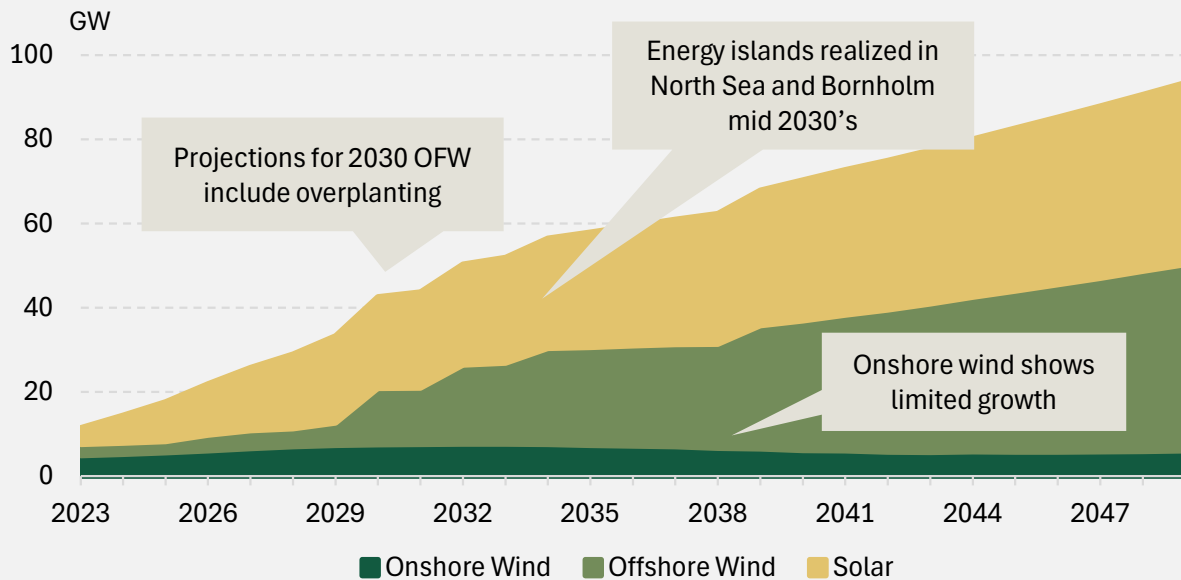
It is important to point out that data centres will also see a substantial rise in energy consumption from 2023-2030 going from 2 to 11TWh of demand (417% increase) in less than 10 years. This is mainly driven by the extensive power needs needed for AI compared to traditional computing needs. In the near-term, this could create an interesting dynamic and scarcity of renewable energy supply⁶⁰ as AI could potentially compete against PtX for new RES capacity, if the captured willingness to pay is higher in datacentres, or if PPA's with data centre operators lock-in the upcoming near-term supply.

Figure 6.2: Electricity use projections 2023-2050



| | 2023 | 2030 | 2050 |
|-----------------|-------|-------|--------|
| Total Use (TWh) | 39.05 | 73.37 | 213.50 |
| PtX Use (TWh) | 0.025 | 15.82 | 126.65 |
| PtX (%) | <0.1% | 21.6% | 59.3% |

Source: Danish Energy Agency AF23: Analysis prerequisites for Energinet, 2023.²⁴

Figure 6.3: Renewable capacity additions 2023-2050 (projected)

Source: Danish Energy Agency AF23: Analysis prerequisites for Energinet, 2023.²⁴

Water availability and sourcing in Denmark

Denmark is generally rich in water resources. The country's average annual rainfall is approximately 800 millimeters, providing a substantial replenishment of these resources. Water abstraction (taking water from a natural resource such as a lake or groundwater) in 2022 was 935 million cubic meters of which was dominated by agricultural use, followed by industrial and domestic use.⁶¹ To minimize local water stress and improve sustainability, Denmark has implemented smart water management practices to ensure conservation of water resources.

The water demand for producing green hydrogen through electrolysis is modest relative to Denmark's total water availability. Producing one kilogram of hydrogen requires about 9 litres of water, with an additional 10-20 litres needed for associated processes like cooling and purification.⁶² To achieve its target of 4-6 GW of electrolysis capacity, Denmark would require an estimated 4.8 to 7.2 million cubic meters of water, which represents less than 1% of the country's total water consumption.

While the overall water demand for hydrogen production is minimal compared to other uses, such as irrigation and cooling in thermal power plants, regional constraints could arise. Industrial-scale PtX projects may face challenges related to local water availability and infrastructure capacity. Therefore, intentional siting of PtX facilities is essential, with permitting processes that assess local and downstream water availability, competing uses, and rights

Denmark's water management policies, which

emphasize sustainable use and efficient allocation, are well-positioned to support the integration of hydrogen production into existing frameworks without compromising other critical needs. Additionally, the potential for water recycling and reuse in hydrogen production through the use of wastewater, or desalinated water, could further reduce the reliance on freshwater resources.⁶³

Bio-resources

Denmark's bioresource potential is characterized by significant opportunities across agricultural, forestry, and potentially marine sectors. For a land area covering approximately 43,000 km²: 61% is used for agriculture, 13% for forestry, 14% for urban development, while natural areas, including lakes and streams, make up 12%.⁶⁴ Previous studies indicate that around 20 million tonnes of dry biomass are produced annually from cultivated land, with approximately 18 million tonnes being harvested. Strategies suggest this can be increased by an additional 10 million tonnes through improvements in agricultural practices, utilization of perennial crops, and enhanced forestry management.

A minimal portion of Denmark's agricultural land is allocated for dedicated energy production, with approximately 8,500 hectares planted with willow and poplar for wood chip production. Currently, large-scale cultivation of energy crops in Denmark is not feasible without impacting food and feed production. Due to the potential competition for land between energy crops and food/feed crops, the current emphasis in Denmark is on utilizing agricultural and forestry residues, along with organic waste, for energy production.⁶⁵

Importantly, as straw-based or wood-chip combined heat and power (CHP) plants transitions heat production to electricity-based heat pumps, the demand for straw in CHP production is expected to decrease, potentially freeing up large quantities of biomass for other uses such as green fuels production.⁶⁶

In terms of fats, oils, and greases (FOG) Denmark has a limited availability which can be used for biofuel production including HVO Hydrotreated Vegetable Oil (HVO) and biodiesel. The primary sources of these FOGs in Denmark include used cooking oil from the food service industry, animal fats from the rendering industry, and grease trap waste. However, due to the country's relatively small size and population, the domestic supply of these materials is limited. An estimate places the total energetic potential of FOG at ~0.3PJ/year which is much less than the potentials seen in agricultural residues, manure, etc.⁶⁷ Therefore, technology advancement is sought in lignocellulosic biomass conversion to produce bio-oils which can be later converted to HVO via hydroprocessing, etc.

Studies on Danish biomass potentials theorize several ways to sustainably increase bio-resources available for biogas and biofuels production via:

- Increasing the recovery of agricultural residues such

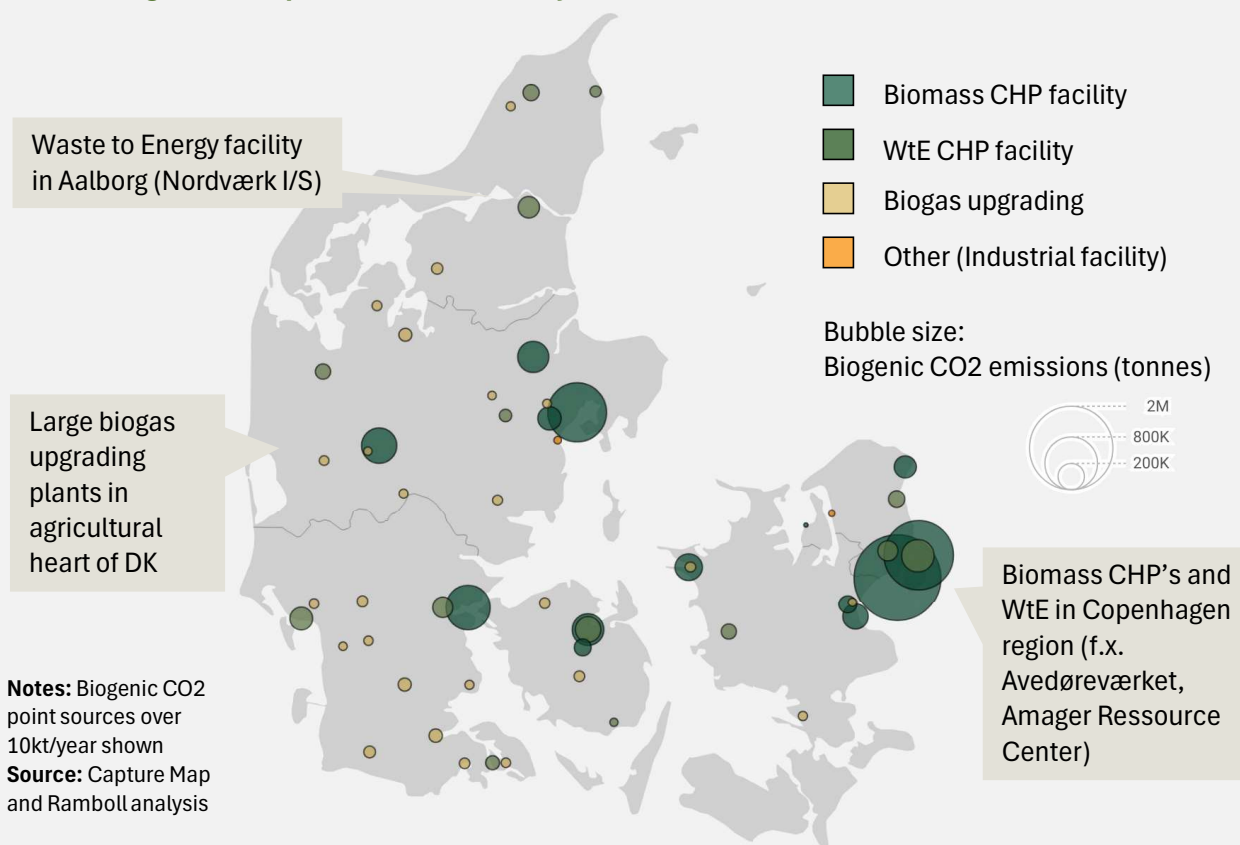
as straw and shifting to crops with higher biomass yields can provide additional raw feedstock.

- Cultivating perennial energy crops like willow, poplar, and Miscanthus on marginal lands can provide a steady source of biomass without impacting food production.
- Increasing the usage of forestry residues and improving forest management practices can boost the availability of woody biomass.
- Leveraging Denmark's marine resources by cultivating sugar kelp, sea lettuce, etc.
- Improving biorefinery technologies to convert biomass more efficiently, improving yield.

Biogenic CO₂

Biogenic CO₂ is carbon dioxide released from natural processes like the decomposition of organic matter or the combustion of biomass. It is considered carbon-neutral because the CO₂ released is roughly equal to what the biomass absorbed during its growth, making it part of a closed carbon loop. This is why biogenic CO₂ is often targeted in sustainability efforts, as its capture and utilization can contribute to reducing overall atmospheric CO₂ levels when managed properly.

Figure 6.4: Biogenic CO₂ point sources >10kt/year in Denmark



The technical potential for point-source capture of biogenic CO₂ in Denmark is estimated to reach approximately 7 Mtpa by 2030 (INNO-CCUS).⁶⁸ Key sources include large-scale biomass combined heat and power (CHP) plants, Waste-to-Energy facilities (which emit both biogenic and non-biogenic CO₂ due to their heterogeneous feedstock), and biogas upgrading plants. The total capturable biogenic CO₂ will depend on the capture technology used, its efficiency, and the biogenic content of the feedstock. While Denmark may have sufficient biogenic CO₂ available in the near-term, economic factors could limit the viability of capturing, transporting, and integrating it into PtX processes.

Biogenic CO₂ will be driven by market dynamics including emissions trading schemes and incentives, influencing how biogenic CO₂ is valued and utilized in the market. The CO₂ market in Denmark is primarily driven by the demand for capturing and storing both biogenic and fossil CO₂ emissions, a focus strongly supported by government policies.⁶⁹ There will also be a growing demand for biogenic CO₂ in the green fuels sector, particularly for carbon-based efuels. However, in the short term, most of the CO₂ captured in Denmark is earmarked for storage rather than utilization. Additionally, the availability of biogenic CO₂ from biomass CHP plants may decline over time as the adoption of other technologies, such as renewables and heat pumps, changes their operational patterns.



7. Sector Pathways

This section outlines key sectors within industry and transport and their associated energy transition end-use pathways to meet the Danish climate targets. Data for these sections are taken from the Danish Ministry of Climate, Energy, and Utilities KF23 and KF24 reports which provide the latest overview of current and projected energy use, CO₂ emissions, and sectoral trends for industry, transport, shipping, and aviation.⁵⁶ This is supported by the latest AF projections produced by the DEA for Energinet.²⁴ Total Danish emissions are shown in Figure 7.1.

The sectors pathways considered include the following:

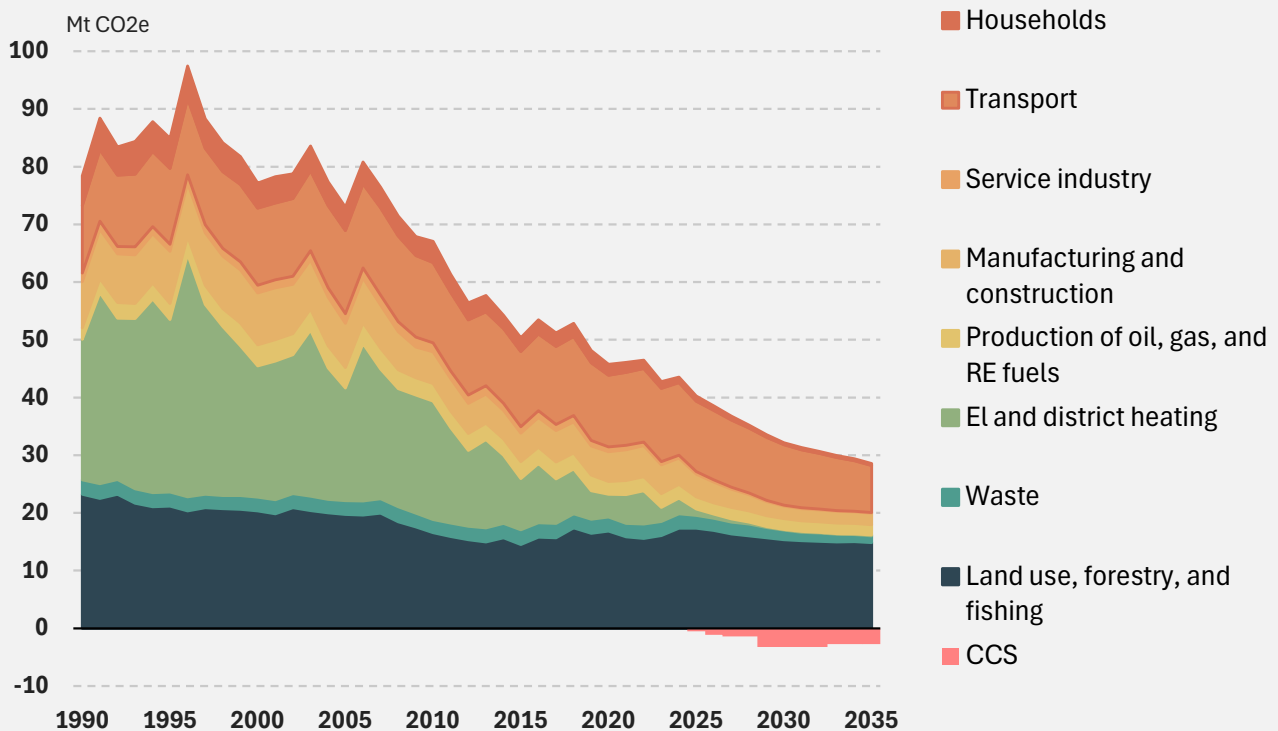
Industry: Manufacturing and energy intensive industry

Road transport: Heavy and light toad transport

Maritime: Domestic and international shipping

Aviation: Domestic and international air travel

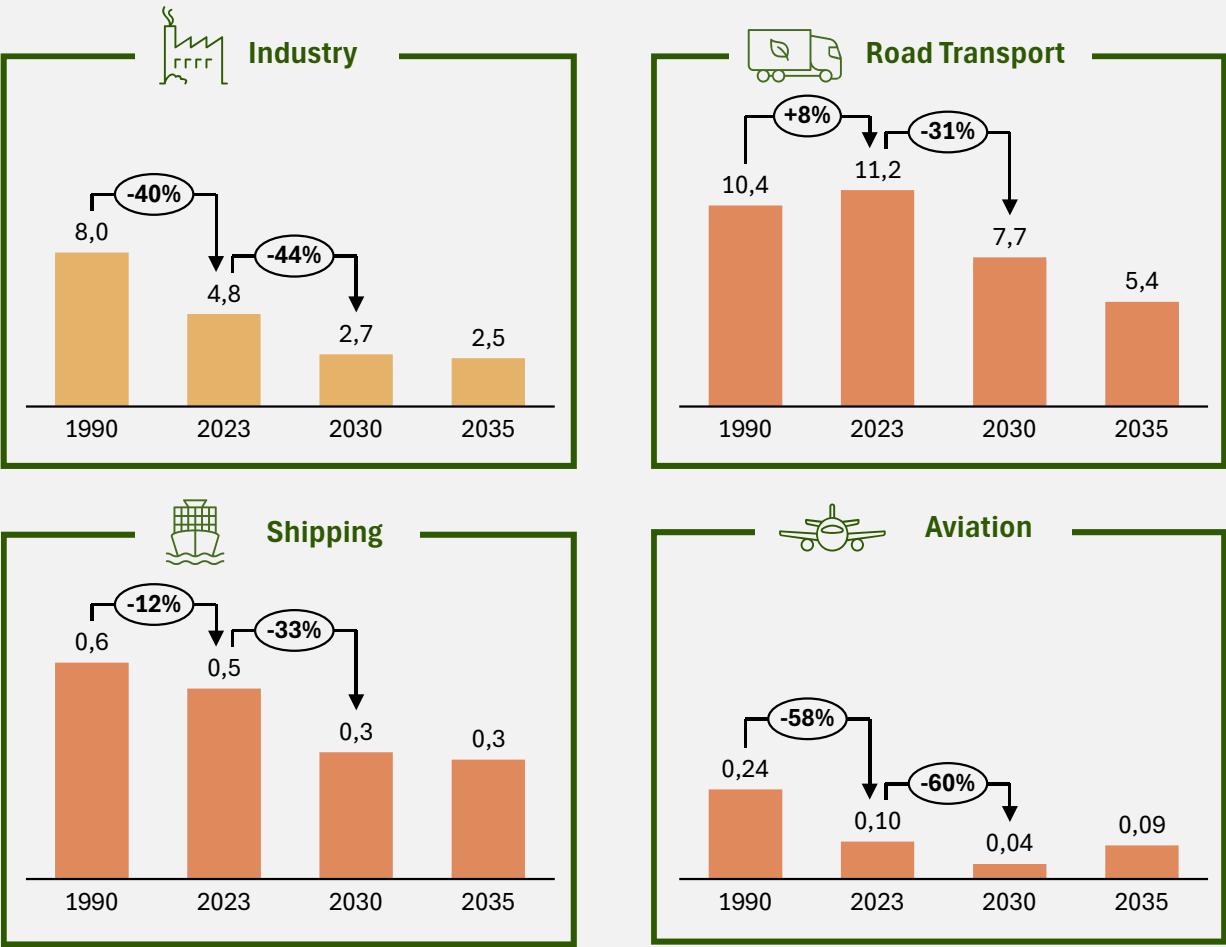
Figure 7.1: Combined emissions (1990-2035) from KF23



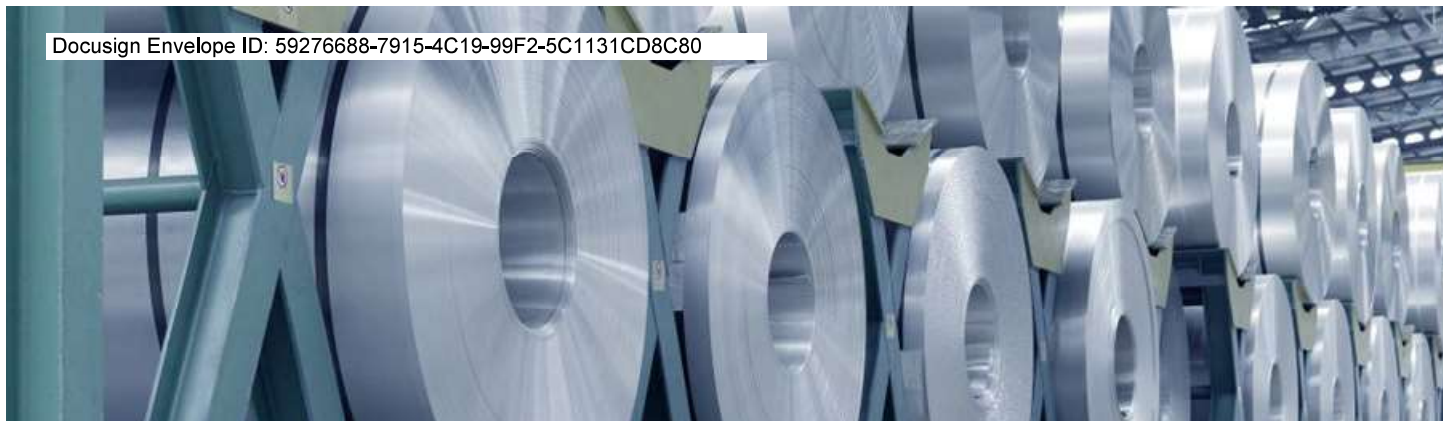
Notes: Projections include negative emissions from CCS

Source: Danish Energy Agency KF23: Klimastatus og Fremskrivning, 2023.⁵⁶

Figure 7.2: Sectoral emissions in industry and transport (Mt CO_{2e})



Source: Danish Energy Agency KF23: Klimastatus og Fremskrivning, 2023.⁵⁶



7.1 Industry

Current emissions profile

The industrial sector, which includes manufacturing and construction, is fundamental to the Danish economy accounting for over 20% of GDP.⁷⁰ This sector encompasses a wide range of activities from producing consumer goods, high-value manufactured goods for export, to building infrastructure and dwellings. While it has reduced its emissions by 40% since 1990, primarily through fuel switching from coal and energy efficiency, the sector in 2023 still accounts for 4.8 Mt CO₂e annually, amounting to 12.6% of total Danish emissions. Other greenhouse gas emissions, from methane leakage, f-gases, or nitrous oxide are minimal and will not be covered in this pathway.

Of these 4.8 Mt CO₂e, over half result from emissions from energy use in heavy industry. Cement production which still uses coal and petroleum coke as fuel or feedstock is a significant industrial emitter. Cement production, of which Aalborg Portland is the biggest player, is the largest emitter in Denmark and responsible for more than 5% of national emissions in 2022 (1.98 Mt CO₂e).⁷¹

Decarbonization trajectory

Decarbonization of industry will primarily come from greening the energy used for industrial processes and then cleaning up emissions associated with cement production. For electrical energy users as motors, compressors, lighting, etc., carbon emissions will inherently decline as additional renewable energy capacity is added with a lower carbon intensity. Energy efficiency will make processes less energy hungry while electrification using heat pumps will be applied to low and medium temperature industrial heating needs. For high temperature applications, natural gas or biomethane can be used to create steam. As more biogas plants come online the share of biomethane in the grid is expected to increase and this the carbon intensity of blended natural gas will reduce.

For the cement industry, biomass (e.g. wood or

agriculture residues) and waste can replace coal and petroleum coke for use in kilns. Enhancements in process efficiency, including the reduction of the clinker content in cement, are key. Clinker production is the most CO₂-intensive part of cement manufacturing, and reducing its proportion in the final product, via biomass or industrial by-products such as fly ash can significantly lower emissions. For hard-to-abate emissions, CCS could also be an option for cement, being able to capture point source emissions and store them geologically.

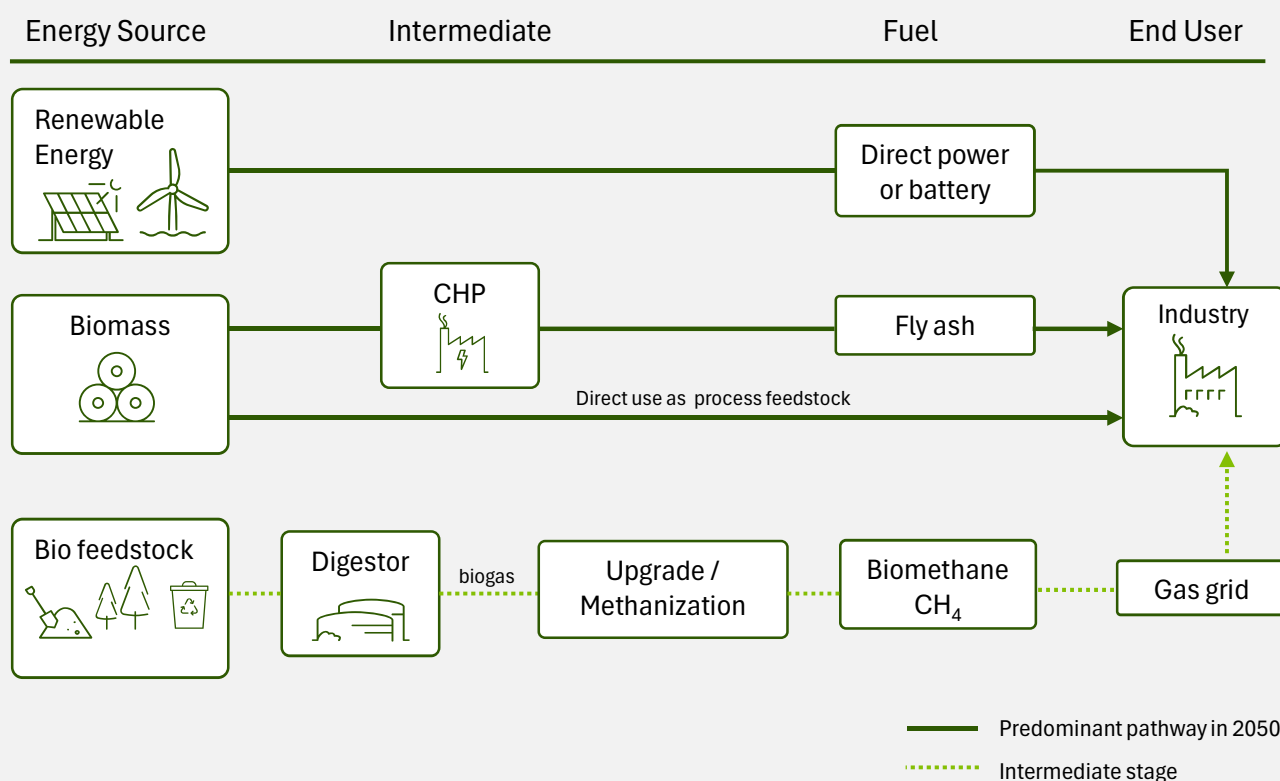
Policy drivers

Policy drivers to enact decarbonization along the industrial pathway include the Green Tax Reform Agreement of 2022 which aims to incentive industries to reduce their emissions via financial penalties. The implementation of a CO₂ tax will drive significant emission reductions. In addition to the CO₂ tax, the Agreement on the Allocation of Transition Support from the Green Tax Reform for Industry from March 19, 2024, allocates approximately 2 billion DKK for transition support targeted at companies that have the most difficulty transitioning.

