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Analysis of the Market Potential for a Hydrogen and Carbon Dioxide Infrastructure on Lolland-Falster

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Analysis of the Market Potential for a Hydrogen and Carbon Dioxide Infrastructure on Lolland-Falster

Pre-Feasibility Study

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1. EXECUTIVE SUMMARY

1.1 Formål med opgaven

Opgaven undersøger potentialet for grøn infrastrukturudvikling på Lolland-Falster med fokus på kuldioxid- og brintinfrastruktur. Regionen har store muligheder inden for Power-to-X (PtX), CO2-lagring og grøn industri, baseret på vedvarende energi, lokale biomasseressourcer og eksisterende infrastruktur, hvilket tiltrækker grønne virksomheder.

Analysen omfatter en markedsvurdering af potentialet for brint- og CO2-infrastruktur, baseret på planlagte PtX- og CCSU-projekter i regionen. Der fokuseres på synergier mellem lokale CO2-kilder og brintproduktion for at foreslå strategier for infrastrukturudvikling, der støtter nuværende og fremtidige forretningsmodeller.

Der udvikles scenarier for etablering af CO2- og brintinfrastruktur på Lolland-Falster, især omkring Rødbyhavn og Nakskov, med integration i både national og international infrastruktur. Dette inkluderer vurderinger af kapacitet, potentielle ubalancer og integration med eksisterende energisystemer. Den teknisk-økonomisk analyse vurderer investeringer i forskellige infrastrukturscenarier, herunder udviklingsomkostninger, kapitaludgifter (CAPEX), driftsudgifter (OPEX) og økonomisk gennemførlighed.

Analysens hovedformål er at skabe en vidensbase for strategiske beslutninger om grøn infrastruktur på Lolland-Falster samt fremme investeringer i vedvarende energi. Konklusionen indeholder anbefalinger til udvikling af energiinfrastruktur og -markedet på Lolland-Falster for at fremme vækst i vedvarende energi og tiltrække industri og PtX-aktører.

1.2 Markedsafdækning

Markedsafdækningen identificerer de virksomheder, der er relevante for udviklingen af Lolland-Falsters fremtidige energiinfrastruktur, og giver indsigt i forventede ændringer i energiproduktion, -forbrug og CO2-udledninger fra punktkilder. Der er allerede udviklere af vedvarende energi, CO2-punktkilder, netværksoperatører til stede på Lolland-Falster, hvilket skaber potentiale for lokale PtX- og CCUS-værdikæder.

Hvis de planlagte vedvarende energiprojekter gennemføres, vil elproduktionskapaciteten på Lolland-Falster stige fire gange til over 4,500 MW inden for det næste årti. Dette er nødvendigt for at understøtte de fire planlagte PtX-projekter, som kræver næsten 1,500 MW kapacitet. PtX-projekterne er primært placeret på Lolland, sandsynligvis på grund af tilgængeligheden af CO2 og vedvarende energi.

Lolland-Falster har i øjeblikket 500 kton CO2 til rådighed, hvilket forventes at falde til ca. 300 kton i 2032 og frem. Hele mængden er biogen, men CO2 skal indfanges fra en blanding af biogas og industrielle kilder, hvilket kan være omkostningstungt. Ser man kun på biogas, er der 180 kton CO2 til rådighed, nok til ét af de planlagte metanolanlæg, som kræver 140 kton biogen CO2.

Der er potentiale for CO2-lagring i Rødby undergrunden, som Carbon Cuts i øjeblikket undersøger. Hvis et CO2-lager udvikles, vil der være behov for havne- og transportinfrastruktur, der også kan understøtte andre anvendelser (CCU).

Selvom der endnu ikke er planlagt rørinfrastruktur til brint på Lolland-Falster, kan dette blive en del af anden fase af den europæiske brint-backbone i 2040, hvilket vil åbne adgang til internationale markeder som Tyskland. Den lange udsigt til international brintinfrastruktur kan gøre, at man bør satse på andre PtX produkter såsom metanol eller alternativt ammoniak.

Tre scenarier er udarbejdet til den teknisk-økonomiske analyse:

- et konservativt scenarie, hvor kun solcelleprojekter udvikles, og vindkraft ikke fornyes;
- et udviklingsscenarie, hvor elproduktionskapaciteten stiger til over 4,500 MW baseret på planlagte sol- og vindprojekter på land;
- og et udvidet til udvikoingsscenariet, der inkluderer "åben dør"-projekter for offshore-vind omkring Lolland-Falster.