Role of green fuels

In the near-term, the use of green hydrogen (or any other hydrogen derivative) is not foreseen, as direct electrification is considered a more economically attractive path than green hydrogen. An exception would be if hydrogen is blended into the natural gas grid, used to improve biomethane yields, or if e-methane becomes economically competitive with biomethane. Otherwise, hydrogen's use will be limited. However, it is important to note that the door should not shut on green hydrogen's use in industry; there is a possibility that cheap and abundant green hydrogen could attract heavy industry to Denmark in the longer term. This includes industries that use hydrogen as a feedstock, including fertilizer production, steel production, and certain manufacturing and chemical processes.

Figure 7.3: Fuel Pathway - Industry



Industry

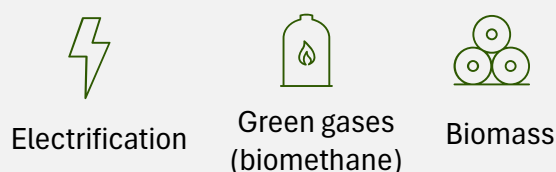
Key points

- 1 **Energy efficiency** and **electrification** are the key pathways to reduction in the industry with **biomethane** (or high-temp heat pumps) replacing natural gas for **high-temp processes**
- 2 The **adoption of biomass and waste** (fly ash) to replace coal and petcoke in **cement production** is expected to reduce energy-related emissions
- 3 The CO₂ tax introduced in the **Green Tax Reform Agreement** of June 2022 is a key driver of emission reductions (e.g. cement)

Emissions (Mt CO_{2e})

| 1990 | 2023 | 2030 | 2035 |
|------|------|------|------|
| 8.0 | 4.8 | 2.7 | 2.5 |

Relevant technologies



Long term-outlook (2035+)

- Limited use of green fuels outside of biomethane or biomass
- Existing natural gas infrastructure can be utilized with biomethane
- Heavy-industries wherein H₂ can be used, limited in DK (steel, fertilizers, etc.)
- Possibility of attracting industry to DK with cheap green hydrogen
- Possible use of green H₂ to improve biomethane yields or for e-methane production



7.2 Road Transport

Current emissions profile

Of the four sectors covered in this roadmap, the emissions from road transport are the highest, when considering domestic emissions. In fact, emissions rose 8% between 1990 and 2023 levels amounting to 11.3 million tonnes in 2023. To hit the 2030 target, emissions must drop more than 30% by 2030. Of the road transport emissions in 2023, 60% originated with light or personal cars, 33% from goods and cargo trucks, and 7% from busses, motorcycles, or other forms of road transport. Historical emissions since 1990 are shown below in Figure 7.4.

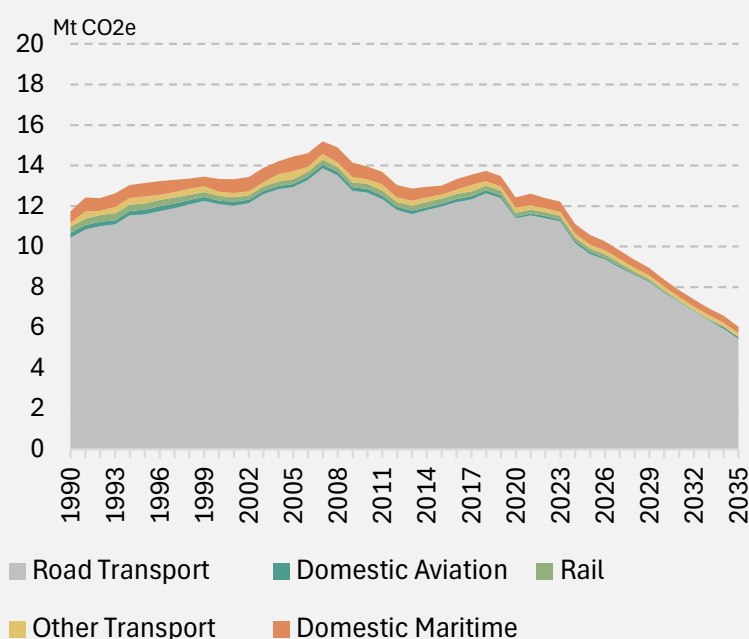
Decarbonization trajectory

For light road transport, including personal mobility, the reduction in emissions will come from a shift from conventional internal combustion engines (ICE) vehicles to electric vehicles (EVs), plug-in hybrids, and

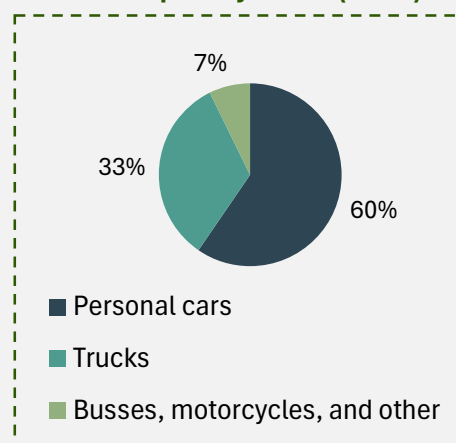
improved engine efficiency (mileage). The success in adoption rates in EVs will come from the availability of charging networks, improved battery technologies lifespan and charging time, and overall cost reductions in the total cost of ownership for these vehicles. Hydrogen or e-fuels are not expected to be competitive as a fuel type for light road transport.

Carbon reduction will also come from blending renewable energy (RE) fuels into conventional fuels. Denmark is subject to the EU's Fuel Quality Directive, which requires EU Member States to reduce cradle-to-grave emissions of greenhouse gases in transport fuel by 6% per energy unit in 2020 relative to 2010.⁷³ Fuel specifications aim to ensure compatibility with engines and exhaust after-treatment systems, such as catalytic converters. Consequently, blending certain biofuels is limited due to incompatibility with some engines.

Figure 7.4: Transport emissions shown by source (Mt CO_{2e})



Road transport by mode (2023)



The majority of road related emissions come from personal vehicles for mobility (60%)

In diesel, biodiesel (FAME) content is typically capped at 7%, while ethanol content in petrol is restricted to 10%. To accommodate higher blends of bioethanol, engines require upgrades to fuel system components with corrosion-resistant materials, recalibrated engine control units for optimization, and enhanced cold start systems. This is a barrier to increased biofuels.

Engines that can run on Methanol and DME are also an option but require engine modifications or special flex fuel vehicle (FFV) kits. Additionally, engines that are E85 (meaning 85% ethanol) are also a possibility. However, this may not be realistic based on the current trajectory of electric vehicles and the cost/limited availability of sustainably sourced biofuels. Corn ethanol, for example, does not meet the criteria for advanced biofuels. E85 is also limited by the number of fuelling stations offering this type of fuel as there are none in Denmark.

Other biofuels such as Hydrotreated vegetable oil (HVO), FAME, or methanol are also potential options in

the intermediary stage due to ability to be “drop-in” or utilized in engines with minimal engine modifications. These fuels are compared in Table 7.1. Benefits of using biofuels in the near-term include the ability for easy transport and use in existing infrastructure and the ability to be further synthesized into sustainable aviation fuel when existing vehicle packages become electrified or run on hydrogen. This is shown on the intermediate fuels pathway in Figure 7.7.

Fuel Blending

- Since 2010, biofuels such as biodiesel or bioethanol have been blended into conventional fuels to lower their emissions intensity
- In 2023, bioethanol made up 6.8% of the energy content of conventional gasoline and biodiesel 5.5% of diesel fuels
- These numbers are driven by blending obligation minimums (DK and EU level)

Table 7.1: Comparison of intermediary biofuels for road applications

| Criteria | FAME | HVO | Bio-methanol (MeOH) | Bio-Ethanol (EtOH) |
|-----------------------------|--|--|--|--|
| Feedstock | Vegetable oils, animal fats, and waste oils | Vegetable oils and animal fats | Natural gas, biomass | Biomass such as corn, sugarcane, and cellulose |
| Production process | Transesterification | Hydrogenation | Biomass conversion or syngas reforming | Fermentation |
| Energy density | Moderate (about 37 MJ/kg) | High (about 44 MJ/kg) | Lower (about 20 MJ/kg) | Lower (about 27 MJ/kg) |
| Engine compatibility | May require modifications to engine and fuel systems | Drop-in fuel; compatible with existing diesel engines and infrastructure | Requires modifications for corrosion resistance | May require modifications for higher blends; corrosive to some materials |
| Infrastructure | Existing diesel infrastructure with minor modifications | Can use existing diesel infrastructure | Requires dedicated storage and handling infrastructure | Requires modifications to storage and distribution systems |
| Cost | Affected by feedstocks prices and availability. May be impacted by seasonality and certification of sustainable or “advanced” feedstocks | | | |
| Environmental impact | Reduces GHG emissions; could lead to land-use change (ILUC) | Reduces GHG emissions; promotes waste recycling | Reduces GHG emissions; can produce toxic by-products | Reduces GHG emissions; Controversial: food vs fuel debate ⁱ |

i. If not sustainably sourced (e.g. corn ethanol). It is possible to create ethanol from waste products and lignocellulose that meet Annex IX criteria for sustainability: “Advanced Biofuels”


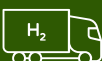
Heavy Road

For heavy road-transport, electrification and hydrogen will be relevant. Despite the higher efficiency of electric engines, the weight, space, and fuelling behaviour of large trucks may make the electric option less attractive. However, improvements in battery density, charging times, or battery-swapping technologies may change this dynamic over time. Hydrogen is an option and can be used in fuel cell electric vehicles (FCEVs). It is attractive for heavy trucking because it offers a high energy density, allowing for longer driving ranges and shorter refuelling times compared to battery electric trucks, which is crucial for the logistics in the transportation industry. The decision of whether to go with an electric or hydrogen trucks depends on the requirements for the vehicle, the status of charging or refuelling infrastructure, and the total cost of

ownership between the options. A comparison of electric and hydrogen trucks are shown in Table 7.2.

The adoption rate of electric vehicles is an important factor to consider when aiming to reduce carbon emissions in transport. KF projects that electric truck vehicle sales will start to accelerate in 2027-2028 as the technology sees maturity and commercialization. By 2029, over half of new truck sales are expected to be electric. In the models, hydrogen trucks start seeing sales from 2030 onward but are projected to make up only 6% of new truck sales by 2035, while electric trucks will make up 62% of the total sales. The projections in truck sales are shown in Figure 7.5.

Table 7.2: Comparison of electric versus hydrogen fuel cell trucks

| Criteria | Electric Trucks  | Hydrogen Trucks  |
|-------------------------------|---|--|
| Energy density | Lower energy density; suitable for shorter routes and urban deliveries | Higher energy density; ideal for long-haul routes |
| Efficiency | Higher energy efficiency (~70%); electric drivetrains convert more stored energy into movement | Lower overall energy efficiency (~30%); hydrogen production, compression, and conversion result in energy losses |
| Refueling time | Longer charging times (30 minutes to several hours) depending on battery capacity and charger type | Short refuelling times (typically 10-20 minutes) |
| Infrastructure | Requires widespread charging infrastructure; currently limited but growing | Requires hydrogen refuelling stations; infrastructure is currently less developed but expanding |
| Operational range | Typically shorter ranges (160-480 km per charge) | Longer ranges (480-800 km or more per tank) |
| Cost | High initial cost; operational costs are lower due to cheaper electricity and fewer maintenance needs | High initial cost; operational costs higher due to hydrogen price and additional fuel cell maintenance |
| Weight | Heavier due to large battery packs, potentially reducing payload capacity | Lighter than electric trucks for similar energy storage capacity, potentially allowing higher payload |
| Maintenance | Fewer moving parts; lower maintenance requirements and costs | Requires maintenance of fuel cells and hydrogen tanks; more complex |
| Technological maturity | More mature with a broader range of models | Emerging technology; fewer models currently available but rapidly developing |

Energy Mixes

When considering total energy use in road transport, gasoline and diesel are still projected to lead the energy mix through 2030 and 2035. This dominance is attributed to the existing vehicle fleets and the time required for a significant transition to low-emission vehicles and the necessary infrastructure build-out.

However, starting in the mid-2020s, biofuels, electricity, and hydrogen are expected to make notable inroads into the total energy use. This shift is driven by advancements in technology, supportive policies, and increasing market adoption of alternative fuel vehicles. Long-term, electricity, hydrogen, and a mix of green fuels are expected to overtake diesel and gasoline.

Figure 7.5: Projected sale of heavy-trucks (2019-2035), number of trucks

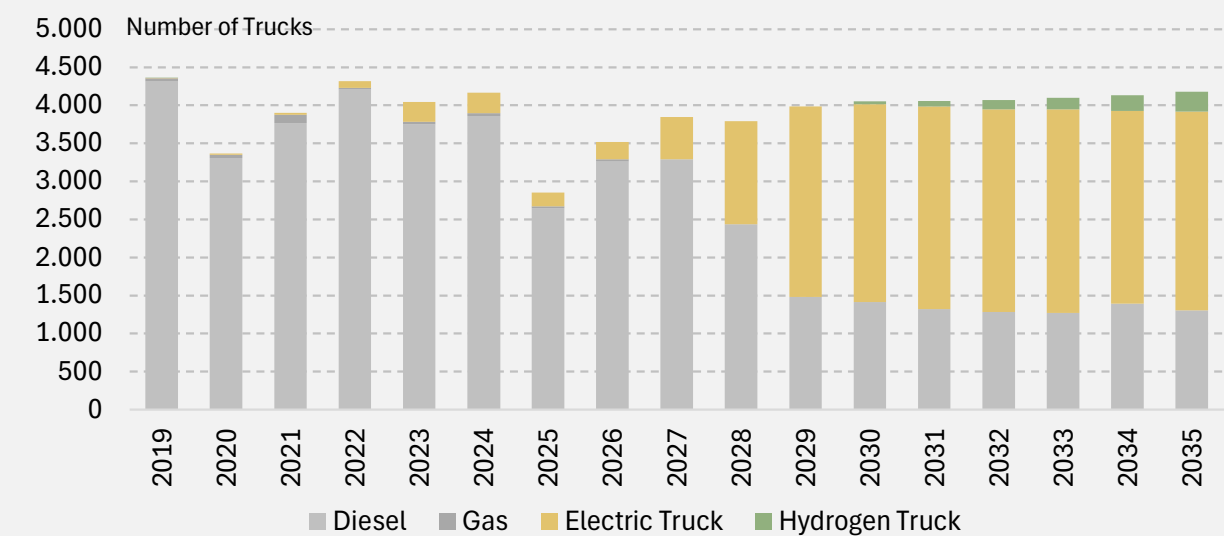


Figure 7.6: Energy use developments in road transport (1990-2035), PJ

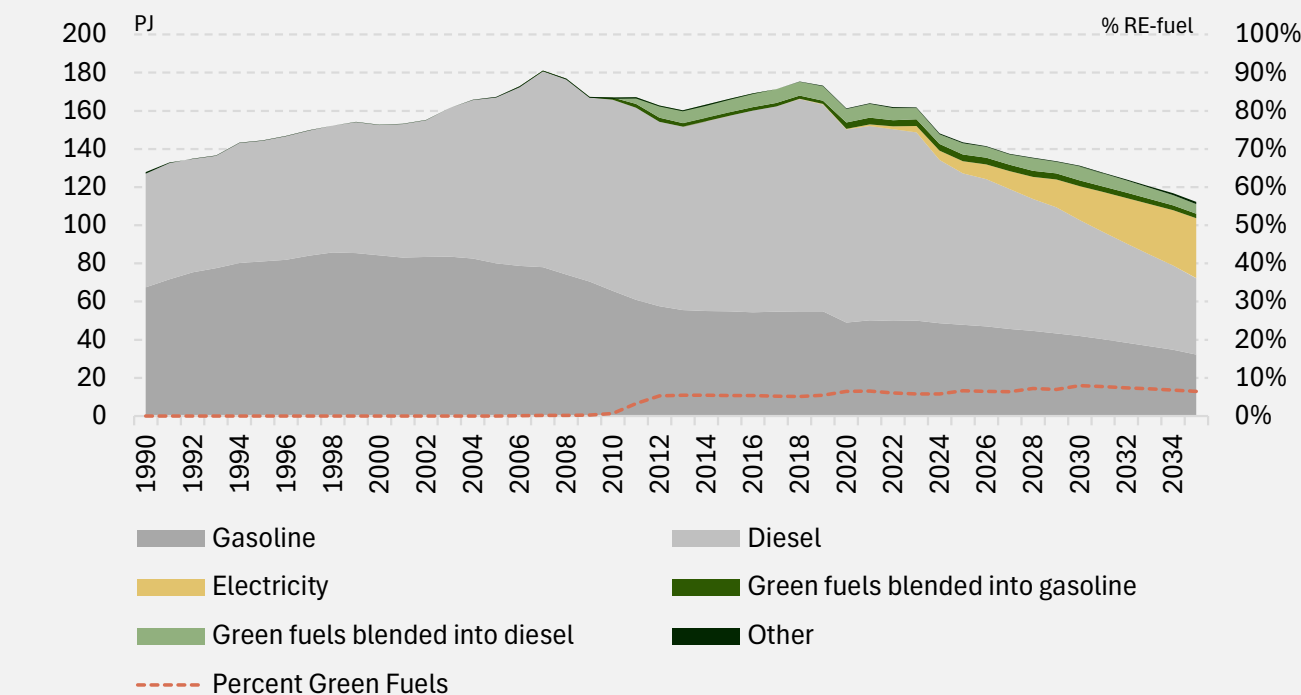


Figure 7.7: Fuel Pathway – Light road transport

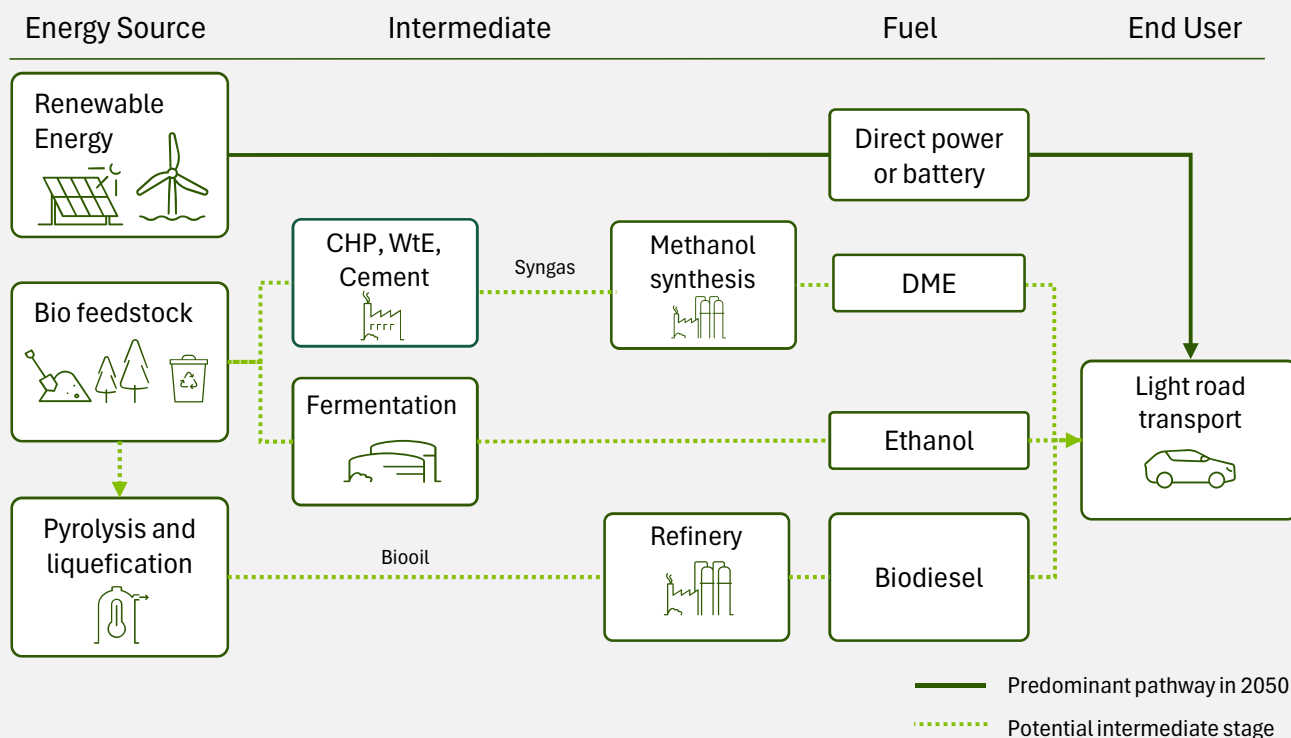
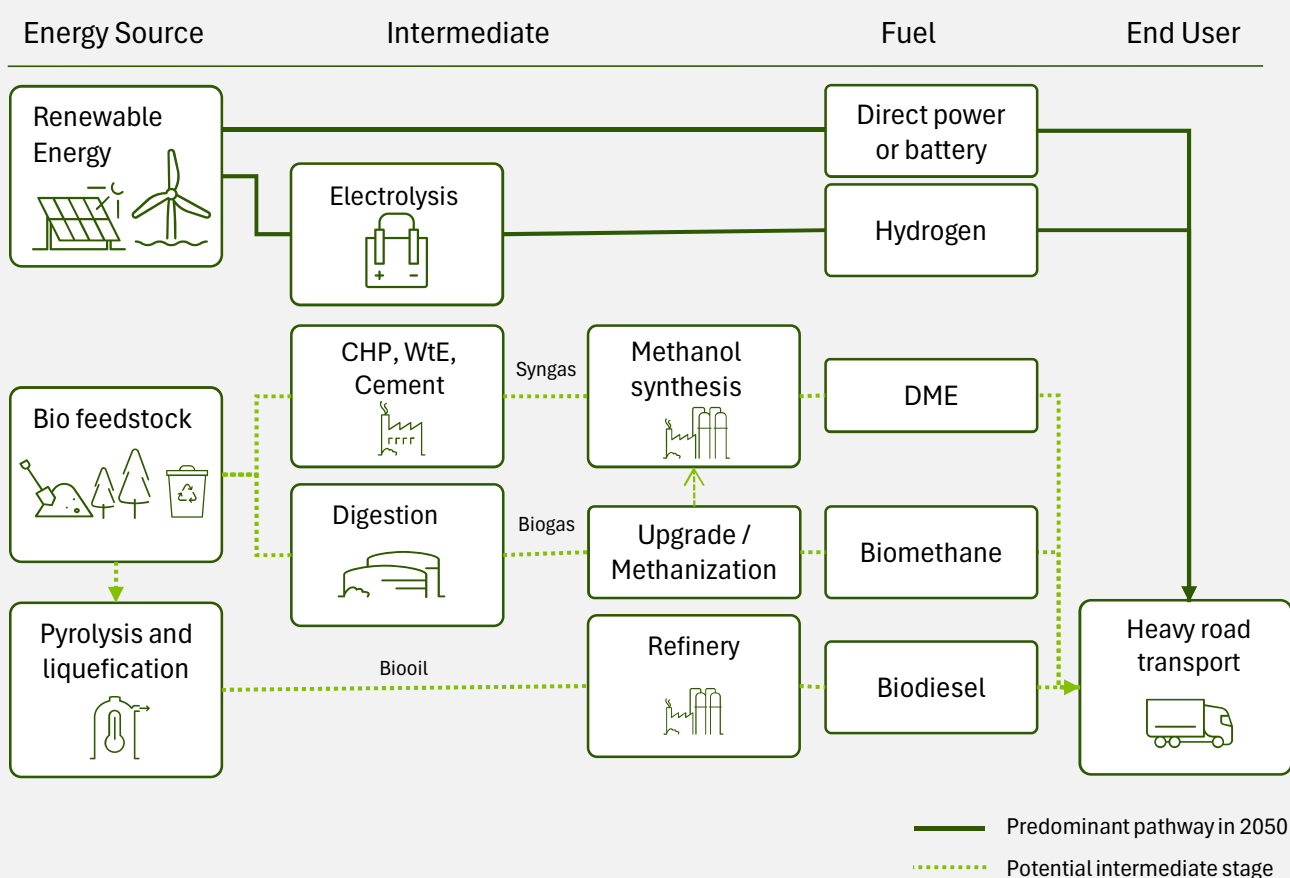


Figure 7.8: Fuel Pathway – Heavy road transport





Road Transport

Key points

- ① Light road and personal vehicles will be electrified.
- ② Intermediate fuels (HVO, FAME, MeOH, EtOH) can be considered in the transitional phase to electric and H₂ as drop in fuels.
- ③ Heavy-road expected to be a combination of electrification, blended green-fuels, and hydrogen fuel cells. Use-case dependent.