Grafen herunder viser den forventede udvikling i elproduktion og -forbrug for udviklingsscenariet. For at gøre PtX økonomisk bæredygtigt skal udviklingsscenariet som minimum realiseres, da mindre tilgængelig energi vil gøre PtX urentabelt. På figuren herunder vises energiproduktion og elproduktionskapacitet for udviklingsscenariet over de næste tyve år. Grundet forskellen imellem forventet produktion og forbrug, vil det være nødvendigt at installere mere vedvarende energi kapacitet end PtX forbrugskapacitet.

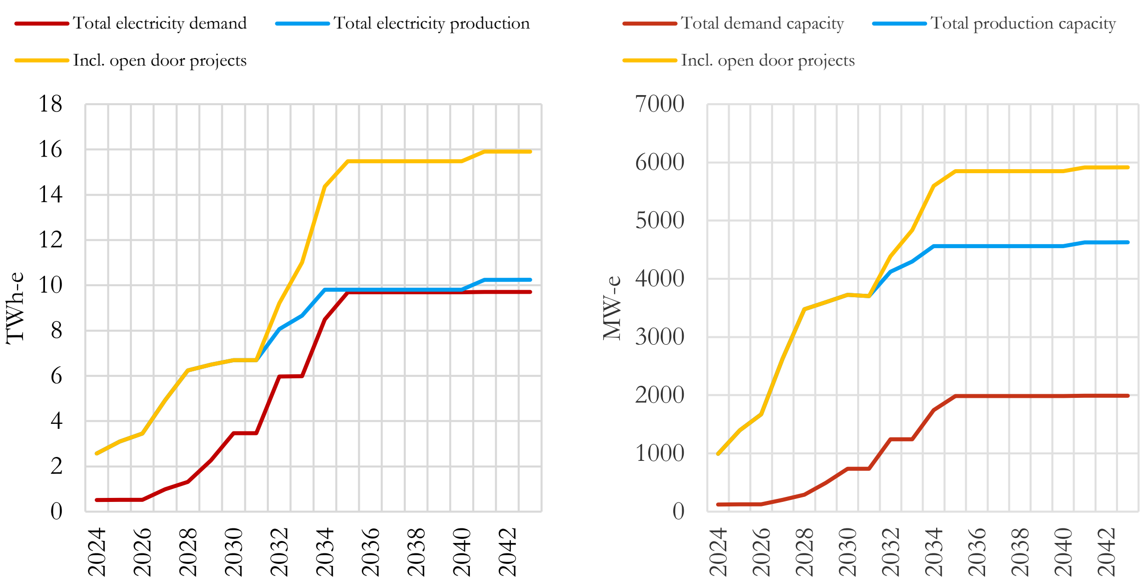


Figure 1 Elforbrug og produktion over tid på årsbasis for udviklingsscenariet (TWh og MW)

Source: Rambøll analyse; Gate21 Ressourcekortlægning (2023); Sweco Energiøer på Lolland (2022)

PtX-projekter, der producerer kulbrinter som e-metanol eller e-metan, kræver biogen CO2 for at klassificere e-brændstoffer som vedvarende brændstoffer af ikke-biologisk oprindelse (RFNBO) i henhold til EU's direktiv for vedvarende energi (RED). Fra 2026 vil flere biogasanlæg på Lolland-Falster opgradere biogas til gasnettet. Ifølge Biogas Danmark omfatter disse projekter et eksisterende biogasanlæg i Kettinge og tre nye projekter på Lolland, mens projektet på Falster stadig er usikkert, men dog medtaget i denne analyse.

CO2 fra fjernvarme stammer fra små biomassekedler, og den eneste tilgængelige CO2 til fangst vil være fra biogasanlæg, sukkerfabrikker og ny industri. I dag er der omkring 500 kton CO2 tilgængelig fra fjernvarme og industri, men dette forventes at falde til ca. 300 kton pga. færre driftstimer og nedlæggelse af anlæg som affaldsforbrændingsanlægget i Nykøbing.

CO2-forbruget på metanolanlæg forventes at være omkring 300 kton årligt. Da der er forskel imellem CO2-produktion og forbrug, kræves lagring for at balancere dette. De primære industrielle CO2-kilder er sukkerfabrikkerne i Nakskov og Nykøbing, som kun opererer fra september til januar. Ny industriel aktivitet i Nakskov kan tilføre yderligere 30 kton CO2 fra 2030, men dette er ikke inkluderet i den nuværende vurdering.

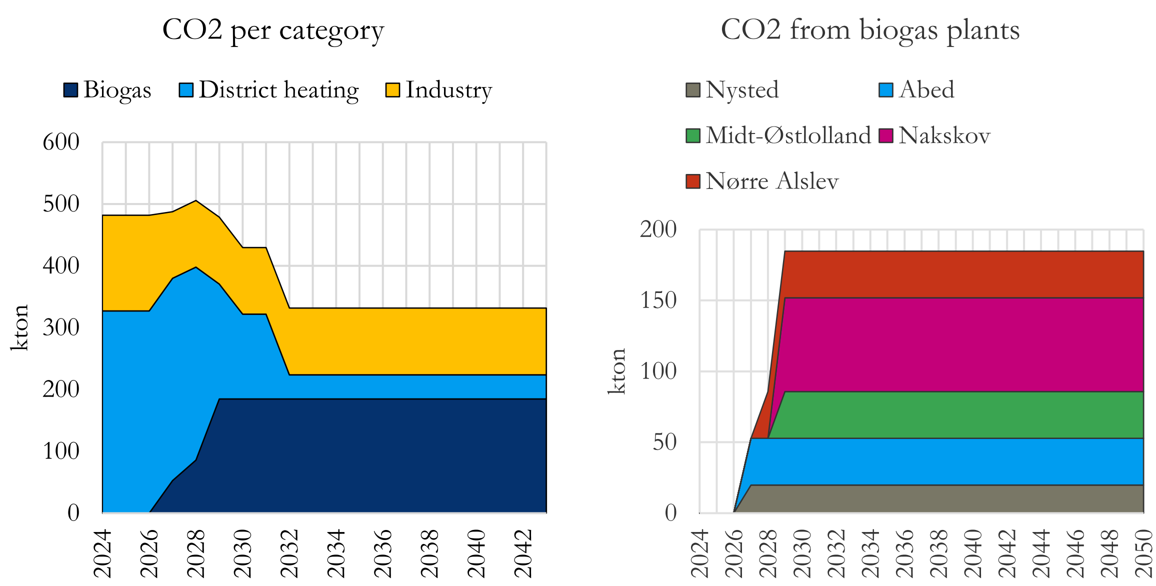


Figure 2 Tilgængelig CO2 per kilde på årsbasis (kton)

Source: Rambøll analyse

1.3 Rørført infrastruktur

CO2-netværket forbinder CO2-punktkilder som biogasanlæg og sukkerfabrikker med metanolfabrikker og underjordiske lagre ved Rødbyhavn til import, korttidslagring og permanent lagring. Lageret ved Rødbyhavn er centralt for netværkets økonomi og muliggør bufferlagring af biogen CO2, der er nødvendig for grøn metanolproduktion.

Hvis underjordisk lagring ved Rødbyhavn ikke er mulig, kan alternative løsninger som CO2-udveksling eller lokal CO2-fangst anvendes. I så fald kræves lokal lagringskapacitet, og transport forventes at ske med lastbil i stedet for rørledninger. CO2 fra biogasanlæg og sukkerfabrikker kan transporteres gennem CO2-rørledninger til PtX-anlæg, og overskydende CO2 kan lagres underjordisk. Kortet viser en mulig rute for et regionalt CO2-system.