Emissions (Mt CO_{2e})

| 1990 | 2023 | 2030 | 2035 |
|------|------|------|------|
| 10.4 | 11.2 | 7.7 | 5.4 |

Relevant technologies



Electric
Vehicles



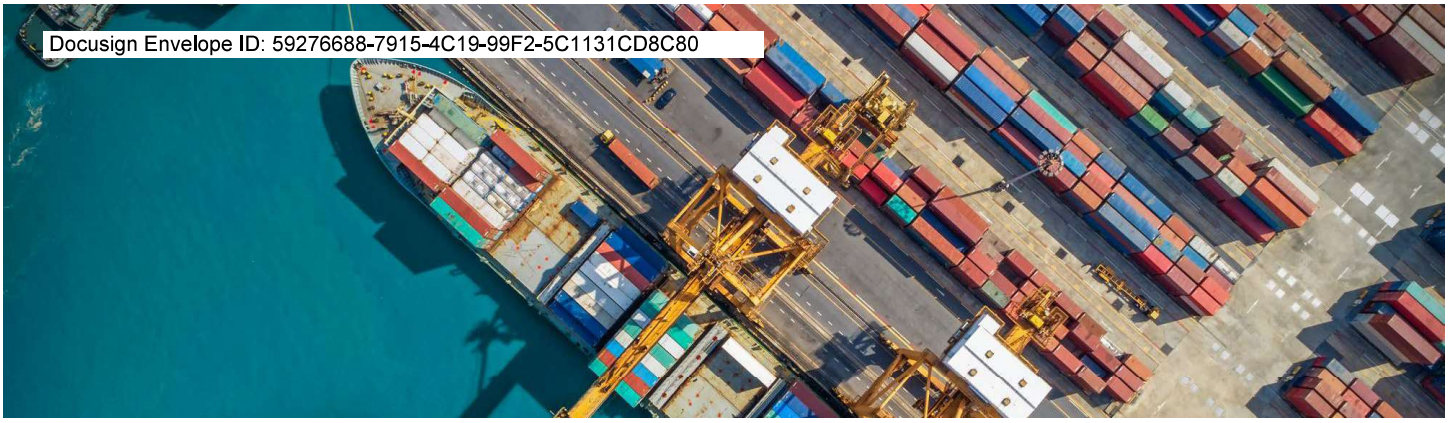
H₂ Fuel cell
vehicles



Biofuels

Long term-outlook (2035+)

- Electrification of trucks likely as battery technologies improve
- Use cases for hydrogen fuel cells exist in heavy transport where batteries are not practical
- Intermediate fuels can be considered to lower emissions in the transitional phase to electric and H₂



7.3 Maritime

Current emissions profile

In 2023, the domestic shipping and maritime sector accounted for 4.1% (0.52 Mt CO₂e) of total transport emissions which equates to ~1% of total national emissions. Like domestic aviation, maritime activity within Denmark is a small piece of the national emissions inventory when zooming out and considering the 70% goal. The primary sources for domestic maritime emissions include domestic ferry routes and goods transport (including to and from Greenland and the Faroe Islands) that rely primarily on diesel fuel. The sectoral emissions are shown in Figure 7.9.

International shipping

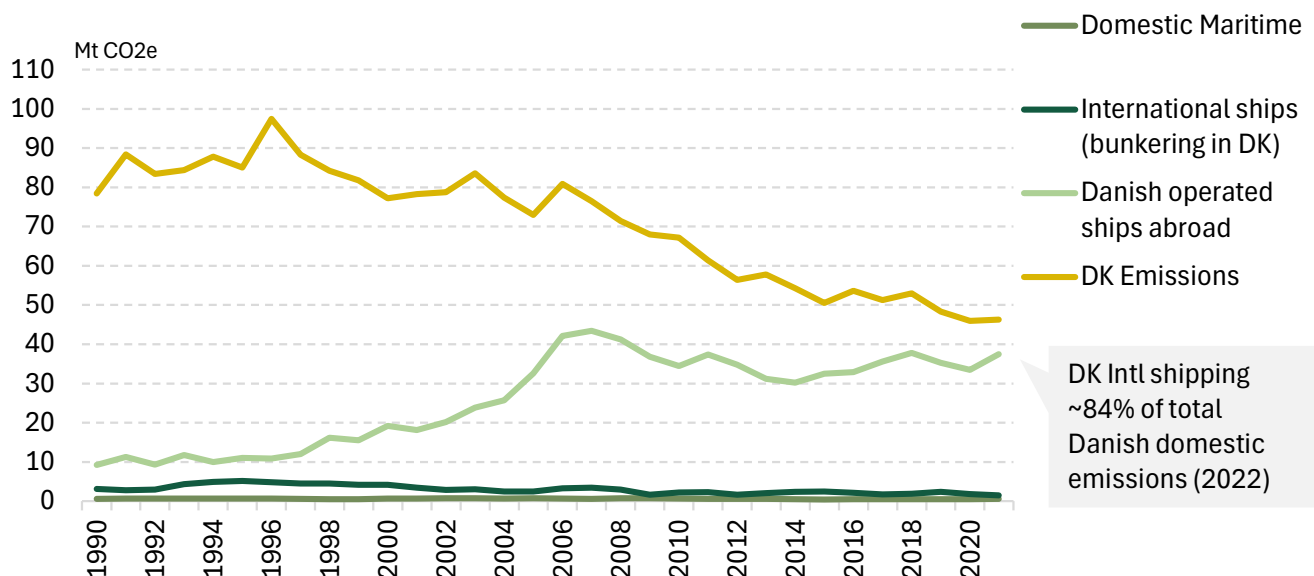
On an aggregate level, 95% of Danish shipping activities take place outside of Denmark and international shipping is a significant source of carbon emissions. In fact, Danish operated ships abroad and international ships bunkering in Denmark accounted for a substantial 39 million tonnes of CO₂e.⁷⁴

Emissions from these two sources have risen more than 200% since 1990. The major contributors to carbon emissions from Danish-operated ships include international logistics giants such as Maersk, DFDS, and more. They are significant contributors to the today's globalized economy. When compared, these emissions are more than 80% of Danish emissions (compared to domestic inventory) and represents perhaps the greatest opportunity for decarbonization via green fuels and the most impactful on a global stage, where Danish innovation and strategic positioning can have the greatest outsized influence.

Fuel usage today

Currently, most vessels are fuelled by conventional fuels: marine diesel oil (MDO), heavy fuel oil (HFO). Other names or derivations of these bunker fuels include Low sulphur fuel oils (LSFO), or marine Gas Oil (MGO). Their usage will vary based on application and particulate and sulphur content and regulated by different emissions requirements.

Figure 7.9: Emissions in the domestic and international maritime sector



LNG and LPG

Recently liquified natural gas (LNG) and liquefied petroleum gas (LPG) have made some advances in replacing heavy fuels, but their usage remains limited and is not technically a long-term green solution considering carbon intensity and methane leakage. Nonetheless, their usage as fuels will likely see use as a bridging technology. More than 40% on new ships on order are LNG/LPG vessels, while 8% are methanol, according to DNV.⁷⁵ There could be some “lock-in” effects here, but this could present an interesting entry point for liquified biomethane or synthetic natural gas in the near to medium term.

Green fuels

Green fuels proposed for the maritime sector include biofuels (HVO/advanced biodiesel, bio-oils), methanol, ammonia, and hydrogen. Their usage and potential are constrained by feedstock availability, retrofit ability of existing ship fleets, production volumes of the fuels, and health and safety considerations, among others. Their main characteristics compared to conventional fuels are shown in Table 7.3. The assessment of parameter ratings of the different fuels is generic and may change on a case-by-case basis. The table is meant to give an overview of the main fuel types and some of the barriers to overcome for proposed fuel alternatives.

Table 7.3: Evaluation of maritime fuel options across key parameters

| Fuel Type | <div> <div>Favourable / Mature</div> <div>Neutral / Minor challenges</div> <div>Unfavourable / Major challenges</div> </div> | | | | | | | | | |
|--|--|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|----------------------------|---------------------------------|---------------------------------|---------------------------------|
| | LSFO / HFO | LNG | LPG | HVO / biodiesel | Bio-oil | Bio-LNG / SNG | Methanol | Ammonia | Hydrogen ^{vi} | Electric Battery |
| Energy density (volumetric) ⁱ | Favourable / Mature | Neutral / Minor challenges | Neutral / Minor challenges | Favourable / Mature | Favourable / Mature | Neutral / Minor challenges | Neutral / Minor challenges | Neutral / Minor challenges | Unfavourable / Major challenges | Unfavourable / Major challenges |
| GHG emissions ⁱⁱ | Unfavourable / Major challenges | Neutral / Minor challenges | Neutral / Minor challenges | Favourable / Mature | Favourable / Mature | Neutral / Minor challenges | Favourable / Mature | Favourable / Mature | Favourable / Mature | Favourable / Mature |
| NOx, SOx, PM emissions ⁱⁱⁱ | Unfavourable / Major challenges | Neutral / Minor challenges | Neutral / Minor challenges | Unfavourable / Major challenges | Neutral / Minor challenges | Neutral / Minor challenges | Favourable / Mature | Neutral / Minor challenges | Favourable / Mature | Favourable / Mature |
| Flammability | Favourable / Mature | Favourable / Mature | Favourable / Mature | Favourable / Mature | Favourable / Mature | Favourable / Mature | Neutral / Minor challenges | Neutral / Minor challenges | Unfavourable / Major challenges | Favourable / Mature |
| Toxicity | Favourable / Mature | Favourable / Mature | Favourable / Mature | Favourable / Mature | Favourable / Mature | Favourable / Mature | Neutral / Minor challenges | Unfavourable / Major challenges | Favourable / Mature | Favourable / Mature |
| Engine compatibility ^{iv} | Favourable / Mature | Unfavourable / Major challenges | Unfavourable / Major challenges | Favourable / Mature | Favourable / Mature | Unfavourable / Major challenges | Neutral / Minor challenges | Unfavourable / Major challenges | Unfavourable / Major challenges | Unfavourable / Major challenges |
| Storage convenience | Favourable / Mature | Unfavourable / Major challenges | Unfavourable / Major challenges | Favourable / Mature | Favourable / Mature | Unfavourable / Major challenges | Neutral / Minor challenges | Unfavourable / Major challenges | Unfavourable / Major challenges | Neutral / Minor challenges |
| Bunkering availability | Favourable / Mature | Neutral / Minor challenges | Neutral / Minor challenges | Neutral / Minor challenges | Unfavourable / Major challenges | Unfavourable / Major challenges | Neutral / Minor challenges | Unfavourable / Major challenges | Unfavourable / Major challenges | Neutral / Minor challenges |
| Commercial readiness ^v | Favourable / Mature | Favourable / Mature | Neutral / Minor challenges | Favourable / Mature | Unfavourable / Major challenges | Neutral / Minor challenges | Neutral / Minor challenges | Unfavourable / Major challenges | Unfavourable / Major challenges | Neutral / Minor challenges |
| Regulations and guidelines | Favourable / Mature | Favourable / Mature | Neutral / Minor challenges | Favourable / Mature | Favourable / Mature | Neutral / Minor challenges | Neutral / Minor challenges | Unfavourable / Major challenges | Unfavourable / Major challenges | Neutral / Minor challenges |

Notes: i. Compared to that of HFO. The energy density tells you how much storage volume is needed on the ship to obtain the energy required to propel a vessel. Can be a limiting factor for long-range applications. ii. Highly dependent on well-to-tank production process, renewable sourcing of feedstock, and the calculation methodology for methane slippage. Modelling lifecycle fuel emissions highly depending on case-by-case basis. iii. Emissions of sulphur oxides (SOx), nitrogen oxides (NOx) and particulate matter (PM) from ships. Highly dependent on the engine/energy conversion process and scrubber technologies employed on the vessel. iv. Capability of fuel to be used in existing engine stock with little to no modifications. Fuels that are unfavorable require significant retrofits or completely new engines to be able to be utilized. v. Considering availability of fuel, and current technology readiness levels. vi. Renewable hydrogen used in a fuel cell considered.

Sources: DNV Comparison of Alternative Marine Fuels⁷⁶, Challenges and opportunities for alternative fuels in the maritime sector – Foretich et. al.⁷⁷, Fuel Pathway Maturity Map – Mærsk McKinney Møller Center for Zero Carbon shipping.⁷⁸

Cruising range

Another critical factor for fuel types are the typical bunkering intervals, cruising time, or the amount of time which a vessel can operate without refuelling. This metric indicates the amount of energy that can be stored onboard. The length of route and the type of vessel (bulk carrier, container, ferry, tankers, passenger ferries, etc) will dictate what fuels will be relevant. There are other factors at play including vessel cruising speed, weight, etc. A simplified table, based on analysis from DNV is shown below in Table 7.4.

For the Danish domestic maritime sector, routes will be on the shorter end and the amount of cargo limited when compared to large international cargo ships. This allows for lower onboard storage needs and operation profiles that align more with hydrogen and electric batteries. Notably, there exists already four electric ferry routes in Denmark with an additional 14 proposed routes.⁷⁹ Many of these routes are short and connect the various islands south of Fyn and Sjælland. For domestic maritime, the DEA expects limited to no usage of green fuels for decarbonization by 2035 in the latest climate status and projection (KF) analysis. However, long-term there may be local usage of methanol, ammonia, biofuels, etc for coastal routes within Danish waters.

For international shipping, the pathways are more limited and must rely on energy dense fuels to cross international bodies of water with vessels often carrying thousands of containers on major import/export routes such as Aarhus to New York (25 days) or Fredericia to Yantian, China (37 days). Electric

batteries and compressed hydrogen will likely not be feasible for these applications without great leaps forward in their respective technologies. A mix of biofuels, methanol, and ammonia (emerging in that order) will be the likely candidates for international shipping in the long-term. Nuclear propulsion could also be a dark horse and warrant a second look.

Fuel Costs

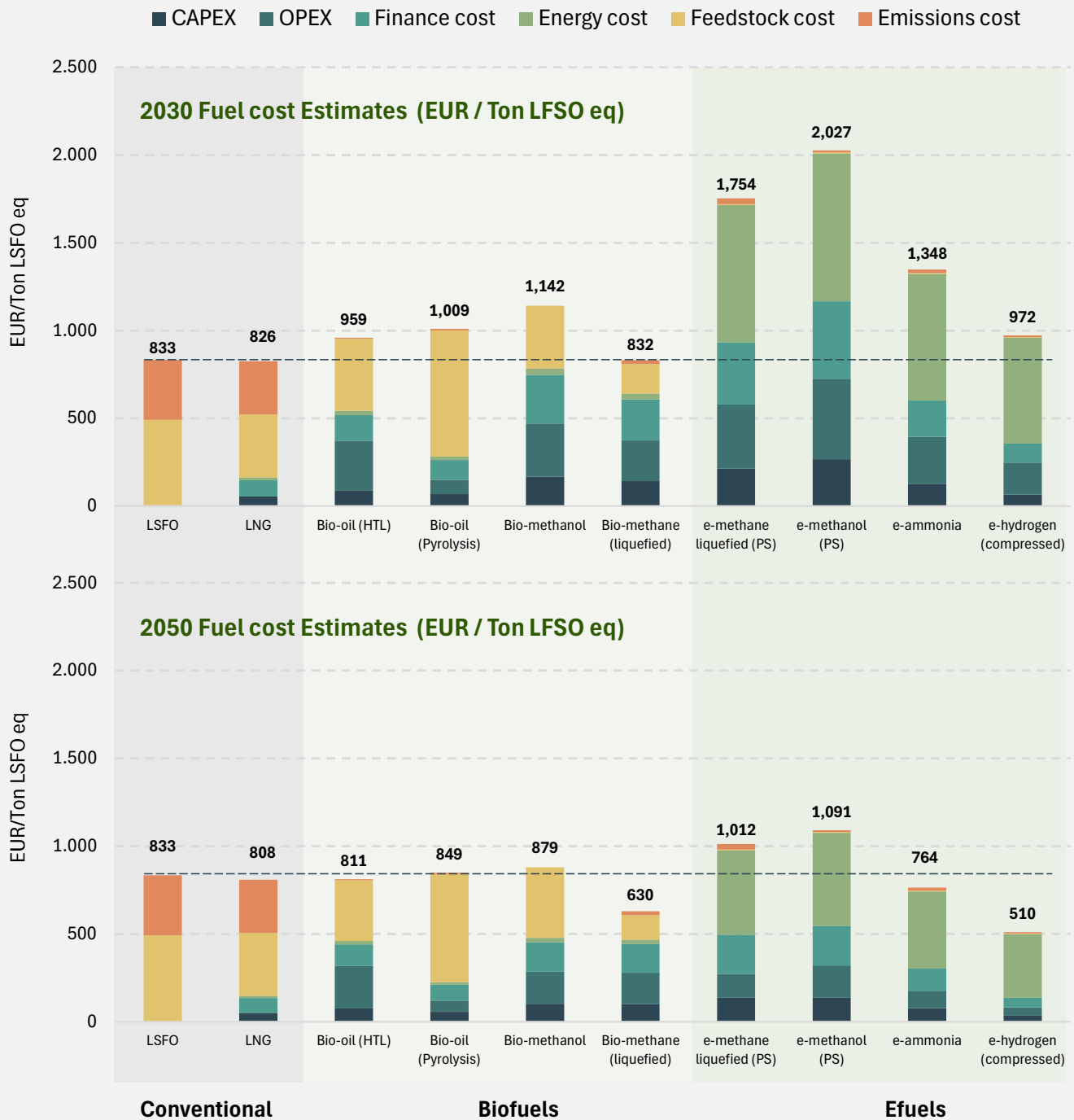
For fuel costs, efuels such as methanol and ammonia will be considerably more expensive than conventional fuels in the short to medium term. The main cost components are the energy costs and opex for producing these fuels (low conversion efficiency from RES input). In 2030, methanol and ammonia are estimated to be 2x-3x the cost of HFO/LSFO ammonia. However, costs are expected to come down and reach closer cost parity by 2050, albeit being more expensive simply due to the inherent nature producing efuels and the amount of conversion steps needed. Cost parity depends strongly on the carbon pricing dynamics of the future, which are difficult to predict. Biofuels are more cost competitive in the near-term, being slightly costlier than conventional fuels in 2030. By 2050, they are expected to be on the same level as conventional LSFO and LNG – assuming ample availability of feedstock. Long-term, two of the cheapest fuel types to produce are expected to be biomethane and compressed hydrogen. However, handling and compression costs are excluded which may add additional costs to using these fuels on a vessel. Cost estimates for 2030 and 2050 are shown in Figure 7.10 and are produced using Maersk fuel cost calculator.⁸⁰

Table 7.4: Typical bunkering intervals by fuel type

| | LSFO / HFO | HVO / biodiesel | Bto-oil | LNG | LPG | Methanol | Ammonia | Liquid H2 | Compressed H2 | Electric Battery |
|--|-------------------|-------------------|-------------------|--------------------|--------------------|--------------------|--------------------|---------------------|-------------------|---------------------|
| Vessel cruising rangeⁱ | Months | Months | Months | Weeks | Weeks | Weeks | Weeks | Days | Hours-Days | Hours |
| Typical vessel typeⁱⁱ | Large cargo ships | Large cargo ships | Large cargo ships | Medium cargo ships | Medium cargo ships | Medium cargo ships | Medium cargo ships | Small cargo ships | Small cargo ships | Short range ferries |
| Applicability | International | | | | | | | Domestic / regional | | |

Notes: i. Endurance will depend on ship operations, speed, and onboard storage capacity. ii. Large cargo = vessels designed for long-haul routes and can carry massive amounts of cargo, including bulk commodities, containers, and oil (e.g. ultra-large or very large crude carriers). Medium cargo = Most common shipping vessels - bulk and container carriers (e.g. ships designed to fit through Panama or Suez canals). Small cargo = vessels used for short-haul routes, feeder services, and specialized cargo operations.

Source: Adapted from DNV Comparison of Alternative Marine Fuels.⁷⁶

Figure 7.10: Marine fuel cost estimates in 2030 and 2050

Notes: LSFO: Low Sulfur Fuel Oil, HTL: hydrothermal liquefaction, PS: point source carbon capture, e-methane also referred to as synthetic natural gas (SNG). Bio-oils shown for different conversion technologies HTL and pyrolysis (share similar technical characteristics to HVO)

Ton LSFO eq ~42 GJ of energy.

Emissions considered on well-to-wake (WTW) with an applied cost of 100 USD per ton CO₂e and held static for 2030 and 2050.

Conversion rate USD to EUR = 0.92

Source: Adapted from Maersk Fuel Cost Calculator v0.9.2 (public).⁸⁰

No single winner

It is important to note that most analyses that assess the roadmaps for sustainable maritime fuels highlight significant uncertainties do not crown a single “winner”; the overall conclusion is that a number of fuels will likely be required. Intermediary fuels (LNG/LPG) will be needed to bridge existing fleets to lower emissions fuels and the projected long-term mix of methanol, ammonia, biomethane, synthetic, methane, etc will depend on several factors including biomass availability, renewable energy build out, technological advancement, and regulations. Analyses from DNV project that by 2050, green fuels uptake will accelerate in the mid 2030's, culminating to an estimated ~14,000 PJ/year in 2050.⁷⁵ The estimated fuel mix for the maritime sector is shown in Figure 7.11.

Pathways

Based on what is currently known, the pathways for the maritime sector are theorized below:

Short-term pathways (before 2030)

Short-term emission reduction levers include the electrification of short-distance ferry and goods transport routes, implementation of energy efficiency measures (such as hull design, propulsion efficiency, hybrid systems, route optimization), and the reduction of carbon intensity in fuels through blending with green fuels. In parallel, demonstration projects and technology development for methanol-powered ships (e.g. *Laura Maersk*), ammonia engines, and the planning of infrastructure and "green shipping corridors" for green fuels will advance. The emergence of dual-fuel engines, which can run on both diesel and methanol, will be instrumental during this transitional period as production capacities of green fuels will be limited in the scale up period. Additionally, the use of HVO and biofuels as drop-in replacements for conventional engines will be prevalent in the short to medium term. This will be complemented by the introduction of new vessels, advancement of technology readiness levels (TRLs) for ammonia engines, and the development of necessary bunkering infrastructure.

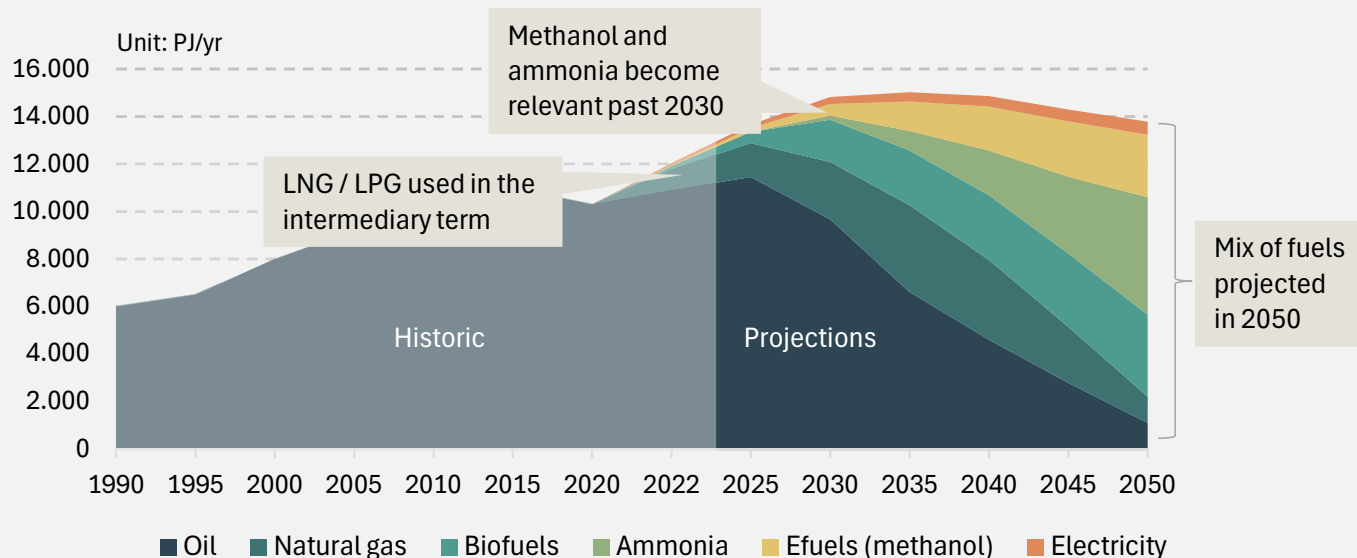
Medium-term pathways (2030-2040)

In the medium term, the maritime industry will see a significant shift towards the widespread introduction of green fuels, such as green hydrogen, methanol, and ammonia, as technological advancements and infrastructure development mature. The deployment of zero-emission vessels will be accelerated, supported by the establishment of comprehensive bunkering infrastructure, green shipping corridors, and global regulatory frameworks. Policy and emissions pricing

are expected to incentive this shift as well as voluntary corporate sustainability goals. Dual-fuel engines will continue to play a crucial role, gradually transitioning to pure green fuel operations (e.g. diesel to methanol). Continued research and development will enhance the combustion efficiency and safety of these fuels, while strategic investments in renewable energy production and supply chains will improve their economic viability. Bridging technologies such as LNG ships could see a shift towards biomethane or synthetic natural gas as the fuel, given their availabilities.

Long-term pathways (2040+)

The long-term pathway for decarbonizing the maritime industry envisions the full-scale adoption of efuels, such as ammonia and methanol. By 2050, these fuels will be readily available on the marine fuel market, facilitated by an expansive global bunkering infrastructure capable of supporting large-scale distribution and storage. Vessels will be equipped with advanced propulsion systems, including high-efficiency fuel cells and next-generation internal combustion engines specifically designed for these green fuels. Comprehensive international regulations will mandate the use of zero-emission fuels, enforced by organizations such as the International Maritime Organization (IMO), aiming for net-zero emissions with intermediate targets of 20% reduction by 2030 and 70% by 2040.⁸¹ The high initial costs of transitioning to alternative fuels could be mitigated by financial incentive mechanisms and carbon pricing. Significant investments in infrastructure, including the establishment of green shipping corridors, will support the widespread use of alternative fuels. Achieving these decarbonization goals will require a lifecycle approach to evaluating fuel sustainability, ensuring that well-to-wake emissions are minimized.

Figure 7.11: World maritime energy demand projections by fuel type

Source: Adapted from DNV Energy Transition Outlook 2023 report.⁷⁵ Historic data from IEA word Energy Balance 2022.⁸²



Maritime

Key points

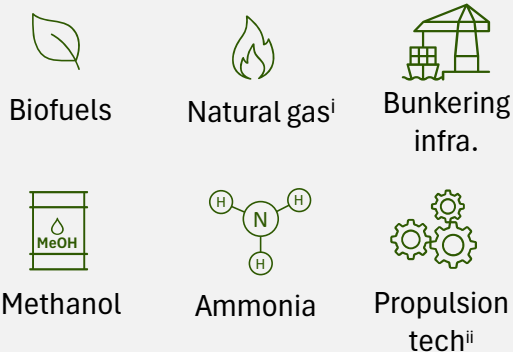
- 1 **International shipping** emissions are substantial, with Danish-operated ships emitting ~39 million tonnes of CO₂e/yr, presenting a **major decarbonization opportunity**.
- 2 The majority of vessels currently use conventional fuels like marine diesel oil (MDO) and heavy fuel oil (HFO), with some adoption of **LNG and LPG as interim solutions**.

Proposed green fuels for shipping include **biofuels, methanol, ammonia, and hydrogen**, though they face challenges related to feedstock availability, retrofitting existing fleets, production volumes, cost, and safety considerations
- 3 No clear winner: a **mix of green fuels (and batteries)** is expected to be utilized in the maritime sector in 2050
- 4

Emissions (Mt CO₂e)

| | 1990 | 2023 | 2030 | 2035 |
|----------------------|------|------|------|------|
| Domestic | 0.58 | 0.52 | 0.49 | 0.49 |
| Intl. ⁱⁱⁱ | 12.4 | 39.0 | 35.4 | 24.3 |

Relevant technologies



Outlooks

Short-term (before 2030)

- Use of intermediary fuels (biofuels, LNG/LPG), or electrification of small vessels
- Emissions intensity reductions via fuel blending any efficiency improvements
- Technology maturity of efuel technologies and associated propulsion/handling tech

Long-term (after 2030)

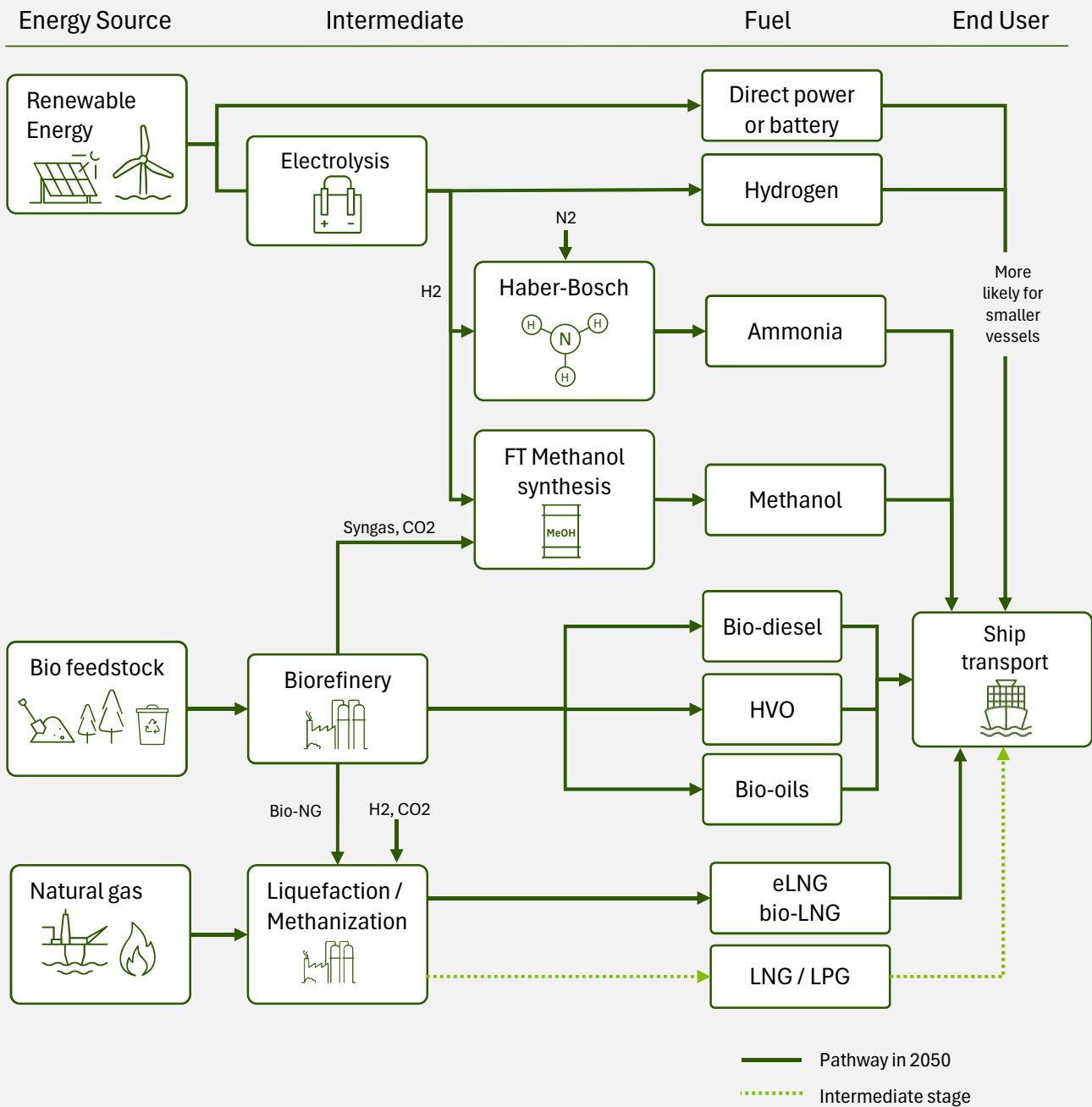
- Conversion of existing maritime fleets to green fuel compatibility (retrofit or new)
- Scale up of methanol, ammonia, hydrogen fuel types and widespread usage

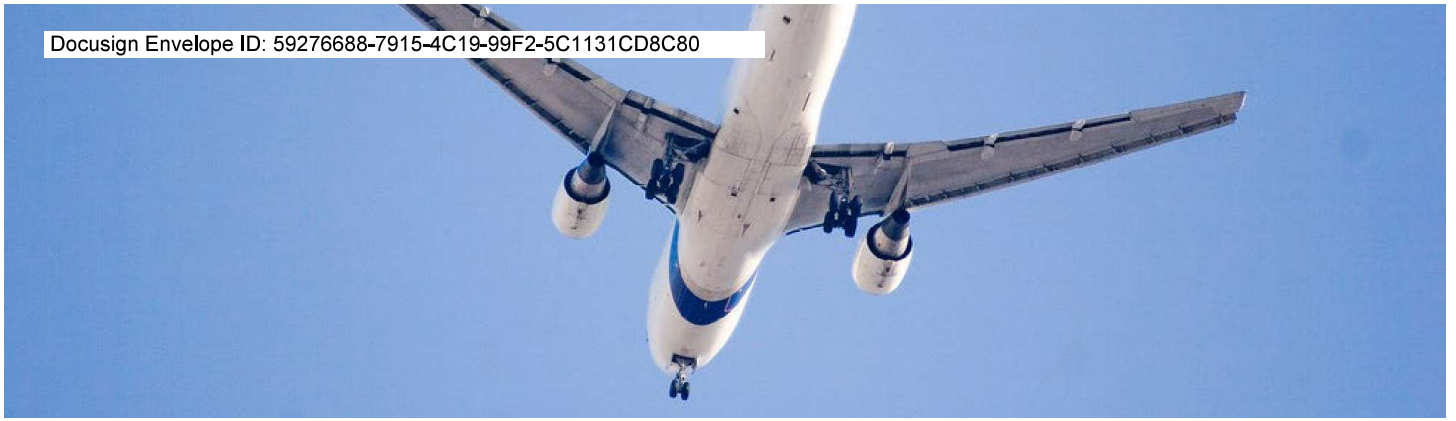
i. Includes LNG, LPG, SNG, of bio-LNG

ii. Propulsion tech includes battery-electric propulsion, methanol and ammonia engines, and ammonia/H₂ fuel cell technologies

iii. For international shipping, projections to 2030 and 2035 use IMO's targets for 20% and 70% reduction by 2030 and 2040 (over 2008 levels) to project a conceivable emissions profile in those years

Figure 7.12: Fuel Pathway – Maritime





7.4 Aviation

Current emissions profile

Domestic aviation emitted 0.12Mt CO₂e in 2023 accounting for 1% of total domestic transport sectors emissions. When compared to the 70% GHG reduction target by 2030, domestic aviation is almost negligible, with the total sector emission only accounting for 0.26% of total Danish emissions. However, for international or cross-border (long-haul) aviation, aviation emissions peaked at ~6Mt CO₂e in 2019 (pre-covid) and have now sit at 4.2 Mt CO₂e for 2022. For international aviation, passenger flights constitute most of the aviation activities and, consequently, the majority of greenhouse gas emissions from the sector. Domestic and International emissions are shown comparatively below.

A hard-to-decarbonize sector

The aviation sector has limited pathways to decarbonize due to aircraft range/weight constraints as well as limitations imposed by existing airport infrastructure and operating models. Sustainable aviation fuel (SAF), produced through bio-based or synthetic (power-to-liquid or PtL) technologies, provides a “drop-in” replacement that can be blended up to 50% in existing aircraft.⁸³ Other technologies that have been theorized to decarbonize the aviation sector include novel propulsion technologies in the form of hydrogen and battery-electric aircraft. Each have their own set of unique barriers and challenges that are listed in Table 7.5 on the following page.

Figure 7.13: Emissions in domestic and international aviation sector (2009-2022)

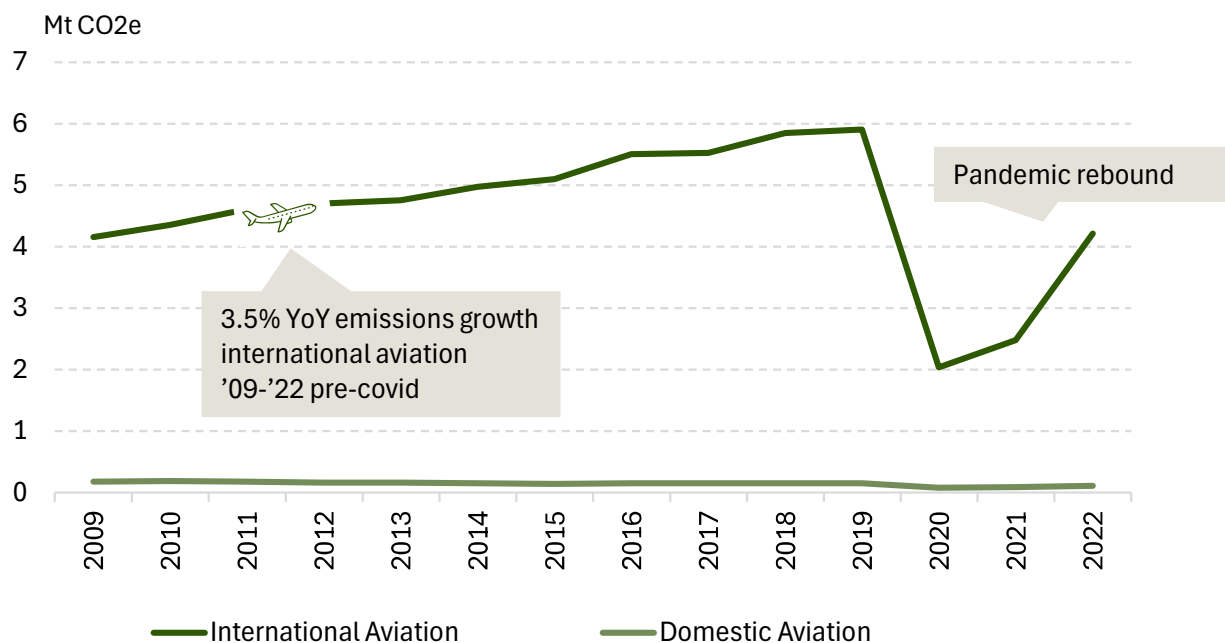









Table 7.5: Comparison of aviation fuels

| Comparison vs traditional jetfuel | SAF (bio + e)  | Battery-Electric  | H2 Fuel Cell  | H2 Turbine  |
|---|---|--|--|--|
| Aircraft design | Used with existing fleet | New aircraft design | | |
| Airport infrastructure | Existing fueling infrastructure | Battery exchange of fast-charging needed | Liquified H2 distribution and storage needed | |
| Aircraft operations | No change | Longer; depending on technology | 1-2x longer fueling time | 2-3x longer fueling time |
| Climate impactⁱ | 30- 60% reduction | 100% reduction | 75-90% reduction | 50-75% reduction |
| Efficiency of propulsion systemⁱⁱ | ~15-20% | ~60-75%+ | 25-45% | ~30% |
| Expected market entry | Before 2030 | Estimated 2035-2040 | | |

 Clear advantage
 Minor obstacle or drawback
 Major obstacle or drawback

Notes: i. Climate impact assumes 100% RES. Includes CO₂, NO_x, and water vapour contrails for combustion (SAF + turbines)

ii. Well-to-wake efficiency estimates – highly dependent on well-to-tank efficiency and upstream losses

Sources: Mission Possible Partnership⁸⁴, Clean Aviation EU⁸⁵

Sustainable Aviation Fuels (SAF)

Overall, SAF has the clear advantage pre-2030 based on the ease to integrate SAF into existing aircraft and airport operations. Based on the immaturity of battery-electric and hydrogen and the need for aircraft redesign, and associated development costs and regulatory hurdles associated with novel technologies, SAF will be the primary pathway focused on in this roadmap. It is expected that bio-based SAF will be the most relevant in the short-term before e-SAF (power-to-liquid) technologies scale. However, the other technologies come into play in the medium and long term and may play a role in domestic aviation decarbonization, especially with shorter domestic routes (e.g. Copenhagen to Aalborg ~240kms).

SAF Properties

Like Jet fuel, SAF consists of various hydrocarbons and is defined by performance specifications rather than a specific chemical composition, with kerosene-type fuels having carbon numbers between 8 and 16 (Jet-A) and naphtha-type fuels between 5 and 15 (Jet-B). The composition varies based on the petroleum (or other feedstock) source and can be optimized during the production process for specific requirements like freezing and smoke points. For SAF, there are four pathways that are the most likely candidates to scale and attract attention: bio-oils such as HVO or hydroprocessed esters and fatty acids (HEFA); alcohol-to-jet (AtJ); gasification/Fischer-Tropsch (gas/FT); and power-to-liquid (PtL) efuels. These production pathways are compared in Table 7.6

Table 7.6: Comparison of SAF pathways (bio and eSAF)

| Category | Bio-based SAF | | | eSAF (PtX) ⁱ |
|-------------------------------|--|--|--|--|
| Name | Bio-oils (HVO/HEFA) | Alcohol-to-jet (AtJ) | Gasification + Fischer-Tropsch | Power-to-liquid (PtL) |
| Feedstock | Vegetable oils, animal fats, and waste oils, lipids | Any bio feedstock that can produce alcohols (forestry residues, wood waste and agricultural residues), MSW | | Green electricity + CO ₂ (biogenic or point source) |
| Production process | Hydrotreatment commonly used at petroleum refineries | Fermentation followed by catalytic upgrading | Gasification followed by Fischer-Tropsch synthesis | H ₂ electrolysis, combined with CO ₂ to produce hydrocarbons |
| Technology maturity | Mature TRL = 9 | Emerging TRL ~7 | Emerging TRL~7 | Pilot/Prototype TRL ~5-6 |
| GHG reduction % ⁱⁱ | 73-85% | 85-94% | 85-94% | 99-100% |
| Timing for scale up | Now : Proven and scalable technology | <2030: Significant near-term potential however techno-economic issues to overcome | | After 2030: PtX , RES, and CO ₂ infra build-out needed |
| Limitations / barriers | Inherent limitations on waste oil feedstock | High production costs, fragmented feedstock availability, technical complexity | | High energy requirements, cost, biogenic CO ₂ availability |
| Sustainability considerations | Potential competition with food crops, deforestation risks | Land use, potential competition with food production | Water, air pollution, ash, and by-product disposal | Requires significant renewable electricity supply |

Notes: i. Synergies with hydrogen utilization in (G/FT) process to optimize syngas/H₂ ratios for SAF production (bio-e-SAF)

ii. Compared to fossil kerosene. LCA values from CORSIA

Sources:, Mission Possible Partnership⁸⁴, Clean Aviation EU⁸⁵, World Economic Forum⁸⁶, ICAO⁸⁷, SDU (2019)⁸⁸

SAF Timing

Based on maturity and technical feasibility the pathway for SAF will likely be: A) production of HVO/HEFA based biofuels in the short-term until feedstock is tapped B) production of alcohols upgraded to jet and gasification/FT based biofuels in the short and medium term, and finally C) the emergence of PtL liquids post 2030 when the technology is mature and there is ample RES to produce vast quantities of efuels. If production of HVO/HEFA is uneconomical in DK, jump to points B or C and rely on imports for HEFA based SAF in the near-term. These SAF pathways, alongside battery/H₂ technologies, are described in the next sections.

Short-term pathways (before 2030)

Due to infancy of SAF and limited production quantities, immediate near-term CO₂ reduction in the aviation sector will come in the form of demand reduction (via taxation, consumer behaviour shift) or alternative transportation modes becoming more attractive. Additionally, enhancing fuel efficiency, optimizing flight operations, and increasing the use of SAF via blending mandates will help reduce CO₂. SAF based on HVO/HEFA will be the first to see widespread traction and typically blended with conventional jet fuels of ratios of 50%. In the short-term, this will likely be imported. Technological maturity of gasification/FT, and Alcohol-to-Jet will take place and demo plants scaled up.

Medium-term pathways (2030-2040)

Between 2030 and 2040, the mass-scale up of bio-based SAF refineries including gasification-FT plants, Alcohol-to-jet plants, and the required feedstock collection infrastructure will be needed. The emerging technologies will mature and see widespread adoption. E-SAF based on electrolysis will start to mature as additional gigawatt scale electrolysis plants start entering operation. On a parallel pathway, the focus may shift towards the introduction of novel propulsion technologies, such as hydrogen and battery-electric aircraft. Hydrogen combustion and fuel cell technologies offer significant potential for reducing CO₂ emissions but may only be relevant for short and medium-haul flights. However, the deployment of these technologies requires overcoming substantial technical and infrastructural hurdles, including the development of new aircraft designs and airport refuelling infrastructure. SAF is likely the most realistic solution in the short and medium term due to existing fleets and the infrastructure and supply chain around fuel bunkering and the needs for an energy-dense drop-in fuel that can replace conventional jet kerosene. During the medium term, electric and hydrogen planes may see some niche applications and demo routes as R&D projects from major and novel aircraft manufacturers come to fruition.

Long-term pathways (2040-2050)

By 2040 and beyond, the sector aims to achieve near-total decarbonization through scaled up e-SAF production and the commercial adoption of hydrogen and electric propulsion for medium to long flight ranges. Methanol/ethanol plants that have been producing road fuels can be converted to upgrade to SAF (as that sector will become electrified). The scale needed will be enormous: globally, hundreds of SAF production plants will be needed.⁸⁶

Production synergies with other green fuels

It is important to note that the production of SAF there are also synergies with the production of sustainable road fuels or chemicals. Synthesis processes such as AtJ, gasification/FT, and PtL yield other products than SAF such as biodiesel, naphtha, and other light hydrocarbons. For example, a typical gasification/FT process with a 20% conversion rate will yield ~60% kerosene (SAF), with 22% of road fuels (biodiesel), and 18% light hydrocarbons gases and liquids such as LPG and naphtha. These ratios can be optimized depending on the amount of introduced hydrogen feedstock and the plant operating parameters.



Aviation

Key points

- ① In Denmark, **domestic aviation is a minor piece** of overall transport emissions and the use of green fuels to make significant climate impact on the 2030 70% goal is limited
- ② **International aviation and potential exports** of DK based SAF is **more consequential** to the Danish green fuels industry
- ③ Policy drivers include **ReFuelEU targets** and DK national level goals, and voluntary targets
- ④ Based on inherent **bio feedstock constraints**, PtL e-SAF will become a long-term solution. Intermediate fuel production from other pathways (road, shipping) should eventually be **converted to SAF**

Emissions (Mt CO₂e)ⁱⁱⁱ

| | 1990 | 2023 | 2030 | 2035 |
|----------|------|------|------|------|
| Domestic | 0.24 | 0.12 | 0.14 | 0.14 |
| Intl. | 2.3 | 4.2 | 5.3 | 5.3 |

Relevant technologies



Bio-SAF
tech



Power-to-liquid
(PtL) efuels



Novel
propulsion

Outlooks

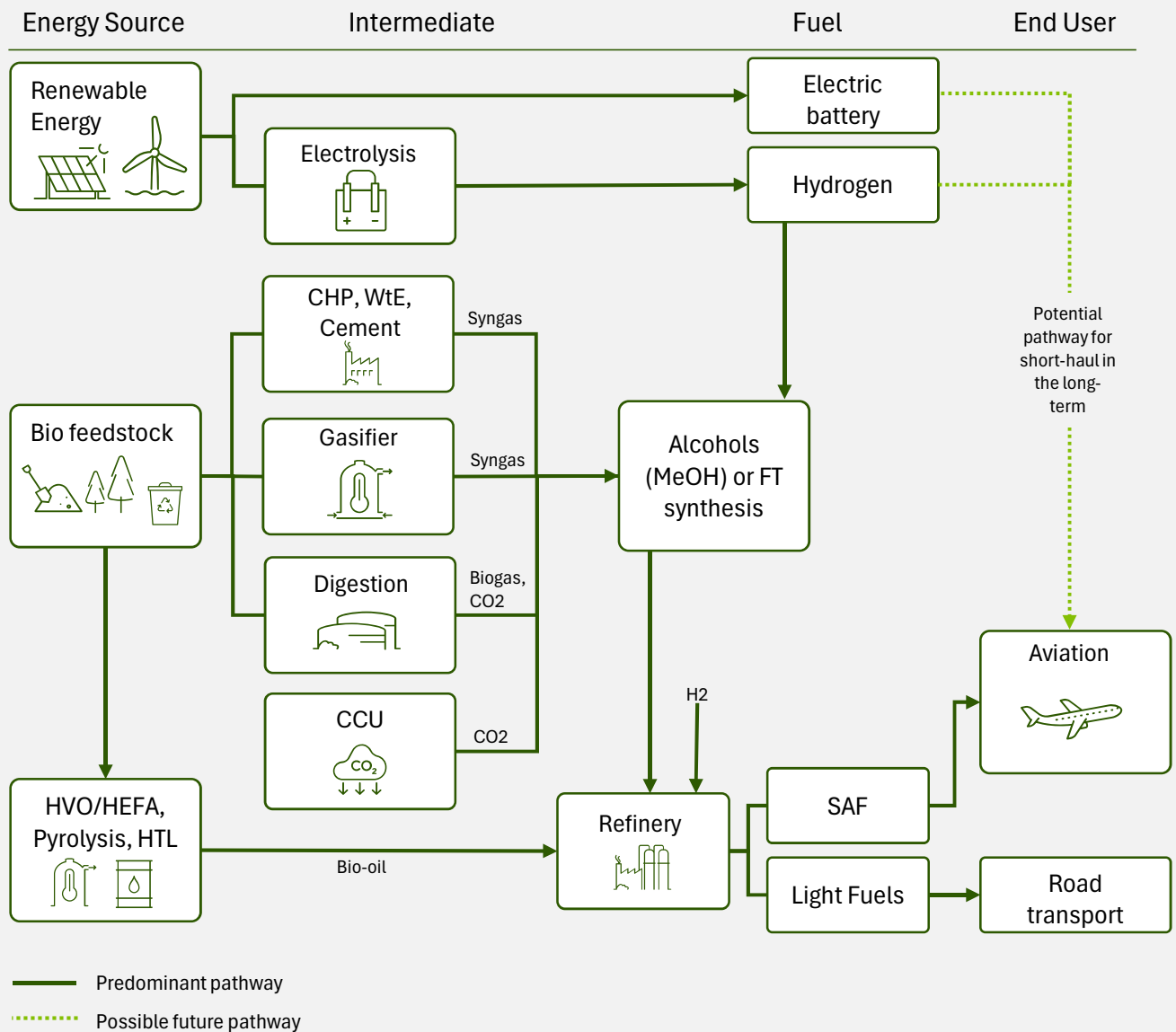
Short-term (before 2030)

- Bio-SAF in the form of HEFA/HVO the most relevant and proven. Potentially imported
- Continued technological maturity of gasification/FT, alcohol-to-jet, HTL, PtL synthesis via first-of-a-kind plants in DK

Long-term (after 2030)

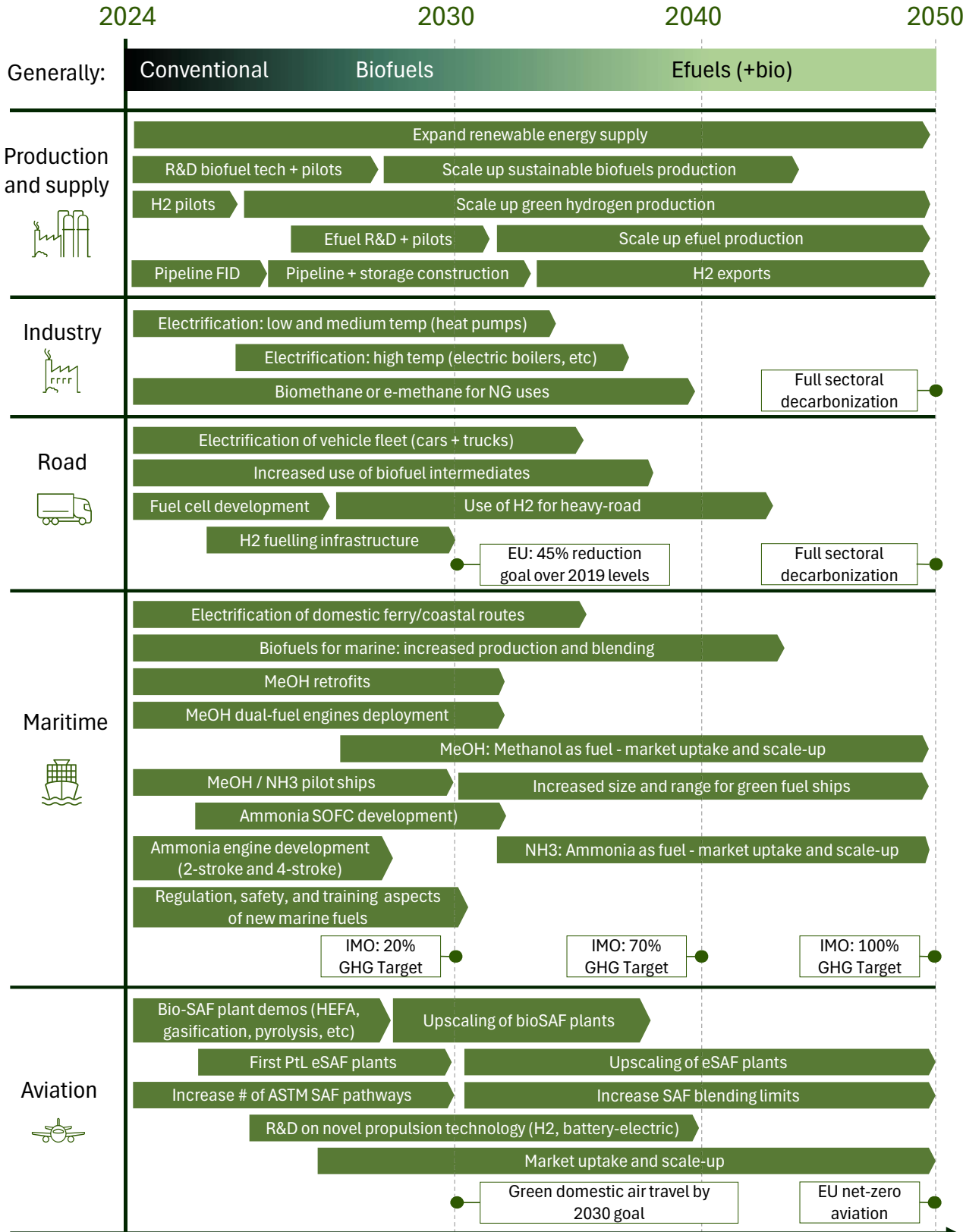
- Continued scale up of bio-SAF, mass scale up and adoption of PtL
- Conversion of MeOH plants to AtJ plants
- Novel propulsion systems (electric / H₂ fuel cell or turbine) may become relevant

Figure 7.14: Fuel Pathway – Aviation



7.5 Sector Timing

The below figure estimates timing on the path towards 2050 for various segments in the green fuels sector. Overall, the figure shows a phased approach to scaling from pilots to industrial-scale operations, supported by infrastructure build-out, technology development of both supply and offtake, and market adoption in various industrial and transport sectors. Policy targets in 2030, 2040, 2050 are shown alongside the developments.