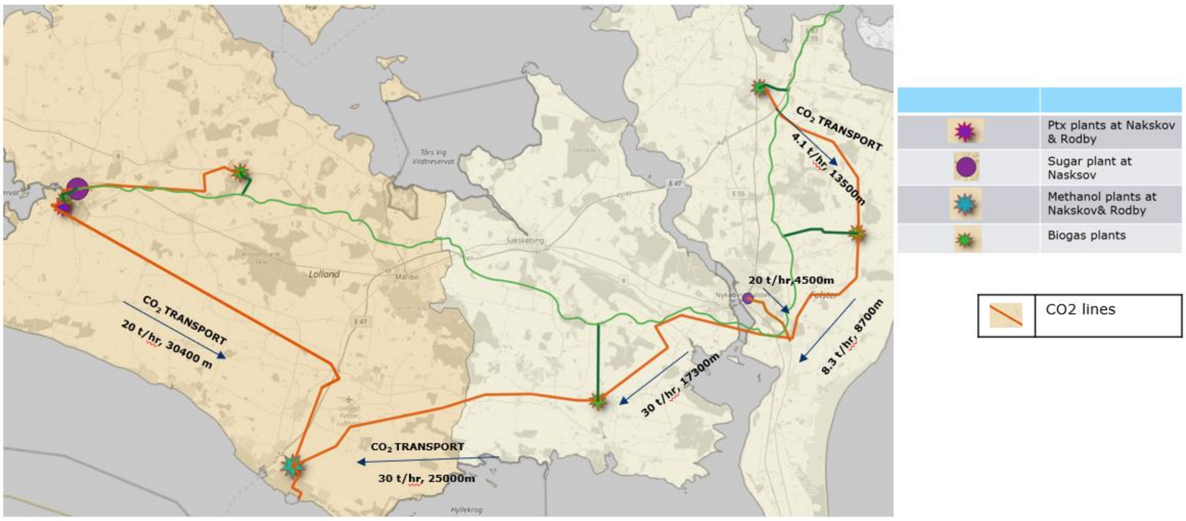


Figure 3 Carbon dioxide pipeline network layout

Source: Ramboll

I nogle scenarier vurderer vi, om det er mere fordelagtigt at producere opgraderet biometan på biogasanlæggene frem for at bruge CO2´en til metanolproduktion. Vi antager, at biogassen opgraderes til standarden for injektion i den nye naturgasledning.

Den stigende interesse for biogasanlæg på Lolland-Falster indikerer, at området er velegnet til sådanne projekter, understøttet af lokale landbrugsressourcer og den nye gasledning. Rørledningen, der oprindeligt var beregnet til sukkerfabrikker, kan dermed skabe nye forretningsmuligheder og vækst i området.

Et regionalt brintnetværk kan få forskellige funktioner afhængigt af fremtidig efterspørgsel. I øjeblikket er efterspørgslen lav, så netværkets succes afhænger af fremtidige behov, f.eks. til biometan produktion på biogasanlæg eller brint til metanolfabrikker.

Hvis efterspørgslen stiger, kan et brintnetværk producere brint nær vedvarende energikilder og distribuere det til biogasanlæg og metanolproduktion. Det kan også øge lokal efterspørgsel på elektricitet og reducere flaskehalse i elnettet. Underjordisk brintlagring i saltstrukturer, som muligvis kan etableres ved Øllebølle på Lolland-Falster, kan understøtte produktionen af vedvarende brint. Der er dog behov for mere forskning i, hvordan brintlagring i kaverner kan påvirke CO2-lagring og grundvandsforskydning.

En nøglefaktor er brintnetværkets konkurrence med udvidelsen af elnettet. Det undersøges i analysen om det er mest fordelagtigt at etablere et brintnetværk eller fortsat udbygge elinfrastrukturen på Lolland-Falster.

1.4 Økonomisk analyse

I den økonomiske analyse sammenlignes seks scenarier med basis-scenariet, som kun baserer sig på elnettet. De seks scenarier er:

- Basis-scenarie: Kun elnet udvikling og ingen brint- eller CO2 netværk. Dette fungerer som sammenligningsgrundlag.
- Sc. 1.1: Regionalt CO_2-netværk, hvor CO_2 opsamles fra punktkilder (f.eks. sukkerfabrikker, biogasanlæg) og transporteres til underjordiske lagre og importfaciliteter i Rødbyhavn.
- Sc. 1.2: Regional CO_2-transport med lastbiler, hvor CO_2 opsamles fra punktkilder og transporteres til underjordiske lagre og importfaciliteter i Rødbyhavn.
- Sc. 2.1: Regionalt brintnetværk med lagring i kaverner til lokal metanolproduktion og biometanisering. CO_2 importeres til metanolanlægget i Nakskov via Rødbyhavn, men resten af CO_2-netværket er ikke inkluderet.
- Sc. 2.2: Decentral biometanproduktion via elnettet, hvor brintnetværket udelukkes, og brint produceres lokalt på biogasanlæg og metanolanlæg.
- Sc. 3.1: Fælles brint- og CO_2-netværk, hvor CO_2 opsamles på biogasanlæg og føres ind i CO_2-netværket. Brintnetværket er kun forbundet til metanolanlæg og placerer elektrolyseenheder optimalt i forhold til vedvarende energiproduktion.
- Sc. 3.2: Internationalt brintnetværk, der udvider scenarie 3.1 ved at inkludere brintanlæg fra Copenhagen Energy og en forbindelse til den europæiske brintbackbone, som forbinder Lolland-Falster med Sjælland og Tyskland for eksport.

Disse scenarier vurderer forskellige udviklingsveje for Lolland-Falster under de tre scenarier for udvikling af vedvarende energi, som beskrevet i markedsafdækningen.