8. Green Fuel Roadmaps

Methodology

The following sections present the insights from MissionGreenFuels stakeholders along the various fuel types: green hydrogen, intermediary fuels, maritime fuels, and aviation fuels. Key activities, potential challenges, and opportunities in the scale-up of these fuels are informed by **expert interviews, stakeholder surveys, and workshops** held during the data and insights collection phase of the roadmap updating process.

The **key activities in the short-and-long term are identified** by stakeholders and presented across various themes including technical, commercial, regulatory, and financial, and social elements. Timing of when activities will happen is informed by the latest developments in industry and policy, however longer-term activities are uncertain and estimates of when developments will likely happen instead of will surely happen. Ramboll insights and interviews were used as complementary information sources. Extensive public

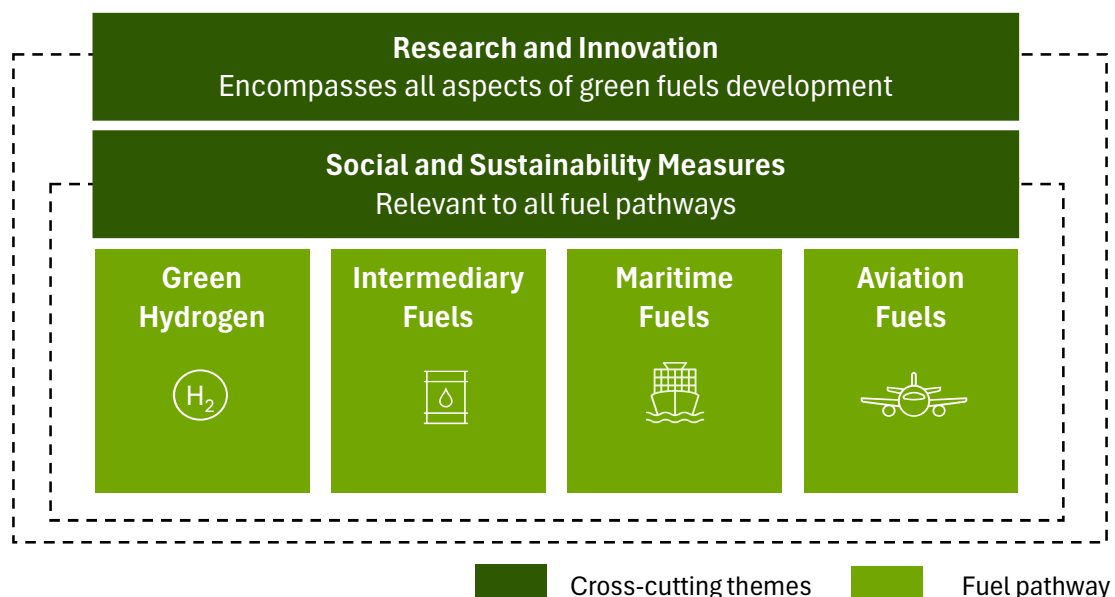
sources such as academic papers, industry reports, and grey literature were consulted and can be found in the references section. It is important to note that MGF supports new and low-TRL technologies not mentioned in the roadmap.

Cross-cutting themes: social Sustainability and Innovation

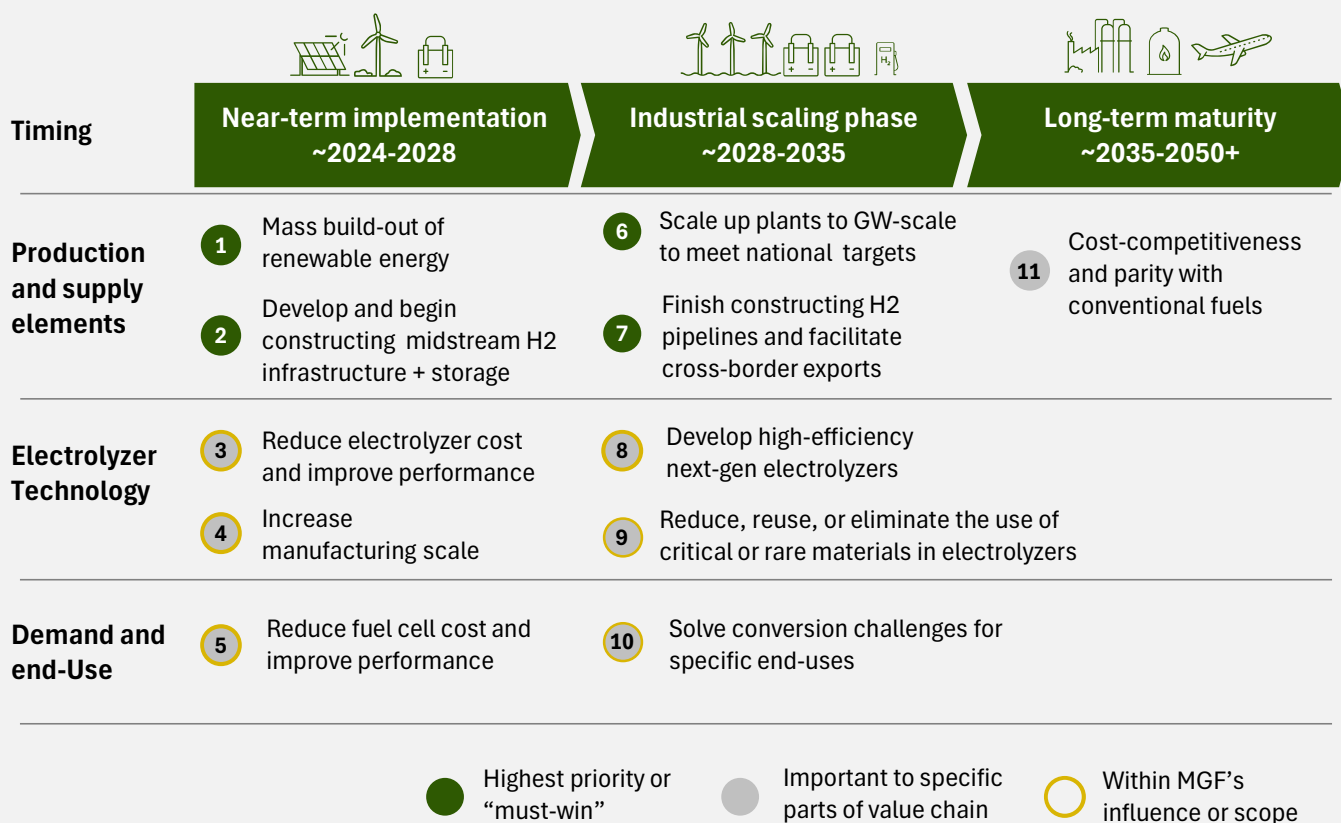
It is important to note that the roadmaps presented in chapter 10 are technically focused, however **social and sustainability issues are cross-cutting** and can be found in Chapter 5. Similarly, commercial, regulatory and financial needs can be found in in Chapters 9 and 10, respectively.

While the roadmaps pinpoint specific R&D measures along each fuel pathway, **innovation is relevant for all fuel pathways**. This includes research in citizen engagement, sustainability, and the development of frameworks for measuring the environmental and social impacts of green fuel projects.

Figure 8.1: Innovation underpins all aspects of green fuel development



8.1 Key activities in the green hydrogen roadmap



1 Mass build-out of renewable energy

Significantly more wind, solar, and grid infrastructure will be required to feed energy intensive hydrogen and efuel production. As shown in the Chapter 4, Denmark would need an additional 30+GW and 80+GW by 2030 and 2050 respectively to power PtX and other electrification technologies. To achieve this, extensive investments and streamlined permitting processes in wind farms, particularly offshore wind, and solar power installations are key.

Overcoming barriers includes addressing grid integration challenges, regulatory hurdles, and land/resource acquisition issues. Denmark must enhance its grid infrastructure to handle increasing amounts of intermittency and invest in short- and long-term energy storage solutions. Collaboration and dialogue between government and private sectors for tendering and creating attractive investment frameworks as well as developing robust supply chains and a skilled workforce, will be essential.

Continuous technological advancements and cost reductions are also needed to improve bankability of projects, particularly offshore wind.

Recommendations to increase the speed and success of renewables deployment has been extensively outlined in the 2023 report “More sun and wind on land” by NEKST (DK’s national energy crisis team) and should be referred to for concrete recommendations.⁸⁹

2 Develop and begin constructing midstream H2 infrastructure and storage

Infrastructure will be needed to offtake green hydrogen production and to transport it to relevant markets and end-users. Deciding to fund and construct this pipeline is neither cheap nor without risk. However, without a viable offtake, many of the current projects in the concept and feasibility stage projects will fail to culminate. For many projects, this offtake is industrial centers in Germany (chemical, steel manufacturing) which need cross-border H2 pipelines to facilitate the transfer of green molecules. For the proposed Jutland backbone West, final investment decision (FID), by Energinet with approval by the Danish Ministry of Climate, Energy and Utilities, is expected to occur in Q1 2025, after Energinet has conducted market dialogue and due diligence on potential users of the pipeline.

After a decision is made, a phased build out of the main pipeline is expected to occur (south to North) from 2027-2030 with an eventual connection to storage facilities in Lille Torup around 2030.

3 Reduce electrolyzer cost and improve performance

Improved electrolyzer performance means less RES input for the same amount of H₂ output and an improved production cost as electricity costs can typically represent in excess of 50% of the levelized cost of green hydrogen. At scale, even small efficiency improvements will be important. The difference between a 60% (typical for AEC electrolyzer system - LHV) to a 70% efficient system for a 1GW electrolyzer plant running at 5000 full load hours results in an avoided use of 0.5TWh of electricity, around the consumption of annual of 90,000 Danish citizens. Less energy consumption also means less RES build-out and less environmental impact on land and offshore resources. The importance of electrolyzer efficiency in the success of hydrogen cannot be understated.

4 Increase the scale of electrolyzer manufacturing

Denmark aims to lead in green technology manufacturing, necessitating the development of large-scale production facilities. Domestic manufacturing of AEC, PEM, and SOEC technologies will need to be scaled up to provide the technologies domestically but also to export abroad. Scaling up SOEC manufacturing is currently being done, with Topsoe expected to finish construction of a 500MW/yr factory in 2025 in Herning.⁹⁰ This will be coupled with an announced sister factory in USA (with a capacity of 1GW/yr), expanding the geographic reach of manufacturing with Danish technology.

Competition from China may prove challenging. It is unlikely that Danish OEMs can match the cheap cost of Chinese electrolyzers in the near-term. The recent European Hydrogen Bank auction results reveal that Chinese electrolyzers are two to five times cheaper to buy than western equipment. Instead, performance, efficiency, and reliability should be the selling points. Additionally, there are proposed regulatory measures in the Net-Zero Industry Act that safeguard European OEMs from unfair competition (dumping) wherein at least 40% of the annual deployment needs for net-zero technologies manufactured in the EU by 2030.⁹¹ Net-zero technologies include electrolyzers.

Nonetheless, increasing production volumes in Europe can help drive down cost via economies of scale and improved manufacturing processes to help the EU compete with cheaper produced electrolyzers from abroad while simultaneously creating local benefits.

5 Reduce fuel cell cost and improve performance

On the application side, fuel cells that consume less hydrogen for the same amount of output will be important for end-use. Improved fuel cell technologies could result in longer vehicle ranges, reduced weight, and enhanced viability for transport applications. Overcoming barriers such as the high costs of rare metals and durability issues is crucial. Developing alternative catalysts and improving fuel cell designs to increase efficiency and longevity should be a priority for innovation and research activities in the near and medium term.

6 Scale up plants to GW-scale to meet national targets

Many Danish gigawatt-scale concept plants are currently slated to be built in phases, such as a 50-100 MW phase-1 plant followed by later enlargement to 1 GW or more. The second or third phases are typically contingent on securing access to renewable energy sources (e.g., large-scale offshore wind connected to the upcoming auctions), viable offtake via H₂ pipelines, and a positive business case. Strategic planning and phased implementation that align with infrastructure build-out and demand growth will be essential to managing risks and ensuring project viability.

7 Complete the construction of the H₂ backbone and necessary branching infrastructure

In relation to the development of a hydrogen backbone, prioritizing key routes and leveraging existing infrastructure (e.g., repurposed gas lines) where possible will facilitate progress on creating a hydrogen network that connects supply to demand. Overcoming regulatory approvals, environmental impact assessments, and land acquisition challenges are crucial steps. Engaging stakeholders early in the planning process can help mitigate opposition and streamline approvals.

8 Develop high-efficiency next generation electrolyzers

Denmark's vision of producing cost-effective green hydrogen requires the development of high-efficiency next-generation electrolyzers. These include, but not limited to, high temperature SOEC and AEM electrolyzers. Challenges include expenses and limited availability of precious materials used in high-performance catalysts. Focused R&D programs and collaboration with academic and industry partners are necessary to overcome these technical hurdles via new materials and designs can enhance efficiency and durability or reduce the need for rare materials. Scaling up production processes will reduce costs and ensure that Denmark remains at the forefront of next gen electrolyzer technologies.

9 Reduce or eliminate the use of critical or rare materials in electrolyzers

Eliminating the use of critical metals is important for the long-term sustainability and security of supply in electrolyzer manufacturing. Prioritizing materials that are readily available, recyclable, and sourced from regions with low geopolitical risk can mitigate supply chain vulnerabilities. R&D and innovation in catalysts, such as developing alternatives to platinum-group metals and other rare earth elements, should be a priority. This includes researching non-precious metal catalysts or advanced ceramic materials that can deliver similar performance with a lower environmental and economic footprint. The transition to these alternatives will enhance the scalability of electrolyzer production and make hydrogen more economically viable and sustainable in the long term.

10 Solve challenges for specific end uses

For end-uses that will use hydrogen directly the necessary downstream fuelling infrastructure will be needed. For heavy-duty fuel cell vehicles to be adopted, the fuelling infrastructure must be in place and the trucks must be both demonstrated and made widely available at a reasonable cost. Achieving this requires advancements in vehicle fuel cell technology, including reducing capital expenditure and increasing

availability of fuelling ports. These areas present significant opportunities for further research and development.

11 Cost-competitiveness and parity with conventional fuels

Achieving cost-competitiveness with conventional fuels and making hydrogen a mainstream energy source is an ultimate long-term goal for green hydrogen. A two-pronged approach of lowering H₂ production costs and penalizing fossil fuel usage should be taken in parallel. However, this must be done in a balanced manner—too much penalization risks making industries uncompetitive, inflationary pressures, and cost pass-through to consumers, while excessive incentivization risks creating market distortions and inefficiencies.

MISSION GREEN FUELS

Focus areas and projects within green hydrogen

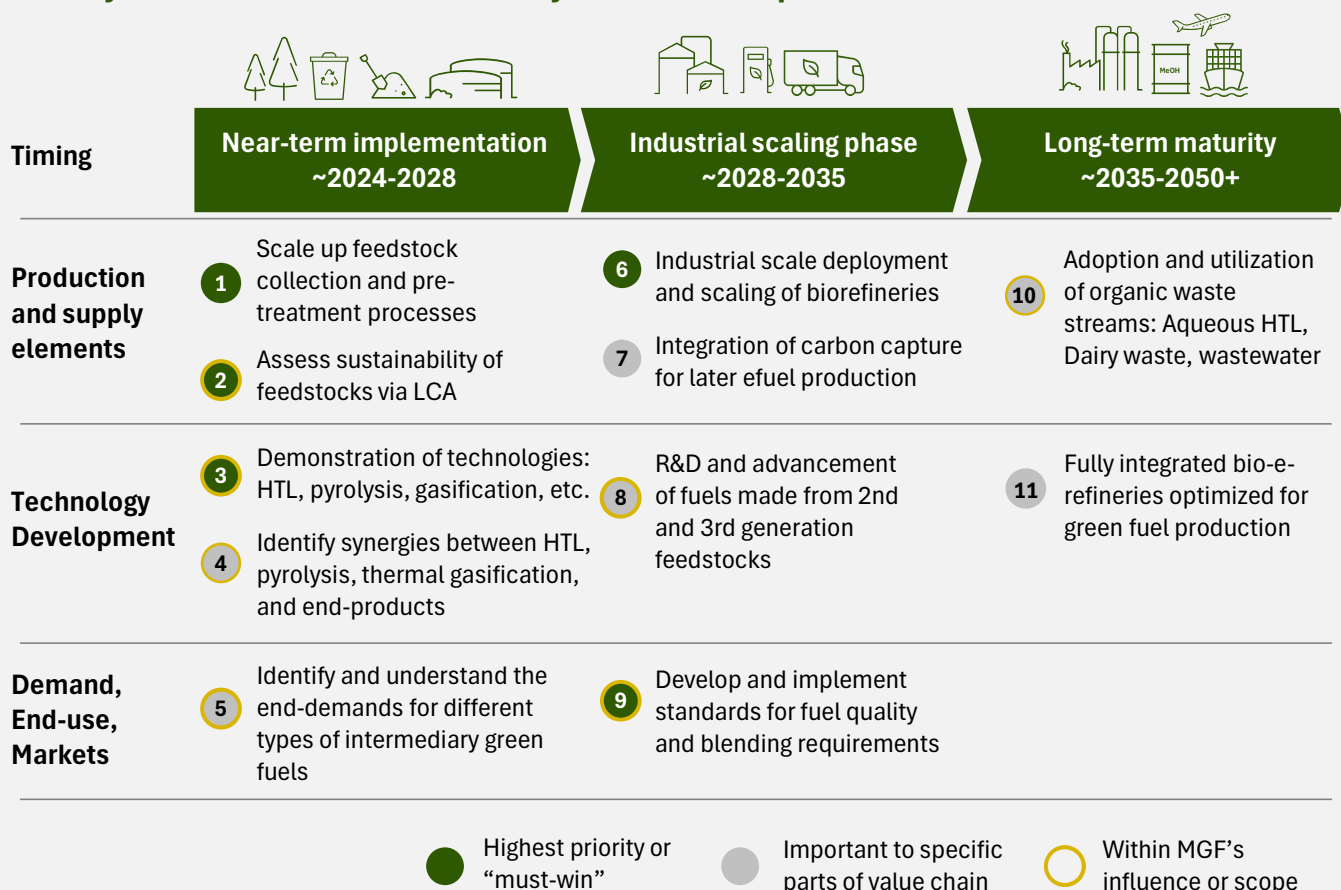
The partnership's focus on fostering collaboration between universities and private companies aligns with the need to enhance green hydrogen production efficiency and integration into the wider energy system. MGF is strategically positioned to drive innovation and R&D, particularly in the following topics:

- Improving electrolyzer stack performance and reducing costs
- Innovation in electrodes, membranes, catalysts
- Optimizing manufacturing processes,
- Advancing next-generation electrolysis technologies
- Materials sustainability
- PtX sector coupling modelling
- LCA tools and methodologies

Examples of past or ongoing MGF funded projects that address the needs identified for green hydrogen:

- **ComElCo:** Competitive Electrolyzer Converters
 - Focuses on enhancing the efficiency and reducing the cost of electrolyzers through innovative converter technologies.
- **H2-SAF:** Low-Cost hydrogen as green fuel enabler
 - Aims to make H₂ production more economically viable by developing low-cost production methods and infrastructure solutions.
- **GREMEOH:** Green H₂ cost leadership and scalability (in manufacturing)
 - Analyse and develop optimal automation processes for the assembly of speed- and quality-critical electrolyser components

8.2 Key activities in the intermediary fuels roadmap



1 Scale up feedstock collection and pre-treatment processes

Scaling up feedstock collection and pre-treatment processes requires the development of sophisticated logistics and supply chain models to efficiently source diverse feedstocks, including agricultural residues, manure, municipal solid waste, and other sustainable materials sourced both domestically and internationally. This involves optimizing the collection, transportation, and storage of these feedstocks, ensuring a steady and reliable supply chain. Advanced pre-treatment technologies are critical to improving feedstock quality, ensuring uniformity, and reducing contaminants, all of which are essential for maximizing conversion efficiency in subsequent processing stages.

Pre-treatment methods such as torrefaction, drying, and size reduction must be engineered to handle large volumes of feedstock while improving homogeneity and minimizing the presence of impurities. Torrefaction, for example, thermally decomposes organic material at lower temperatures to produce a more energy-dense and dry feedstock, which is easier to handle, store, and convert. Drying is crucial to reduce moisture content, which enhances the calorific value and also improves the efficiency of subsequent conversion processes

such as pyrolysis or gasification. Strategically locating pre-treatment facilities close to feedstock sources can significantly reduce transportation costs and logistical complexities, ensuring a more consistent and efficient supply chain.

Innovation in feedstock sourcing and pre-treatment could include the deployment of digital tools for real-time monitoring of feedstock availability and quality, allowing for dynamic adjustments in sourcing and processing. Automation can further improve the efficiency of pre-treatment operations, ultimately leading to better conversion yields and more sustainable biofuel production.⁹²

2 Assess sustainability of feedstocks via LCA

To ensure the sustainability of feedstocks used in green fuel production, comprehensive LCAs must be developed and tailored to specific feedstocks and production pathways. This includes evaluating the environmental impacts associated with the entire lifecycle of feedstocks, from cultivation or collection to conversion and end-use. LCAs should consider factors such as GHG emissions, land use changes (direct or indirect), water and energy consumption, and waste generation.

Comparative LCAs can identify the most sustainable feedstocks, guiding industry stakeholders in selecting optimal bio resources for green fuel production. Furthermore, integrating LCA findings with economic and social impact assessments provides a rounded view of sustainability, balancing environmental benefits with cost and societal impact. Standardizing LCA methodologies and creating accessible databases will ensure consistency and transparency across the industry.

3 Demonstration of technologies: HTL, pyrolysis, gasification, biomethanisation

Demonstrating the technical feasibility and economic viability of advanced conversion technologies such as Hydrothermal Liquefaction (HTL), pyrolysis, biomethanisation, and FT/gasification is critical for future the large-scale production of green fuels that uses 2nd or 3rd generation bio-feedstocks. Pilot and demonstration projects should be designed to validate these technologies under real-world conditions, assessing performance metrics such as conversion efficiency, product yield, and process stability. Collaboration with academic institutions and industry partners can advance the development of these technologies, leveraging cross-sector expertise and resources. Field trials must address the variability in feedstock characteristics and operational environments to ensure robustness and scalability. Securing funding from government programs and private investors is essential to accelerate these demos, providing the necessary support to move from pilot projects to full-scale commercial operations.

4 Identify and exploit synergies between HTL, pyrolysis, gasification, and their end-products

Identifying and exploiting synergies between HTL, pyrolysis, and gasification processes can enhance the efficiency and output of biorefineries. Research should focus on the potential integration points where intermediates from one process can be used as inputs or supplements in another, thereby maximizing resource utilization and reducing waste. For instance, the bio-oil produced from pyrolysis could be further upgraded through gasification or HTL to produce higher-value fuels or chemicals. Similarly, syngas from pyrolysis and gasification can be directly used for hydrogen production, thereby reducing the need for external hydrogen production facilities using electrolysis. Analysing the compatibility of these intermediates with downstream refining and conversion technologies is crucial for ensuring integration and optimizing process flows. Co-processing opportunities should be explored to utilize

diverse feedstocks effectively and improve overall biorefinery economics. Techno-economic models can help identify the most cost-effective pathways for integrating these technologies, providing a framework for designing and operating fully integrated biorefineries.

5 Identify and understand the end-demands for different types of intermediary green fuels

Avoid putting the cart before the horse by fully understanding the market demands for intermediary green fuels. Conduct comprehensive market research and stakeholder engagement to provide insights into which sectors are likely to adopt these fuels and under what conditions (e.g. willingness to pay, substitutability, offtaker terms, etc). Analysing the technical specifications and quality requirements of these end-use applications ensures that the fuels produced will be compatible with existing infrastructure and technologies.

Additionally, developing flexible synthesis plants that can adapt to evolving demands is important for maintaining competitiveness. This includes the capability to switch or upgrade to other fuel types if market conditions change. The demand for certain green fuels may shift, requiring producers to adjust their output or transition to different fuel products that align with new market realities. This adaptability ensures that green fuels can continue to meet the specific needs of different end-use markets, even as technological and market landscapes evolve.

6 Industrial scale deployment and scaling of biorefineries

Construct and deploy biorefineries at an industrial scale after pilot and demo projects are validated. Ensure the plants are optimized for large-scale production, including securing reliable quantities of feedstock supply and ensuring integration with existing infrastructure (utilities and logistics networks). Additionally, securing funding is crucial, often involving a combination of public and private investment, grants, and incentives designed to accelerate and de-risk the deployment of these plants.

7 Integration of carbon capture for later efuel production

Integrate carbon capture technologies within biorefineries to produce biogenic CO₂ for later utilization in efuel production. For example, during the upgrading process of biogas to biomethane, biogas is split into CH₄ and CO₂ wherein this CO₂ can be captured at relatively low cost due to its high purity.⁹³

This CO₂ can then be used for the production of carbon-based efuels. Research should focus on developing carbon capture systems that are compatible with biorefinery processes, ensuring integration without compromising efficiency. High capture rates with low energy penalties are desired to enhance the overall economics. Please refer to the INNO-CCUS roadmap for the latest look at carbon capture technologies.⁶⁸

8 R&D and advancement of fuels made from 2nd and 3rd generation feedstocks

R&D should be conducted to advance the production of fuels from 2nd and 3rd generation feedstocks, with a focus on improving long-term sustainability and increasing production yields. Second-generation feedstocks include agricultural residues, forestry waste or lignocellulosic non-food biomass such as Miscanthus, while third-generation feedstocks primarily involve high-yield, fast-growing sources like algae.⁹⁴ Research should prioritize improving cultivation techniques and leveraging genetic engineering to boost feedstock quality and growth efficiency as well as improving pretreatment steps for handling these feedstocks. Collaborating with academic institutions and industry partners is crucial to accelerate these advancements.

9 Develop and implement standards for fuel quality and blending requirements

Establishing and implementing standards for fuel quality and blending requirements is key for ensuring the reliability and performance of green fuels in various applications. Research into the effects of increasing blending ratios (above the 7% for FAME and 10% on ethanol in the EU Fuel Quality Directive⁷³) on engine

performance, emissions, and overall fuel efficiency is necessary to inform these standards and ensure they are both practical and effective. Ensure fuel quality standards are harmonized across EU member states to allow transfer of liquids and gases cross-border with no differences in performance for the end-use applications.

10 Adoption and utilization of organic waste streams: aqueous HTL, dairy waste, wastewater

Utilizing organic waste streams like HTL by-products, dairy waste, and wastewater offers significant potential for green fuel production. HTL converts wet biomass into bio-crude oil, with the aqueous by-products containing organics that can be processed into biogas or hydrocarbons. Dairy waste, rich in organic matter, can be used for bioethanol or biogas production. Wastewater, also high in organics, can be treated to produce biomethane or biomass for biofuels. Integrating these waste streams into biorefineries enhances resource recovery and minimizes environmental impact.

11 Fully integrated bio-e-refineries optimized for green fuel production

Related to points 4 and 7, the end-goal will be developing fully integrated bio-e-refineries optimized for green fuel production with systems that combine multiple conversion technologies, such as HTL, pyrolysis, and gasification, with carbon capture and e-fuel production. This integration must be optimized to achieve maximum efficiency and output while minimizing waste and emissions. These projects should focus on optimizing process flows, energy integration, and waste management to enhance overall performance.

MISSION GREEN FUELS

MGF is strategically positioned to drive innovation and R&D, particularly in the following topics for intermediary fuels:

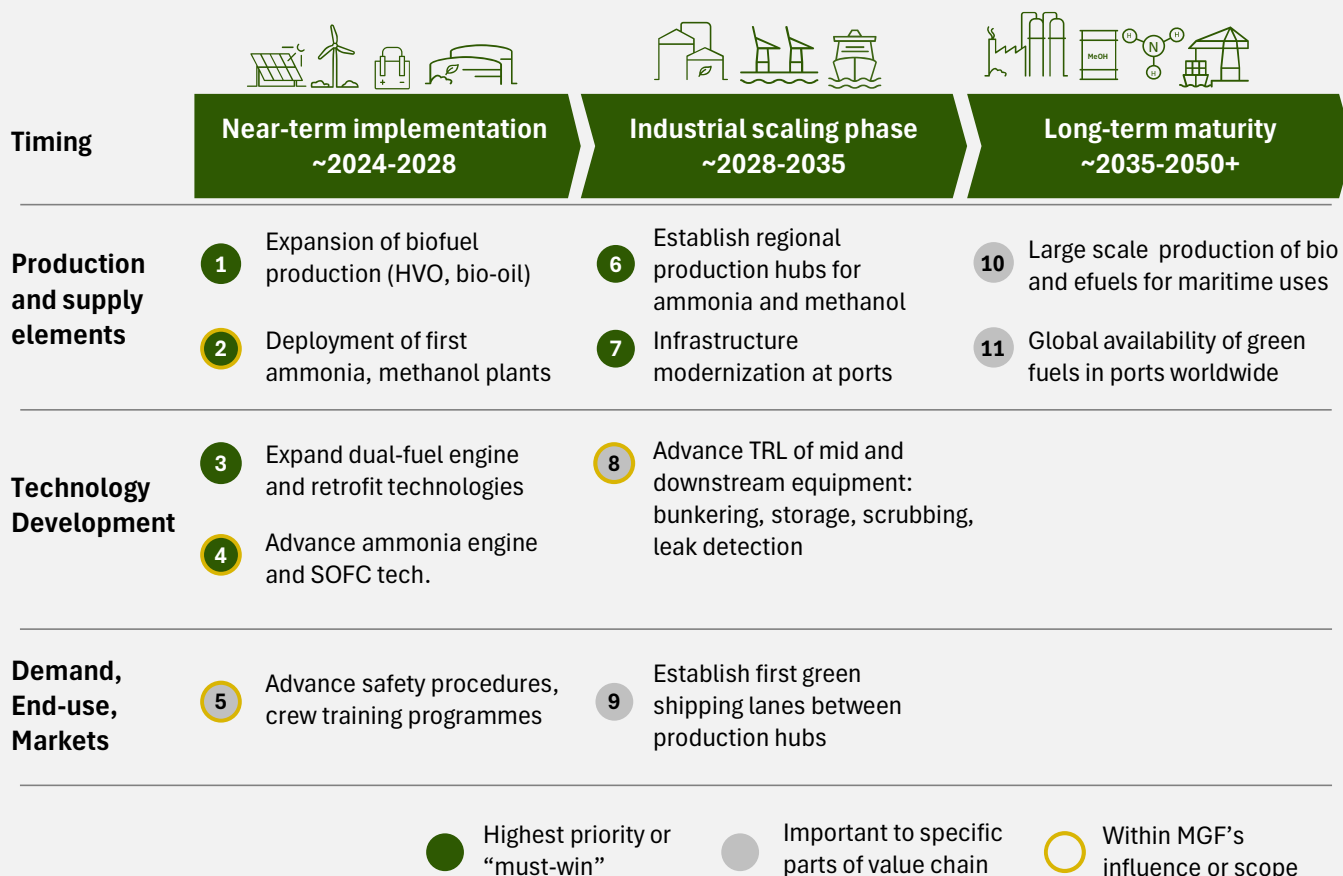
- LCA of biomass production processes and assessment of feedstock sustainability
- R&D in low-TRL bio technologies
- Developing fuel blending improvements and qualities
- Quantifying Danish biomass potentials cross 1st, 2nd, and 3rd generation feedstocks
- Optimizing process and energy flows

Focus areas and projects within intermediary fuels

Examples of past or ongoing MGF funded projects that address the needs identified:

- **CARMA-Green Fuels:** Cross Mission Carbon Management
 - Explores potentials for sustainable biomass production in DK, with scenario development
- **STAB3: Stability Improvement of Biooil-Bunker-Blends**
 - Aims to assess the stability of bio-oils when blended with conventional oils and formulate ways to enhance blend stability

8.3 Key activities in the maritime fuels roadmap



1 Expansion of biofuel production and feedstock collection

Scale up domestic biorefinery capacity and sustainable sourced biomass supply chains to significantly increase production. This is relevant for all transport sectors that will rely on biofuels in the near-term. This includes necessary upstream pieces such as feedstock collection, processing, and pre-treatment to ensure sufficient raw material availability. Exploring new feedstocks and developing the technologies to convert them will be important to ensuring that sufficient raw materials are available.

2 Deployment of first ammonia and methanol plants

Finish construction on the first methanol and ammonia plants within Denmark. Planned sites in Denmark include European Energy’s e-methanol Kassø facility with 52MW of electrolysis to produce an estimated 42,000 tonnes of methanol annually.⁹⁵ This is equivalent to the annual volume of three to four of Maersk’s first green container ships, the Laura Maersk with a capacity of 2,100 TEU. Construction is expected completion in 2024. For ammonia, the REDDAP (Renewable Dynamic Distributed Ammonia Plant) PtX

facility in Northern Jutland will be Denmark’s first, producing 5,000 tons per year of ammonia.⁹⁶ The project is a collaboration between Skovgaard Energy, Topsoe, and Vestas and is expected to enter operation in 2024. These plants will provide practical experience in building and operating PtX facilities in Denmark and will strengthen industry collaboration and technological expertise in green fuel production. The knowledge gained will be critical for refining future projects and scaling up sustainable fuel production.

3 Expand dual-fuel engines and engine retrofit technologies

Dual-fuel engines with the ability to run on conventional fuels but also methanol will be needed in the near-term. This flexibility is crucial as the global supply chains for low-carbon fuels are still developing, and availability may be inconsistent in the short term. Dual-fuel engines mitigate the risk associated with the limited availability of these fuels by allowing ships to switch back to traditional fuels if necessary. For ships ordered today, dual-fuel engines would future proof them (from carbon intensity requirements and emissions compliance) as the average container vessel has a lifetime of 25-30 years.

MAN Energy solutions offers “methanol ready” four stroke engines and Alfa Laval methanol fuel supply systems, among other technologies for green fuel enablement for vessels. Both are seeing real-world usage and commercialization. However, dual-fuel engines are more complex than single-fuel engines, requiring advanced fuel management systems and additional safety measures to handle different types of fuels. This complexity often leads to higher upfront costs and potentially higher maintenance requirements. Retrofits of existing engines is also an increasingly viable solution for ship owners looking to transition to cleaner fuels without the need for new vessel construction. This typically involves modifying the fuel injection and ignition system and upgrading engine components and gaskets with methanol resistant materials. While retrofitting is generally more cost-effective than building new methanol-capable vessels, it still represents a significant investment.

4 Advance ammonia engine and ammonia SOFC technologies

For ammonia engines, ammonia is combusted generating thermal energy which is converted into mechanical work to drive an engine’s pistons. Marine engine developers have been making recent advancements in ammonia engine technologies. In 2023 Wärtsilä launched the world’s first four-stroke engine based on ammonia which is now available on an engine platform suited for small to medium bulk carriers and tankers. Additionally, MAN is working on deploying the world’s first two-stroke ammonia engine with an expected operation onboard a commercial vessel in 2026.⁹⁷ Successful demonstration of an ammonia engine will be a critical milestone for green fuels.

On the fuel cell side, ammonia solid oxide fuel cells (SOFC) directly convert chemical energy into electrical energy without the intermediate step of combustion. The primary emissions are water vapour, with no NOx emissions (unlike ammonia combustion). Typical efficiency is 60% and this can be optimised to 85% with heat recovery. However very high operating temperatures (500-1000 °C) are needed. Ammonia SOFC technology is still in the development phase (TRL 4-5) but will be seeing piloted use on real-world ships in the coming years.⁹⁸ For SOFC, applications will likely target small to medium sized vessels.

5 Advance safety procedures and crew training programmes

Due to the more complicated nature of new engine technologies, the use of new green fuels, and potential safety risks associated with ammonia (toxic) and hydrogen (explosive), specialized crew training

programmes should be established. This includes for on ship operations, fuel bunkering, and storage. Multiple Danish stakeholders are working on advancing this topic. DBI’s “SafeSBU” project (with partners FORCE Technology, Complete Solutions, DFDS, Port of Rønne and Aalborg University) is working to produce comprehensive guidelines for safety, as well as training courses for workers involved in the storage, bunkering, and usage of hydrogen, ammonia, and methanol in the maritime industry.⁹⁹ Similarly, companies such as DNV, Danish Technological Institute, and more and offering theory and training on green fuel safety and handling.¹⁰⁰ A well-prepared workforce is essential for reducing the likelihood of safety incidents and for advancing the integration of green fuels in the sector.

6 Establish regional production hubs for ammonia and methanol

State-designated “energy parks” or industrial energy zones will help speed up the deployment of green fuels facilities. Currently there are over 18 areas for energy parks undergoing dialogue and development with local municipalities.¹⁰¹ These designated energy parks will have streamlined planning and approval processes, allowing for exceptions to certain regulations to facilitate the development of renewable energy projects (wind, solar, PtX) and associated infrastructure. They are also likely to be located in strategic locations in relation to onshore substations or future infrastructure (e.g. H2 backbone), reducing distances for power lines or branching pipelines. Establishing multiple production facilities in one regional hub will leverage shared infrastructure, driving synergies and reducing costs.

7 Infrastructure modernization at ports

Danish port infrastructure is generally very well developed, with key ports such as Aalborg, Esbjerg, Fredericia, Rønne, Hanstholm, Hirtshals, Frederikshavn, Aabenraa, and Aarhus being particularly well-suited for green fuels due to their locations to existing or future renewable energy build-out (e.g. North Sea or energy islands) or strategic positioning on key cargo routes. Upgrading port infrastructure to handle ammonia and methanol involves developing specialized storage and bunkering facilities, implementing rigorous safety and environmental controls, and integrating these operations smoothly with existing port activities. Current innovation projects, such as the multi-stakeholder Marco Polo project in Northern Jutland investigates how green fuels can be integrated at ports to accommodate future volumes of methanol.¹⁰² Safety, and technical challenges as well as community buy-in and social aspect are looked at in detail.

8 Advance TRL and manufacturing of auxiliary components

Scaling up the manufacturing of auxiliary components is crucial to support green fuels value chains. Producing green fuels at scale requires more than just the core production technologies like electrolyzers. It also involves the development and manufacturing of hundreds of other pieces of equipment such as specialized storage tanks, valves, and containment systems, as well as bunkering infrastructure necessary for safe and efficient fuel distribution across the mid and downstream part of the supply chain.

Technologies that are already commercially available but essential to green fuel operations need to be manufactured at scale to avoid bottlenecks in the supply chain. This includes sometimes overlooked equipment, such as electrical components like switchgears, substations, and BOP equipment like gas separators, scrubbers, heat exchangers, and valves. For midstream storage and handling infrastructure, this could involve the development of storage tanks and containment systems designed to handle the sometimes corrosive or toxic properties of green fuels. For downstream applications on ships, it includes the manufacture of onboard storage tanks, fuel supply systems, safety and monitoring equipment, and emissions control equipment.

9 Establish first green shipping lanes between production hubs

In step with port infrastructure modernization, strategic green shipping corridors should be established, connecting green fuel bunkering locations. This could include coastal routes within DK but also cross-border partnerships and agreements with ports in other first-

mover countries such as The Netherlands, Norway, Sweden, or the UK and with partners in important trading ports in Asia. These lanes would connect major production nodes, ensuring a reliable supply of green fuels for vessels operating on these routes. This would not only demonstrate the feasibility of zero-emissions shipping but also create a reference for expanding green shipping corridors globally. Challenges include decisiveness on fuel pathways (whether to adopt a mono or multi-fuel strategy) and the need to explore innovative commercial, business, and financial arrangements for stakeholders taking the first-mover risks.

10 Large scale production of bio and efuels for maritime uses

To meet the expected demand for green fuels in the maritime sector, Denmark must focus on scaling up biofuel and efuel production to levels that can support both its own domestic needs and the bunkering demands of international ships arriving in Danish ports. This involves significantly expanding existing production facilities and constructing new plants designed to operate at industrial scales.

11 Global availability of green fuels in ports worldwide

Long-term end goal for green fuels industry. This will take an enormous amount of global investment and coordination. Establishing a global trade network for green fuels is crucial to ensure consistent supply availability for the maritime industry. This involves creating standardized trading frameworks, developing robust logistics and distribution networks, and fostering international partnerships to secure long-term supply agreements.

MISSION GREEN FUELS

MGF is strategically positioned to drive innovation and R&D, particularly in the following topics for maritime fuels:

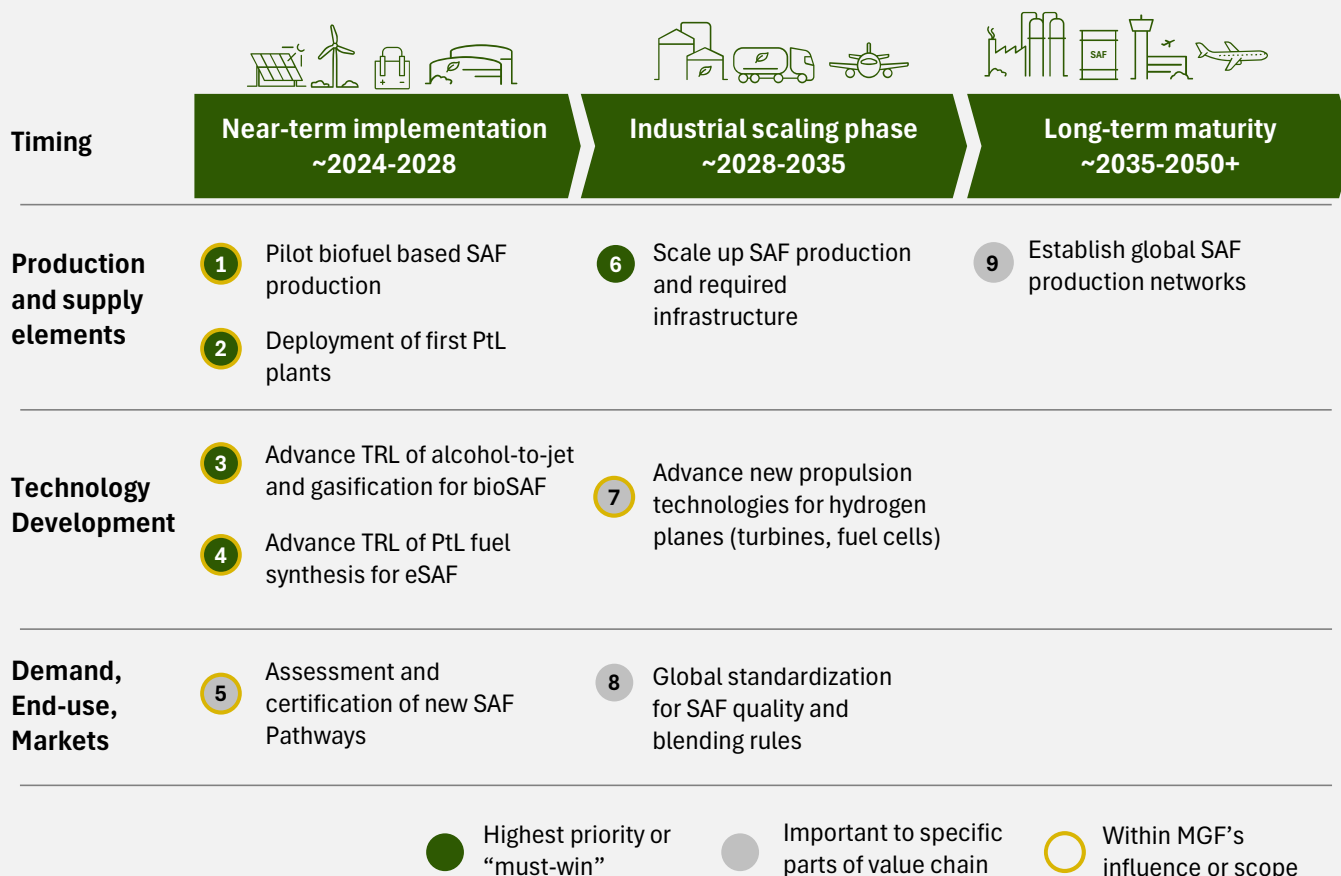
- Support for pilot and demo plants for ammonia and methanol production
- R&D in low TRL technologies (bio and efuel)
- TRL advancement of equipment such as sensors, fuel injection, bunkering equipment, etc
- Safety and handling aspects for green fuels
- Guidebooks, training guides, and implementation roadmaps for ports and port workers

Focus areas and projects within maritime fuels

Examples of past or ongoing MGF funded projects:

- **SafeSBU:** Safe storage, bunkering, and usage of green fuels
 - safety design processes, use cases, and approval processes to support fast and safe implementation among mid- and downstream stakeholders in ports.
- **COMPAS:** competitiveness on ammonia production through flexible ammonia plants
 - Improvement in ammonia tech. Focuses on the techno-economic assessments of technology upgrades on the flexible ammonia plants

8.4 Key activities in the aviation fuels roadmap



1 Pilot biofuel-based SAF production

Increase production of biofuels relevant for aviation such as HEFA and HVO and other bio-oils which can be upgraded to SAF. Currently there is no domestic production of HEFA/HVO bioSAF in Denmark and these fuels are imported from countries such as Finland or France which have established production facilities.¹⁰³ Denmark could develop existing bioSAF production pathways such as HEFA based on used cooking oils or explore new bio-oil production pathways such as HTL based on agricultural residues or pyrolysis based on lignocellulosic biomass of waste plastics. Similarly, biomass-based methanol/ethanol could be upgraded to alcohol-to-jet.

2 Deployment of first PtL SAF plants

The near-term will see the construction and piloting of several PtL eSAF plants, many based on public-private partnerships. These include:

- **MeSAF in Aalborg:** builds on an existing e-methanol pilot project, Power2Met aiming to advance eSAF production from pilot to commercial scale of 10,000 tonnes SAF annually. Partners include European

Energy, Vertimass, Kosan Gas, AAU Energy, Aalborg Airport, Port of Aalborg, and Hydrogen Valley.¹⁰⁴

- **FrontFuel project in Viborg:** The project will pilot Fischer-Tropsch (CO₂ + hydrogen) to synthetic crude further refined to SAF. Project partners include Topsoe, Aarhus University, and Sasol.¹⁰⁵

- **Padborg SAF facility:** Partnership between European Energy and Swiss Metafuels AG to construct eSAF facility next to European Energy's future Padborg PtX facility in Southern Denmark.¹⁰⁶

- **Arcadia efuels Vordingborg:** First planned commercial eSAF plant in Denmark based on Fischer-Tropsch. Slated for completion in 2026 and aims to produce 100 million liters of efuels per year (both eSAF and eNaptha). Technology providers include Topsoe and Sasol with intended offtake with DCC & Shell Aviation.¹⁰⁷

3 Advance TRL of alcohol-to-jet, gasification, and other bioSAF pathways

Currently, alcohol-to-jet (AtJ) technology sits at TRL 7-8, biomass gasification + Fischer-Tropsch is at TRL 7-8, HTL with upgrading at TRL 4, while other pathways such as direct sugars to hydrocarbons from lignocellulosic biomass sits at 5. There are other low TRL and emerging technologies that could increase the total addressable biomass potential for the use in SAF and other green fuels. Please see the table in Appendix 1 for the list of TRL's associated with bioSAF production. Engage in research and development of these technologies to advance them to TRL 9. Benefits of advancing these technologies include the ability to use 2nd and 3rd generation bio feedstocks at larger volumes, increase circularity of feedstocks, and improved efficiencies.

4 Advance TRL of PtL fuel synthesis for eSAF

The Fischer-Tropsch pathway and is fully commercial (TRL 9) and has been used for decades based on the gasification of coal and producing syngas to create hydrocarbons. However, other steps of the PtL process are at lower TRLs, particularly the Reverse Water Gas Shift Reaction (RWGS) which is only at TRL 5-6. The RWGS or "CO₂ reduction" process converts captured CO₂ into CO to produce syngas. This limits the overall

TRL of the integrated Fischer-Tropsch based e-SAF process. The e-methanol pathway to produce e-SAF does not require the RWGS reaction but requires many subsequent processes such as olefin synthesis, oligomerisation, and hydrotreating. The TRL of this process sits at 7-8.⁸³

In addition, the CO₂ source (point source, DAC, etc) will have varying levels of readiness. The availability of biogenic / point source CO₂ could become a bottleneck for the production of eSAF based on availability or competition from other forms of CCU or CCS. The need for TRL advancement in CCU technologies such as DAC will likely be needed in the long-term.⁶⁸

5 Assessment and certification of new SAF pathways

Currently there are 9 approved SAF production pathways from ASTM international with varying blending limits up to 50%. The feedstocks of these fuels vary from fats and oils, energy crops, lignocellulosic biomass, to algae. Some will not meet the EU's sustainability criteria for advanced biofuels if for example produced via energy crops. These list of approved ASTM pathways are shown in Table 8.1.

Table 8.1: ASTM approved SAF production pathways

| Pathway | Certification Name ⁱ | Blending Limit | Feedstocks | Year Approved | Estimated TRL ⁱⁱ |
|--|---------------------------------|----------------|---|---------------|-----------------------------|
| Hydroprocessed Esters and Fatty Acids (HEFA) | HEFA-SPK | 50% | Vegetable and animal fat | 2011 | 9 |
| Biomass Gasification + Fischer Tropsch (Gas + FT) | FT-SPK | 50% | Crops, lignocellulosic biomass, solid waste | 2009 | 7-8 |
| Biomass Gasification + FT with Aromatics | FT-SPK/A | 50% | Crops, lignocellulosic biomass, solid waste | 2015 | 6-7 |
| Alcohols to Jet (AtJ) | ATJ-SPK | 50% | Sugar, starches lignocellulosic biomass | 2016 | 7-8 |
| Catalytic Hydrothermolysis Jet (CHJ) (Also known as HTL) | CHJ of CH-SK | 50% | Vegetable and animal fat | 2020 | 6 |
| Direct Sugars to Hydrocarbons (DSHC) | HFS-SIP | 10% | Sugars, lignocellulosic sugars | 2014 | 7-8, or 5 ⁱⁱⁱ |
| HEFA from Algae | HC-HEFA-SPK | 10% | Microalgae oils | 2020 | 5 |
| FOG Co-processing | FOG | 5% | Fats, oils, and grease | 2018 | - |
| FT Co-processing | FT | 5% | FT biocrude | 2020 | - |

i. ASTM-approved pathway to SAF. The specific production pathway, may not necessarily meet certain regulations (e.g. ReFuelEU Aviation) based on the sustainability of the feedstock.

ii. TRL's from "Drop-in SAF production pathways" by European Union Aviation Safety Agency.⁸³

iii. TRL 5 for lignocellulosic feedstock. TRL 7-8 for conventional sugar feedstock.

There are 11 new SAF pathways that are currently under evaluation including biomass pyrolysis, non-recyclable plastic pyrolysis, among others. New SAF pathways should meet sustainability criteria as set out by Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)⁸⁷ and have LCAs performed to quantify life cycle emissions and validate the reductions potential of the pathway.

6 Scale up of SAF production and required infrastructure

Production should be scaled up significantly to meet national and international GHG emissions reductions targets. Estimates for GHG scenarios conclude that 300-400 SAF plants could be needed globally to produce 40-50Mt SAF by 2030 (13%–15% of total jet fuel demand), the majority of these being HEFA plants.⁸⁶ A mass scale up of SAF production plants must take place between now and 2050 to meet net zero goals in the aviation sector. Some estimates place to total capital investment between now and 2050 in the \$5.1 trillion range which includes upstream inputs to fuel production, and the SAF production plants themselves. Massive investment is needed.

7 Advance new propulsion technologies

In parallel with the development of drop-in SAFs for existing aircraft engines, there should be a focused effort on R&D for novel propulsion technologies using batteries or hydrogen. Innovation in these areas is expected to initially emerge from smaller aircraft but has the potential to scale up to larger planes. Benefits of these technologies include more efficient energy conversion processes, improved LCA performance,

and reduced reliance on bio-feedstocks. Innovation in this space will likely be driven by established aerospace companies and new startups collaborating to overcome technical challenges and bring these technologies to market. This effort will also require regulatory support and infrastructure development to ensure successful adoption and integration into the aviation sector.

8 Global standardization for SAF quality and increase of blending limits

Global standards for SAF quality exist, primarily governed by ASTM D7566, which currently allows a maximum blending limit of 50% with conventional jet fuel. However, blending limits are lower (10% or 5%) for certain SAF pathways that are less advanced or have different chemical compositions. Increasing these blending limits will require research to ensure compatibility with existing aircraft engines and fuel systems, as well as rigorous safety testing and certification.

9 Establish global SAF production networks

To ensure global availability of SAF, it is crucial to establish a robust production network that leverages regional advantages. Certain geographies offer favourable production conditions, such as access to cheap renewable energy, abundant sustainable biomass, and proximity to major ports or aviation hubs. By identifying and investing in these strategic locations, a globally integrated SAF supply chain can be developed, facilitating the widespread adoption of SAF and supporting the aviation industry's transition to sustainable fuels.

MISSION GREEN FUELS

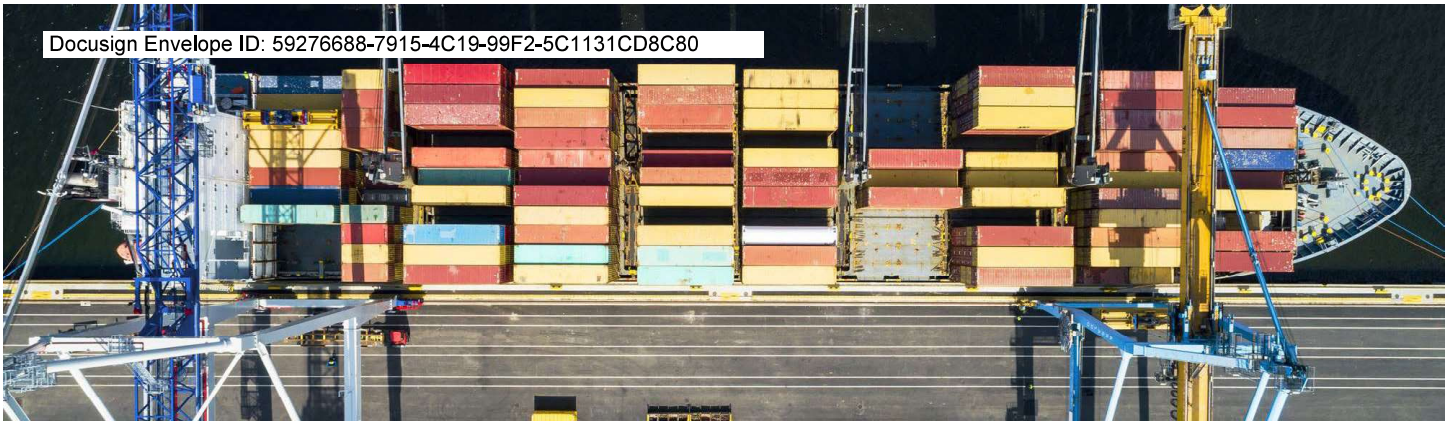
MGF is strategically positioned to drive innovation and R&D, particularly in the following topics for aviation fuels:

- Support for pilot and demo plants for bioSAF and eSAF demonstration
- Assessment and validation of SAF production pathways from a techno-economic perspective
- Support for R&D in low TRL technologies (bio and efuel)
- LCA methodologies for SAF pathways
- Guidebooks and implementation roadmaps for airports

Focus areas and projects within aviation fuels

Examples of past or ongoing MGF funded projects:

- **Methanol-to-Jet:** Fuel Process Development
 - Create a strategy for and commence ASTM certification of the Methanol-to-jet pathway for use of the fuel in commercial aviation. Integration of process into energy systems
- **MTHiO:** Methanol to higher olefins
 - The first step in methanol conversion to SAF.
 - Conduct pilot-scale experiments to investigate and demonstrate the MTO process in large scale for future industrial up-scaling and commercialization

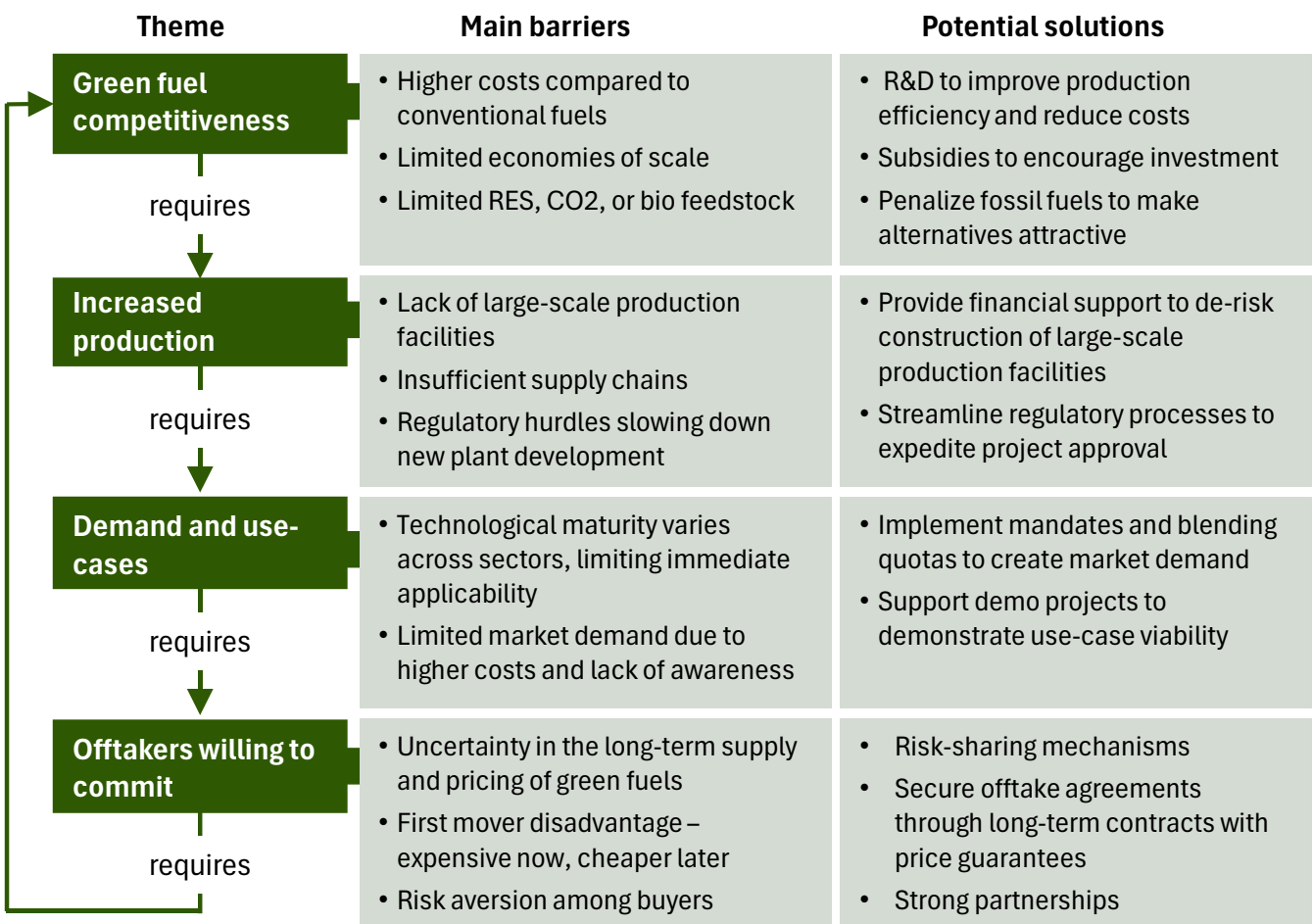


9. Commercial Activities

Market-based measures to accelerate the deployment of green fuels are described more closely in this section. These measures are meant to increase the build out of green fuel supply and stimulate demand. For PtX specifically, stakeholders often describe a chicken-and-the egg paradox where supply and demand are mutually dependent but neither can develop independently. Breaking this paradox requires

commercial mechanisms to de-risk and create certainty in the market for green fuels. The paradox, main barriers, and potential solutions are shown in Figure 9.1. The potential solutions to break the paradox widely relate to lowering costs, reducing uncertainty, and enabling predictability in the market.

Figure 9.1: The green fuels paradox with potential solutions



Additional commercial needs identified by MissionGreenFuels stakeholders emphasize the need to advance infrastructure, develop robust supply chains, and implement market strategies that drive demand and ensure economic viability. By establishing strong supply chains and promoting cross-sector integration, the green fuel industry can overcome significant barriers to market entry and scale-up. These actions are critical to enabling the widespread adoption and impact of advanced technologies, which might otherwise struggle to reach commercial maturity and instead end up in the innovation “valley of death”. Below are description of the top commercial activities, as identified by stakeholders necessary to support the growth of the green fuels sector:

Commercial activities within green fuels

As expressed by MGF stakeholders

- 1 Expand green fuel infrastructure
- 2 Develop robust supply chains
- 3 Stimulate market uptake of green fuels
- 4 Establish project references
- 5 Foster cross-sector integration
- 6 Public-private collaboration
- 7 Align with international developments

● Commercial Activity ○ Within MGF's influence or scope

1 Expand green fuel infrastructure

Expanding green fuel infrastructure is needed to connect supply and demand centres. Producers of green fuels need efficient distribution pathways to be able to offtake their product as well as storage solutions to be able of to balance supply-demand fluctuations. The development of midstream and downstream infrastructure such as pipelines, fuelling stations, storages, bunkering facilities, as well as upstream feedstock infrastructure such CO₂ pipelines is important. The most critical piece of infrastructure in the near-term is arguably the hydrogen pipeline to Germany. Building this will provide an offtake and the ability to scale domestic green hydrogen production. Outside of the actual FID and construction of the pipeline, implementing early connection models or pipeline tariffs, such as competitive pricing and incentives for early adopters, will further lower barriers.

and stimulate demand. Collaborative planning with key markets, like Germany, and a focus on long-term storage solutions will create a connected green fuel network, laying a strong foundation for future expansion.

2 Develop robust supply chains

A single unreliable (or uneconomic) link within various green fuel supply chain can jeopardize the entire system, underscoring the need for a fully developed and economically viable value chain from producer, to distributor, to user. On the production side, strategies to ensure robustness could include diversification of feedstock sources (e.g. multi-feedstock capability for biofuel production or leveraging multiple renewable energy sources). For equipment, this could include diversification of OEMs, standardization of components, supply chain risk management practices. Additionally, collaboration and forming partnerships with stakeholders across different sectors, such as energy producers, transportation providers, and component manufacturers, can strengthen the supply chain. Collaboration can lead to shared resources, joint investments in infrastructure, and coordinated planning.

3 Stimulate market uptake of green fuels on the demand side

To stimulate demand and encourage market uptake of green fuels, there is a need for ambitious, yet realistic policy mandates for the use of green fuels is various end-uses. These could include blending requirements and mandates for a minimum share of green fuels in energy mixes, which would create a baseline level of demand and predictability in green fuels uses by sector. These mandates should be coupled with a financial incentive to comply. Business models that leverage GHG emissions savings via usage of green fuels are also essential, as they provide a financial rationale for adoption and making the switch from conventional fuels. Outside of financial or policy tools, running public awareness campaigns and educating the public and businesses about the environmental benefits and long-term cost savings of green fuels can drive further adoption.

4 Establish project references: demonstrate commercial viability of investments

Demonstrating the commercial viability of green fuel investments is vital for securing stakeholder confidence and increasing additional investments into the sector. Establishing credibility through successful projects and project references is important as these provide tangible proof of the technical and economic viability.

5 Foster cross-sector integration

Integration is necessary to maximize the efficiency and impact of green fuel technologies. Ensuring practical and reliable technology integration across different sectors can unlock new synergies as well as revenue streams (via stacking), such as using surplus heat from electrolysis processes in other industrial applications or using hydrogen production as a way to balance the grid in times of excess renewables generation. Denmark can demonstrate technology leadership and aim to showcase successful integration of large-scale PtX projects.

6 Public-Private collaboration

Public-private collaboration is fundamental to advancing green fuel initiatives in Denmark. Success depends on the cooperative efforts of government entities, private companies, and research institutions to align strategies, share resources, and drive innovation. Examples of effective collaboration include joint ventures in R&D, co-investment in infrastructure, and the development of regulatory frameworks that support innovation. Establishing clear governance structures and communication channels within these collaborations will ensure alignment of goals and efficient use of resources.

7 Align with international developments

The global landscape for green fuels is quickly evolving. Denmark's commercial success in green fuels will depend on making technologies cost-effective to compete globally, especially as it pursues a green fuel export strategy aimed at supplying regional industry and transport needs. Production costs must be competitive with those in other leading markets, such as Norway, Sweden, and Spain, while the cost and performance of electrolyzers should match those produced in Germany, France, and the USA. To achieve this, Denmark should prioritize international collaborations, R&D, and knowledge sharing, ensuring its technologies align with global trends and maintain a competitive edge in the global energy market.

MISSION GREEN FUELS

Focus areas within green fuels markets

MGF is positioned to drive innovation and R&D, particularly in the following commercial topics:

- Models for market development of green hydrogen and other fuels
- Demand sizing for various fuel types
- Quantifying commercial benefits of sector integration + coupling
- Establishing project references via support of pilot and demo projects for upcoming technologies
- Research into energy systems models that combine market forecast and future demands

Examples of past or ongoing MGF funded projects:

- **PtX Markets:** Markets, Policies, and Business Models for Green Fuels:
 - Assessment of green fuel markets and policies for demand uptake, business models, trading, and control strategy
 - Dataset on green fuel demand estimation
- **PtX Sector Coupling and LCA :** Further development of energy system models
 - Analysis on the optimal locations of new plants based on grid capabilities, market forecasts, biomass, carbon availability, and integration opportunities
 - Co-optimisation of gas, electricity, hydrogen and district heating



10. Regulatory and Policy activities

Activities that fall under the regulatory framework for green fuels include setting emissions targets, creating certification schemes for fuel sustainability, implementing carbon pricing mechanisms, establishing clear guidelines for lifecycle emissions analysis, and developing supportive policies. These regulations can be national, on the EU level, or global.

National policy frameworks

Among the national-level regulations and policies in Denmark that drive the adoption of green fuels, the ones that set binding targets are:

- **Danish Climate Act:** The Danish Climate Act sets a legally binding target of reducing greenhouse gas (GHG) emissions by 70% by 2030 compared to 1990 levels, with a goal of achieving climate neutrality by 2050. This binding target underpins many of the other policies and strategies, pushing for the adoption of green fuels as part of the broader decarbonization effort.¹⁰⁸
- **Renewable Energy Act:** While the Renewable Energy Act promotes the use of renewable energy sources, including green fuels, it also includes binding targets for the share of renewable energy in Denmark's overall energy mix. This indirectly drives the adoption of green fuels as part of achieving these renewable energy targets.¹⁰⁹

The other policies and strategies, such as the Power-to-X Strategy, Green Gas Strategy, and Sustainable Aviation Strategy, provide important guidance and support for the transition to green fuels but do not set binding targets. These policies are more focused on providing support and facilitating the conditions necessary to meet the binding targets set by the Climate Act and Renewable Energy Act.

European level policy frameworks and targets

There are numerous EU level policies related to green fuels production, infrastructure, certification, as well as target setting for various transport sectors. These are listed on the next page in Table 10.1.

Global level policy and targets

On a global level, organizations such as the International Maritime Organization (IMO) and the International Civil Aviation Organization (ICAO) have set targets that aim to increase the adoption of green fuels for the aviation and maritime sectors:

- **IMO Strategy on Reduction of GHG Emissions from Ships (2023):** The IMO has set a target to reduce the carbon intensity of international shipping by at least 40% by 2030, 70% by 2040, and to reach net-zero GHG emissions by or around, i.e. close to, 2050. Reduction levels are to be compared to 2008 and account must use LCA guidelines to quantify the well-to-wake GHG emissions of marine fuels.⁸¹
- **Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA):** The ICAO's global market-based aimed at stabilizing CO₂ emissions from international aviation at 2020 levels. Airlines are required to offset any emissions above this baseline by purchasing carbon credits, thereby incentivizing the adoption of sustainable aviation fuels (SAFs) and other green technologies to reduce emissions. The ICAO also promotes the use SAF via the new ICAO Global Framework for Sustainable Aviation Fuels (SAF), Lower Carbon Aviation Fuels (LCAF), and other Cleaner Aviation Energies represents a commitment by ICAO and its Member States to collectively pursue the goal of reducing CO₂ emissions from international aviation by 5% by 2030.⁸⁷

Table 10.1: EU-level policies and frameworks for green fuels

| | |
|---|---|
| RENEWABLE ENERGY DIRECTIVE (REDIII) Renewable Energy Directive EU/2023/2413; amendment of 2023. ¹¹⁰ |  |
| <ul style="list-style-type: none"> Sets a binding target for renewable energy in the EU's overall energy consumption to reach 42.5% by 2030, with a specific sub-target for RFNBOs in transport Defines RFNBOs and sets sustainability criteria, including the need for hydrogen to be produced using renewable electricity | |
| DELEGATED ACT – RULES FOR RENEWABLE HYDROGEN Commission Delegated Regulation (EU) 2023/1184. ¹¹¹ |  |
| <ul style="list-style-type: none"> Establishes specific criteria for renewable hydrogen production, certification schemes and GHG reduction thresholds (70%), rules on traceability and verification of RFNBOs Additionality: Ensuring that the renewable electricity used for hydrogen production is additional to what would have otherwise been generated, often implying new projects. Temporal Correlation: Ensuring that the renewable electricity used for hydrogen production corresponds to the time period during which the hydrogen is being produced | |
| GAS PACKAGE Directive (EU) 2024/1788. ¹¹² |  |
| <ul style="list-style-type: none"> Regulation establishes common internal market rules for renewable and natural gases and hydrogen seeking to facilitate the entry and integration of renewable and low carbon gases into the energy system Supports the creation of a European hydrogen backbone to transport H2 across member states | |
| GREENHOUSE GAS EMISSIONS SAVINGS METHODOLOGY Commission Delegated Regulation (EU) 2023/1185. ¹¹³ |  |
| <ul style="list-style-type: none"> Defines a methodology for calculating greenhouse gas emission savings for RFNBOs Establishes a minimum threshold for greenhouse gas emission savings | |
| ReFuelEU AVIATION Regulation (EU) 2023/2405. ¹¹⁴ |  |
| <ul style="list-style-type: none"> Mandates the incorporation of sustainable aviation fuels (SAF) into aviation fuel supplies. Fuel suppliers will have to incorporate 2% sustainable aviation fuels in 2025, 6% in 2030 and 70% in 2050. From 2030, 1.2% of fuels must also be RFNBOs, rising to 35% in 2050. | |
| FuelEU MARITIME Regulation (EU) 2023/1805. ¹¹⁵ |  |
| <ul style="list-style-type: none"> Requires ships to progressively reduce their GHG emissions and carbon intensity by adopting alternative fuels, including hydrogen-based RFNBOs GHG intensity to gradually decrease over time, by 2% in 2025 to as much as 80% by 2050 | |
| TEN-E REGULATION Trans-European Networks for Energy Regulation (EU) 2022/869. ¹¹⁶ |  |
| <ul style="list-style-type: none"> Supports cross-border hydrogen projects to enhance energy security and integrate the hydrogen market within the EU. Provides funding and streamlined permitting processes for hydrogen infrastructure, promoting the large-scale deployment | |
| NET ZERO INDUSTRY ACT Regulation (EU) 2024/1735. ⁹¹ |  |
| <ul style="list-style-type: none"> Boosts up the EU's manufacturing capacity of technologies that support the energy transition Increase competitiveness of EU industry, create quality jobs, and support the EU's efforts to become energy independent | |

Alongside these in-force regulations and policies, the activities for regulatory and framework activities identified by MGF stakeholders included an emphasis on the following topics:

1 Regulatory and policy support:

- Implement funding mechanisms and subsidies to kickstart the PtX industry, with a focus on value chain projects that connect production and consumption nodes.
- Increase funding amounts. Danish PtX tender = 1.25 billion DKK, CCS tender = 28.3 billion DKK.¹¹⁷
- Policy backing of large-scale infrastructure projects such as the hydrogen backbone with the required branching infrastructure and storage possibilities.
- Streamlined permitting processes to ensure quick deployment of production facilities e.g. energy zones and preferential treatment.
- Support early-stage innovation and R&D efforts.

2 Harmonized EU and International regulation

- Advocate for ambitious EU-wide regulations and international cooperation to standardize and certify green fuels production pathways and emissions reduction potentials.
- Develop cohesive standards and certification schemes for fuel quality to facilitate cross-border trading of green fuels within and beyond the EU.

3 Risk sharing frameworks

- Provide economic support to reduce the financial risks associated with early-stage investment.
- Utilize fixed premiums, Contracts for Difference (CfDs) or Carbon Contracts for Difference (CCfDs)

to provide a guaranteed price for a green fuel to stabilize revenue streams and create predictability for producers.

4 Transparency and documentation:

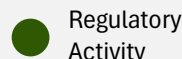
- Standardized reporting frameworks, disclosure requirements, and fuel certifications processes for companies involved in green fuel production and usage to ensure sustainability.
- Comprehensive documentation of the environmental impact of green fuels from production to end-use via different feedstocks and production pathways, including low-TRL ones.

5 Effective citizen engagement frameworks

- Design effective citizen engagement and involvement frameworks working with local municipalities and stakeholders.
- Implement public awareness campaigns to educate citizens on the benefits of green fuels and involve them in the decision-making process.

6 Policy for education and workforce development

- Develop the education and training programs needed to equip the workforce with the necessary skills for the green transition. See Chapter 5: Social and Sustainability for the job profiles needed.
- Collaborate with academic institutions and industry stakeholders to align curricula with the evolving needs of the green energy sector, including courses in innovation.



Regulatory Activity



Within MGF's influence or scope



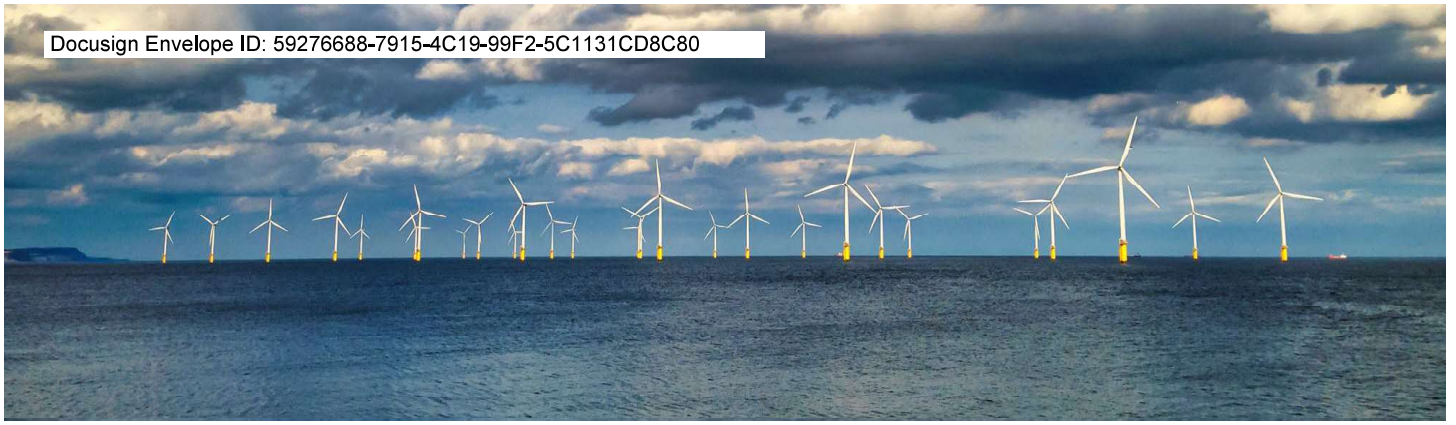
Focus areas within regulation and policy

For regulation and policy, MGF can help drive:

- Regulatory impact analysis to understand how current and proposed regulations affect green fuel markets and investment strategies
- Risk assessment frameworks for early-stage green fuel projects, identifying potential regulatory challenges, or opportunities
- Compliance frameworks for rules around low carbon hydrogen and RFNBOs

Examples of past or ongoing MGF funded projects:

- **RIGHydro:** Regulatory innovation to incentivize green hydrogen:
 - Contribute to the planning of a green hydrogen infrastructure by tackling regulatory, implementation and institutional barriers,
 - Analysis of the latest regulatory developments
- **PtX Markets:** Markets, Policies, and Business Models for Green Fuels:
 - Analysis of regulation for green fuels and market design, and the impacts on European PtX investment



11. Financial and funding activities

Funding estimates

Green fuels and the associated expansion of renewable energy infrastructure will require substantial investment. Achieving the national PtX target necessitates an estimated 20-30 billion DKK for 4-6 GW of electrolyzer capacity, based on 2023 CAPEX costs.¹¹⁸ However, the investment required for the necessary renewable energy capacity—across wind and solar assets—is projected to be more than four times higher, amounting to 135-175 billion DKK.¹¹⁹ Furthermore, significant investments in the billions of DKK will be needed for trucks, ships, and other downstream infrastructure. The Jutland hydrogen pipeline alone is expected to cost between 8-15 billion DKK.¹²⁰ However, more detailed capex and FEED studies are ongoing.¹²¹ Aside from production and use element, investment must also be made into research, innovation, and the ecosystem that will support future technology advancements in the industry.



While these are large sums of money, the put it into perspective, the Danish state spent 120 billion DKK on COVID-19 related expenses¹²² across 2020 and 2022

and will spend around 20 billion DKK on 27 F-35 fighter jets between 2021 and 2026.¹²³ Nonetheless, green fuels must also be compared to other decarbonization options that will be needed to meet the 2030 goals; there are a lot of things to spend money on, and it is essential that state money is spent wisely and act as a force-multiplier stimulating private investment into green projects.

Funding sources

Funding for technology and innovation at lower TRLs in PtX and green fuels technologies will predominantly come from public financial support, as these early-stage innovations require investment without immediate financial returns. However, there are also private foundations such as Villum and the Novo Nordisk Foundation that will fund R&D for lower TRL technologies. Higher TRL technologies, and their deployment in projects, will rely on a combination of private financing potentially assisted with public financing in the form of grants and incentives on a national or EU level. Below are possible sources of public financing for green fuels related technologies:

Table 11.1: National and EU-level funding opportunities

| Project Stage |  National-Level funding |  EU-Level funding |
|--|---|--|
| Low TRL R&D – proof of concept | <ul style="list-style-type: none"> • Innovation Fund Denmark (MissionGreenFuels) • EUDP • Danish National Research Foundation • Various private foundations | <ul style="list-style-type: none"> • Horizon Europe • ERDF and cohesion funds • Just Transition Fund • EIT Innoenergy |
| High TRL Scale-up and deployment | <ul style="list-style-type: none"> • Innovation Fund Denmark (MissionGreenFuels) • EUDP • Danish Green Fund • KIF – Danish climate investment fund • EIFO – Export and investment fund • Various private funds, pension funds | <ul style="list-style-type: none"> • ETS Innovation Fund (Hydrogen Bank) • Connect Europe (Energy and transport infrastructure) • Invest EU + LIFE • IPCEI • ERDF, Just Transition Fund |

Since the last roadmap was published, new funding initiatives have emerged, including the Danish PtX tender and the European Hydrogen Bank, which are described below

Danish PtX tender

As announced in the government's 2022 PtX strategy, the first PtX tender in 2023 awarded 1.25 billion DKK (167 million EUR) to six sites totalling 280MW.¹²⁴ The support will be given as a fixed premium subsidy (DKK per GJ) price over a period of 10 years. However, the total bids submitted totalled over 4 billion DKK (675 MW) meaning that the auction was 2.4X oversubscribed signalling addition demand for state support. It is unclear when the next tender round will take place or what the support amount will be.

European Hydrogen Bank

On a European level, the winners of the first hydrogen bank auction were announced and awarded in 2024. The European Commission is awarding nearly 720 million EUR to seven hydrogen projects in Spain, Portugal, Norway, and Finland totalling a production capacity of 1.5 GW of electrolysis (1.58 million tonnes of green hydrogen).¹⁰ The first auction received 132 bids from 17 European countries requesting over 15 times the available budget. Like the Danish auction, there is significant oversubscription to the available funds. Funding for the hydrogen bank comes from ETS Innovation Fund which itself is financed by revenues generated from the ETS, specifically from the auctioning of allowances. There are plans for a second round of the hydrogen bank auction to be launched by the end of 2024.¹²⁵

Financial and funding Activities

Alongside the funding mechanisms, the activities for financing identified by MGF stakeholders included the following:

1. Financial support for value chain projects outside of production and supply elements

Support for value chain projects outside of production/supply elements is crucial for building an effective green fuels industry. Important linkages such as storage, logistics, fuelling infrastructure should not be overlooked when providing initial support to the industry. This support could even extend to things such as digital trading marketplaces and platforms that assist with the buying and selling of green fuels.

2. Fair tariff models for the first-users of the hydrogen backbone

To incentivize early adoption of hydrogen infrastructure, tariff models that balance initial costs with long-term benefits should be explored. A model that aims to prevent prohibitively high costs for first-users, which can be a barrier to early-stage investment, should be avoided. Possible approaches include staggered tariffs that decrease as more users connect to the hydrogen backbone, or offering other financial incentives to early adopters. This ensures that the economic burden of infrastructure development does not fall disproportionately on initial users and encourages early market participation.

3. Innovation in funding and support models.

PtX has high potential but also comes with high risk – investors may view PtX investments with caution due to uncertainties with infrastructure, renewable energy availability, and inherent risks in emerging low TRL technologies. Creating innovative financing models that attracts additional investment into the sector is important. On the demand side, this could be fuel purchase agreements with price hedging mechanisms or government backed guaranteed to mitigate long-term fuel price volatility. For example, a government backed “buyers club” with guarantees on price for the buyer to provide certainty in longer 10-15 year contracts. Such models would reduce investor risk and provide more stable and predictable demand, enabling more aggressive scaling of PtX technologies and infrastructure.

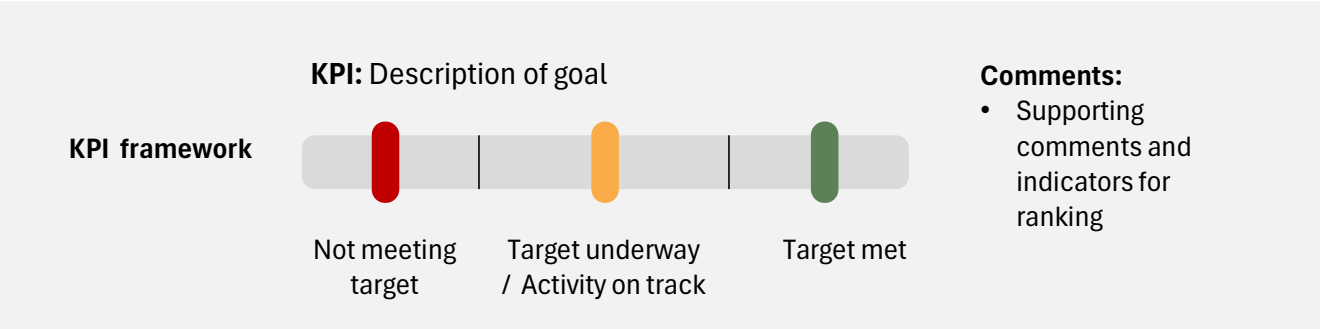
MISSION GREEN FUELS

For funding, MGF can help drive:

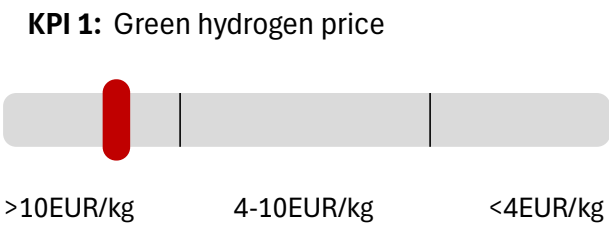
- Direct funding of research, development, and innovation projects within the three main strategic workstreams of the mission:
 - Technologies
 - Infrastructure, PtX plants, Sector Coupling
 - Business and market development and acceptance
- Identify and prioritize key topics and areas for new research and innovation activities, while actively pursuing additional funding to support these initiatives

12. Key Performance Indicators

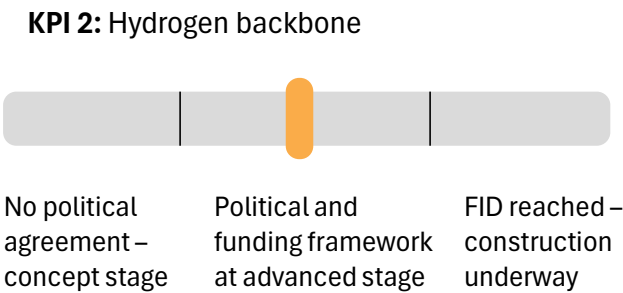
The following Key Performance Indicators (KPIs) are tools used to evaluate the progress of certain elements within Denmark’s within green fuels sector. These KPIs are assessed using a system that provides a visual indication of how well the targets are being met. Each KPI is accompanied by comments that provide context and insights into the progress, challenges, and expected outcomes, along with references to the sources of the information.



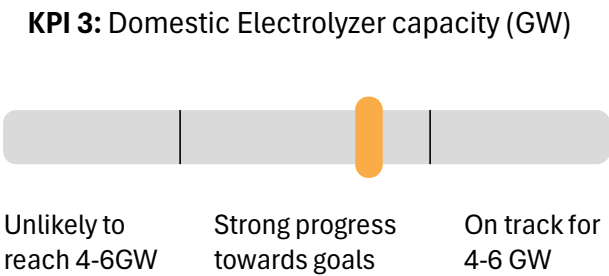
Green hydrogen KPIs
Progress metrics for Denmark’s green hydrogen roadmap



Comments:
The latest hydrogen bank results reveal an average production cost of 11.39 EUR/kg for Danish submitted bids
Individual projects not assessed.
Source: European Commission¹⁰



Comments:
Market dialogue and user commitment process around pipeline underway by Energinet. Conditional investment decision likely to occur in Q1 2025
Source: Energinet June 2024 Information package¹⁶



Comments:

- Projects in concept/feasibility stage total 23+ GW
- Current FID: 0.4GW
- Multiple FIDs on large scale plants will likely be made in 2025

Source: Brintbranchen “brint i tal” August 2024¹³

KPI 4: Green hydrogen end-use (domestic)



Comments:

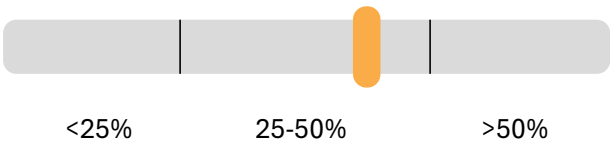
- Hysynergy project (Everfuel / Crossbridge) to use H2 in refining
- Concepts for DFDS ferry to Norway to use compressed H2
- Closure or repurposing of light-duty H2 filling stations serving passenger cars

Source: Project websites

Intermediary Fuels KPIs

Progress metrics for Denmark’s biofuels and intermediary fuels roadmap

KPI 5: Biomethane usage (% of gas usage)

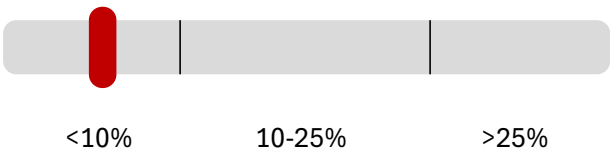


Comments:

In 2023, the percent share of biomethane in Danish gas consumption was ~40%
In Q1 2024 the share was 23%

Source: DEA Energistatistik May 2024²³

KPI 6 Percent of green fuels in transport

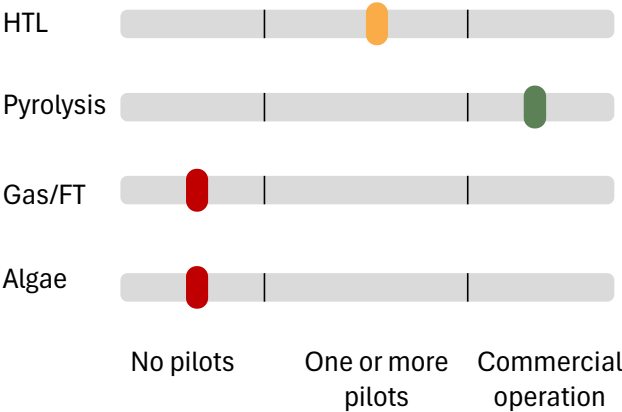


Comments:

Use of green fuels in transport reached levels of 6.5 % in 2022, mostly through fuel blending into diesel and gasoline

Source: KF23⁵⁶

KPI 7: Next-gen biofuels technology plants



Comments:

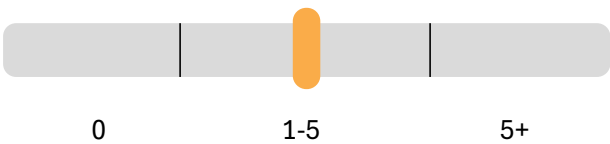
HTL pilot: Aalborg University
Pyrolysis: SkyClean (agricultural waste), QuantaFuel Skive (plastic), Elysium Nordic (tires)
Gasification/FT: No operating pilots identified
Algae: past research projects, no ongoing pilots for biofuels production

Source: Project websites

Maritime Fuels KPIs

Progress metrics for maritime fuels and associated technologies

KPI 8: Number of green shipping corridors planned involving Danish ports

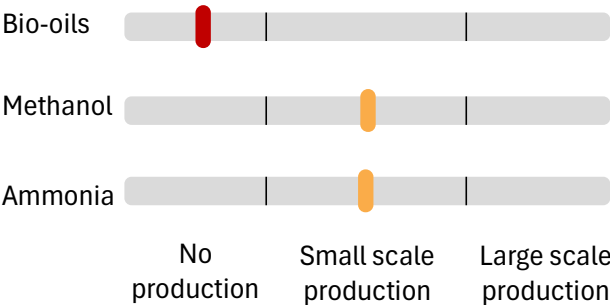


Comments:

DK-UK green shipping corridor in pre-feasibility study
Port of Rønne involved with European green corridor in Northern Europe and the Baltic Sea

Source: Mission Innovation – Green Shipping Corridors tracker¹²⁶

KPI 9: Domestic production of green fuels for maritime uses

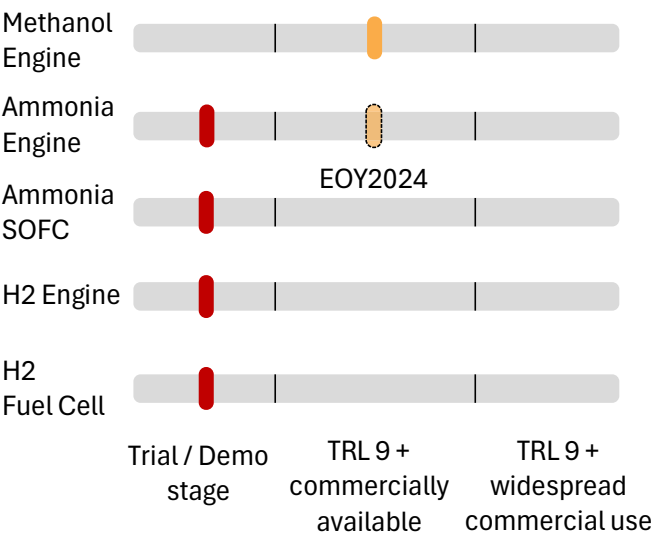


Comments:

- E-Methanol production planned at European Energy Kassø for 2024
- Ammonia production at Skovgaard Energy / REDDAP in Ramme slated for operation in 2024 (offtake for fertilizer of marine uses)
- CIP Høst to produce hydrogen and ammonia
- No current production of bio-oils for maritime use

Source: Project websites

KPI 10: Readiness of Engine / Fuel Cell technologies



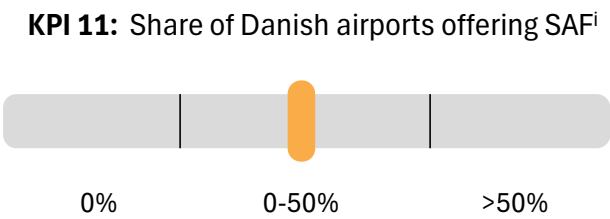
Comments:

- Dual-fuel methanol engines seeing use on Maersk ships (three ships enabled as of Aug 2024)
- Multiple engine OEMs offering methanol engines / retrofits (Europe and Asia)
- MAN ammonia engine advancing quickly, projected TRL 9 and commercial use in late 2024/2025
- Ammonia SOFC is still at TRL4-5
- H2 combustion engine for ships TRL4-5
- H2 Fuel cell for maritime purposes is at TRL 6-8

Source: Project websites, ETP Clean technology guide¹²⁷

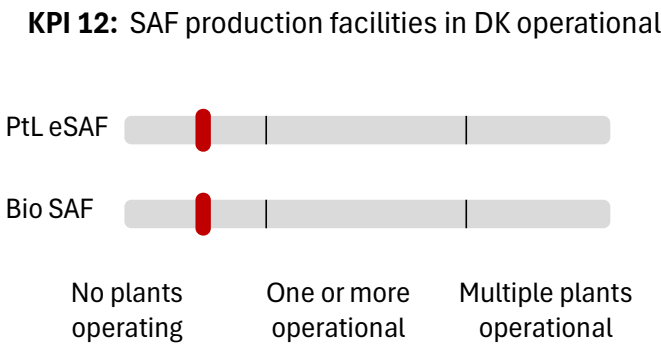
Aviation Fuels KPIs

Progress metrics for aviation fuels and associated technologies



Comments:
Four airports currently have incorporated SAF:
Sønderborg first to offer SAF in 2021
Billund began offering SAF in 2022
CPH began offering SAF in 2023
AAL airport first delivery in 2023 – part of the Norwegian Air AAL-CPH to
Most of the SAF is supplied by DCC and Shell aviation
Source: Projects websites, news announcements

i. Danish airports considered include CPH, BLL, AAL, AAR, RNN, EBJ, SGD, RKE, ODE. Count does not include smaller regional or recreational airports.



Comments:
Multiple PtL SAF plants announced:
MeSAF, FrontFuel, Arcadia efuels, European Energy Padborg
First commercial operation date slated for 2026 (Arcadia)
No current bioSAF plants (HEFA/HVO)
SAF used today in Danish airports is imported
Source: Project websites



Appendix 1. Technology Readiness Levels

Technology Readiness Levels (TRLs) are a standardized metric used to assess the maturity of a technology, ranging from initial research stages (TRL 1) to full market deployment (TRL 9). Including TRLs allows stakeholders to gauge the current maturity of green fuels technologies, understand the remaining challenges, and prioritize investments in research and development across production, distribution and storage, and end-use parts of the value chain.

The **Commercial Readiness Index (CRI)** is a framework used to assess the commercial maturity of emerging technologies, measuring factors such as market confidence, value chain readiness, and

regulatory environment. It helps stakeholders gauge how close a technology is to full-scale commercialization and widespread adoption

Using an **integrated TRL and CRI scale provides a comprehensive assessment** of both the technological maturity and the market readiness of established or emerging technologies within green fuels. TRL's are from IEA ETP guide¹²⁷, CRI's are from Ramboll assessment (best estimate of commercialization).

Figure A1: Integrated TRL and CRI scale

| TRL: Technology Readiness Level ⁱ | | | CRI: Commercial Readiness Index ⁱⁱ | |
|--|---|---|---|---|
| Deployment | Actual System Proven in Operational Environment | 9 | 6 | Bankable asset class |
| | System Complete and Qualified | 8 | 5 | Widespread development and market competition |
| | System Prototype Demonstration in Operational Environment | 7 | 4 | Multiple commercial applications |
| Development | Technology Demonstrated in Relevant Environment | 6 | 3 | Commercial scale up |
| | Technology Validated in Relevant Environment | 5 | 2 | Commercial trial, small scale |
| | Technology Validated in Lab | 4 | 1 | Hypothetical commercial proposition |
| Research | Experimental Validation in lab | 3 | | |
| | Technology Concept Formulated | 2 | | |
| | Basic Principles Observed | 1 | | |

i. TRL scale shown adopted from the EU Horizon 2020 framework
 ii. The CRI is a novel framework developed by the Australian Renewable Energy Agency (ARENA)

H2 Electrolyzer Technologies

| Technology | TRL | CRI |
|---|-----|-----|
| Alkaline electrolyzer (AE) | 9 | 3 |
| Proton exchange membrane electrolyzer (PEM) | 9 | 2 |
| Anion exchange membrane electrolyzer (AEM) | 6 | 1 |
| Solid oxide electrolyzer cell (SOEC) | 8 | 1 |

Other H2 Production technologies

| Technology | TRL | CRI |
|--|-----|-----|
| Steam methane reforming + CCUS (blue H2) | 9 | 3 |
| Biomass waste gasification | 5 | 1 |
| Biomass waste pyrolysis (dry) | 7-9 | 1 |
| Biomass waste pyrolysis (wet) | 4-6 | 1 |
| Natural hydrogen extraction | 5 | 1 |
| Photocatalytic water splitting | 5 | 1 |
| Electric-powered steam reforming | 4 | 1 |

Midstream hydrogen (storage and distribution) technologies

| Technology | | TRL | CRI |
|--------------|---|-----|-----|
| Storage | Hydrogen pressure vessel storage | 9 | 4 |
| | Liquid hydrogen storage tank | 9 | 2 |
| | Metal hybrids storage | 4 | 1 |
| | Aquifer storage | 3 | 1 |
| | Depleted gas fields storage | 4 | 1 |
| | Salt cavern storage | 9 | 2 |
| Processes | Hydrogen liquefaction | 9 | 3 |
| | Liquid organic hydrogen carriers (LOHC) | 7 | 1 |
| | Ammonia cracking | 4 | 1 |
| Distribution | Hydrogen Truck transport | 9 | 5 |
| | Liquid organic hydrogen (LOHC) carrier tanker | 9 | 5 |
| | Liquified hydrogen tanker | 7 | 1 |
| | Hydrogen blending into natural gas network | 7 | 1 |
| | New hydrogen pipelines | 9 | 2 |
| | Repurposed natural gas pipelines | 8 | 1 |
| | Hydrogen turbo compressors | 6 | 1 |
| | Hydrogen bunkering | 4 | 1 |

Hydrogen Technologies

Downstream hydrogen technologies (end-use)

| Technology | | TRL | CRI |
|------------|--|-----|-----|
| Industrial | Hydrogen low temperature heating | 9 | 4 |
| | Hydrogen high temperature heating | 7 | 2 |
| | Direct reduction of iron (DRI) based on 100% H ₂ | 6 | 2 |
| | Direct reduction of iron (DRI) based on H ₂ /NG blend | 8 | 3 |
| Road | Hydrogen fueling (low flow rate) | 9 | 5 |
| | Hydrogen fueling (high flow rate) | 4 | 1 |
| | Hydrogen tank (road vehicles) | 9 | 3 |
| | Hydrogen fuel cell electric vehicle (light) | 9 | 4 |
| | Hydrogen fuel cell bus | 9 | 3 |
| | Hydrogen fuel cell truck | 8 | 2 |
| | Hydrogen combustion (road) vehicles | 6-7 | 2 |
| Ship | Hydrogen fuel cell ship | 6-8 | 1 |
| | Hydrogen combustion engine (ship) | 4-5 | 1 |
| Aviation | Hydrogen storage tank (aircraft) | 4 | 1 |
| | Direct hydrogen combustion in jet engine | 3-4 | 1 |
| | Hybrid fuel cell propulsion system – jet engine | 3-4 | 1 |
| | Hydrogen fuel cell propulsion system | 6-7 | 1 |

Biofuels Technologies

Biofuels production Technologies

| Technology | | TRL | CRI |
|--------------------|---|-----|-----|
| Biogas/Biomethane | Anaerobic digestion (biomethane) | 9 | 6 |
| | Anaerobic digestion and biological methanation with H ₂ (biomethane) | 7 | 1 |
| | Anaerobic digestion and catalytic methanation with H ₂ (biomethane) | 8 | 2 |
| | Biomass gasification - small scale (biomethane) (dry) | 9 | 2 |
| | Biomass gasification - small scale (biomethane) (wet) | 4-6 | 1 |
| | Biomass gasification and catalytic methanation (biomethane) | 7 | 2 |
| | Biomethanisation of syngas | 3-5 | 1 |
| Biodiesel/Bio-oils | Alcohol-to-jet | 7-8 | 2 |
| | FAME production | 9 | 4 |
| | Gasification with Fischer-Tropsch (FT) | 7-8 | 2 |
| | Gasification and hydrogen enhancement and Fischer-Tropsch (FT) | 5 | 1 |
| | HVO / HEFA production | 9 | 6 |
| | Hydrothermal liquefaction (HTL) and upgrading (biodiesel) | 4 | 1 |
| | Pyrolysis and upgrading (biodiesel) | 7 | 2 |
| | Bio-oils from NCS (Non-Conventional Species) or halophytes | 3-5 | 1 |

Biofuels Technologies

Downstream biofuels technologies (End-use)

| Technology | | TRL | CRI |
|----------------|--|-----|-----|
| Biofuels/other | Synthetic Iso-Paraffins “sugars to hydrocarbons” route | 7 | 1 |
| | Hydrothermal liquefaction (HTL) and upgrading of micro-algae | 3-4 | 1 |
| | Micro-algae hydrotreating (bio-oils) | 4 | 1 |
| | Enzymatic fermentation (lignocellulosic bioethanol) | 8 | 3 |
| | Production of Biomass-Derived Light Olefins | 3-5 | 1 |

Downstream biofuels technologies (End-use)

| Technology | TRL | CRI |
|---------------------------------------|-----|-----|
| Compressed biomethane truck transport | 9 | 3-4 |
| Liquified biomethane truck transport | 9 | 3-4 |
| Ethanol/Methanol-fueled diesel engine | 9 | 3-4 |
| Biomethane fueled ship engine | 9 | 3-4 |

Efuels technologies

Efuels production technologies

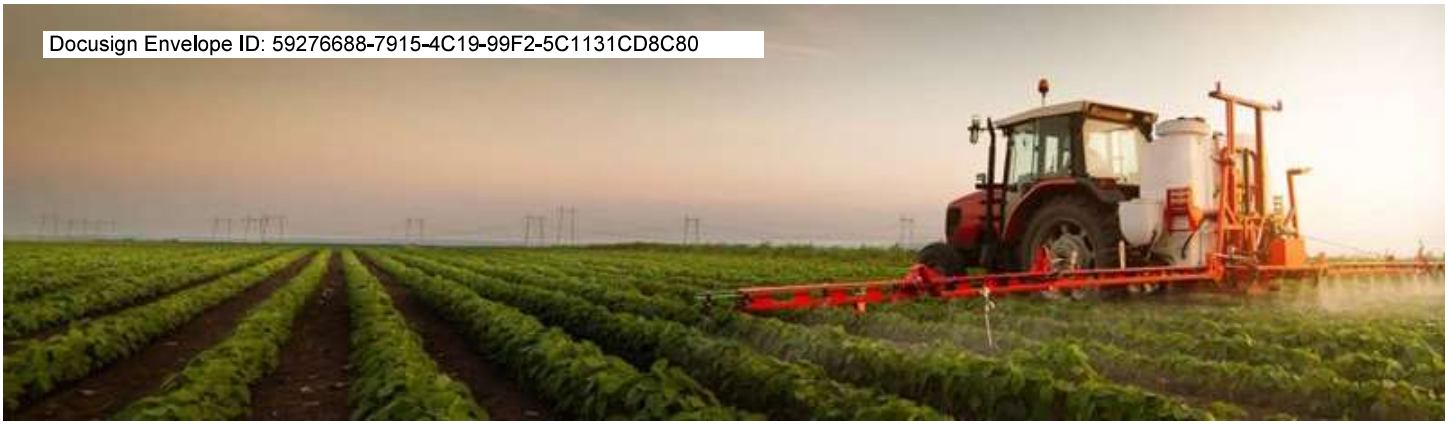
| Technology | TRL | CRI |
|---|-----|-----|
| Chemical methanation via catalyst (e-methane) | 8-9 | 2 |
| Methanol synthesis via catalytic hydrogenation | 8 | 2 |
| Fischer-Tropsch using CO ₂ reduction via reverse water gas shift (RWGS) reaction | 6 | 2 |
| Ammonia synthesis through Haber Bosch process | 9 | 6 |
| CO ₂ + Hydrogen to CH ₄ to syngas to Fischer-Tropsch | 4-7 | 1 |

Midstream efuel (storage and distribution) technologies

| Technology | TRL | CRI |
|--------------------|-----|-----|
| Ammonia storage | 9 | 6 |
| Ammonia bunkering | 9 | 6 |
| Ammonia cracking | 4 | 2 |
| Methanol storage | 9 | 6 |
| Methanol bunkering | 9 | 6 |

Downstream efuel technologies maritime and aviation




| Technology | TRL | CRI |
|---|-----|-----|
| Ammonia fueled ship engine | 6 | 1 |
| Ammonia solid oxide fuel cell | 4-5 | 1 |
| Methanol fueled ship engine | 9 | 3 |
| Methanol fuel cell electric ships | 6 | 1 |
| E-kerosene for use as SAF in jet engine | 9 | 4-5 |



Links to other Innomissions and partnerships



Advancing green fuels to meet the national climate goals is one of four Danish Innomissions and should not be viewed standalone as green fuel production intersects with several key topics such as land use and sustainable agriculture, the use of CO₂ in the production of efuels, and using waste plastics for the production of oils via chemical recycling, among others. These overlaps highlight the necessity of a coordinated approach across multiple missions to effectively drive progress towards Denmark's climate objectives.

| Innomission | Focus area | Overlapping topics |
|--|---|--|
| INNO-CCUS  | Carbon capture, utilization, and storage technologies | <ul style="list-style-type: none"> • Biogenic CO₂ utilization • CO₂ transport and storage infrastructure for efuels production • Advancement of DAC technology for eventual efuel usage |
| AgriFoodTure  | Sustainable agriculture and food production | <ul style="list-style-type: none"> • Use of agricultural waste for biofuel production • Sustainable land use and bio feedstock management |
| Trace  | Circular economy initiatives, focusing on plastics and textiles | <ul style="list-style-type: none"> • Chemical and biological recycling for oil recovery (e.g. pyrolysis, HTL) for plastic waste |

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