1.4.1 Kuldioxidnetværk

Både rørlednings- og lastbiltransport kræver lokale procesanlæg for at sikre, at driften opfylder specifikke krav. Analysen af CO_2-transportomkostningerne mellem rørledninger og lastbiler viser følgende resultater afhængigt af geografien:

- Vestlolland: Hvis både CO_2-lageret i Rødbyhavn og metanolanlægget i Nakskov er i drift, er en rørforbindelse mellem de to omkostningseffektiv. Denne rørledning kan også forbinde sukkerfabrikken og biogasanlægget i Nakskov til det samme netværk.
- Østlolland og Falster: Her er rørinfrastrukturen mindre økonomisk fordelagtig end lastbiltransport, når CO_2 skal transporteres fra sukkerfabrikker og biogasanlæg til lageret i Rødbyhavn og eventuelt metanolanlægget.
- Samlet netværk: Hvis alle CO_2-forbrugs- og forsyningspunkter på Lolland-Falster er forbundet, er rørinfrastruktur mere økonomisk end lastbiltransport. En mulig løsning kan være at etablere en rørinfrastruktur på Vestlolland og bruge lastbiltransport på Østlolland og Falster.

CO2-fangstomkostningerne for punktkilder i netværket vurderes ligesom transportomkostningerne. I modsætning til transport varierer fangstomkostningerne ikke væsentligt mellem øst og vest ift. Rødbyhavn. Omkostningerne baseres på procesanlæg ved sukkerfabrikker, mens kun ekstraudgifter til netværksdrift indgår for biogasanlæg, da CO2 her allerede fjernes under opgradering.

CO2 kan generelt fanges billigere fra biogasanlæg end fra sukkerfabrikker. Fangstomkostninger bør dog sammenlignes med andre muligheder fro import fra kraftværker eller store industrianlæg i Sverige, Danmark eller Tyskland samt transport via CO2-terminalen i Rødbyhavn.

Table 1 Sammenligning mellem CO2-rørledninger og lastbiltransport

Område	Lokation	Enhed	CO2 rør	CO2 lastbil
Vest Lolland	Rødbyhavn – Nakskov (kun methanol anlæg)	EUR / ton CO2	19	42
	Rødbyhavn – Nakskov (alle)	EUR / ton CO2	15	45
	Rødbyhavn-Nakskov-Abed	EUR / ton CO2	16	45
	Nakskov-Abed	EUR / ton CO2	18	38
Øst Lolland og Falster	Rødbyhavn-Nysted	EUR / ton CO2	69	38
	Rødbyhavn-Nysted-Nykøbing	EUR / ton CO2	40	40
	Rødbyhavn-All	EUR / ton CO2	35	39
Samlet ntværk		EUR / ton CO2	**23**	**43**
Kombination (Rørledninger på Vestlolland og lastbiler på Østlolland og Falster)		EUR / ton CO2		**26**

Table 2 Sammenligning af omkostninger ved CO2-fangst

Område	Lokation	Enhed	CO2 fangst
Vest Lolland	Sukkerfbrik Nakskov	EUR / ton CO2	92
	Abed biogas	EUR / ton CO2	30
	Nakskov biogas	EUR / ton CO2	23
Øst Lolland og Falster	Nysted biogas	EUR / ton CO2	35
	Sukkerfabrik Nykøbing	EUR / ton CO2	92
	Midt-Falster biogas	EUR / ton CO2	31
	Nørre Alslev biogas	EUR / ton CO2	31
Samlet		EUR / ton CO2	**52**

Den samlede omkostning for transport og fangst af CO2 på Lolland-Falster findes ved at lægge tallene for de to respektive dele sammen.

1.4.2 Brintnetværk

Det regionale brintnetværk adskiller sig fra CO2-netværket og tilbyder fordele som balancering af vedvarende energi via underjordisk lagring og line packing (ca. 100 MWh). Lokalt brintlagring kan også understøtte kontinuerlig metanolpriduktion.

En anden sammenligning er produktion af opgraderet biometan med lokalt eller centralt produceret brint, hvilket kræver central elektrolyse og elnetforstærkning. Udvikling af både CO2- og brintnetværk giver fleksibilitet mellem opgraderet biometan-produktion eller CO2-fangst til metanol baseret på markedspriser.

Omkostningerne ved brintproduktion vist på figuren herunder afspejler prisen ved rørledningens modtagelsespunkt eller elnetbaseret produktion og inkluderer ikke bredere energisystemperspektiver. Omkostningerne inkluderer alle udgifter til elektricitet og brinttransport.

Figuren viser, at brint kan produceres på Lolland-Falster, hvor omkostninger ved elnet og brintnetværk er relativt ens. Dog kan brintnetværkets systemintegration være mere fordelagtig.

Sammenlignet med havvindprojekter (typisk 3,5 EUR/kg H2) er produktionsomkostningerne lavere her, da billigere landvind- og solanlæg kan udnyttes hen over årstiderne.

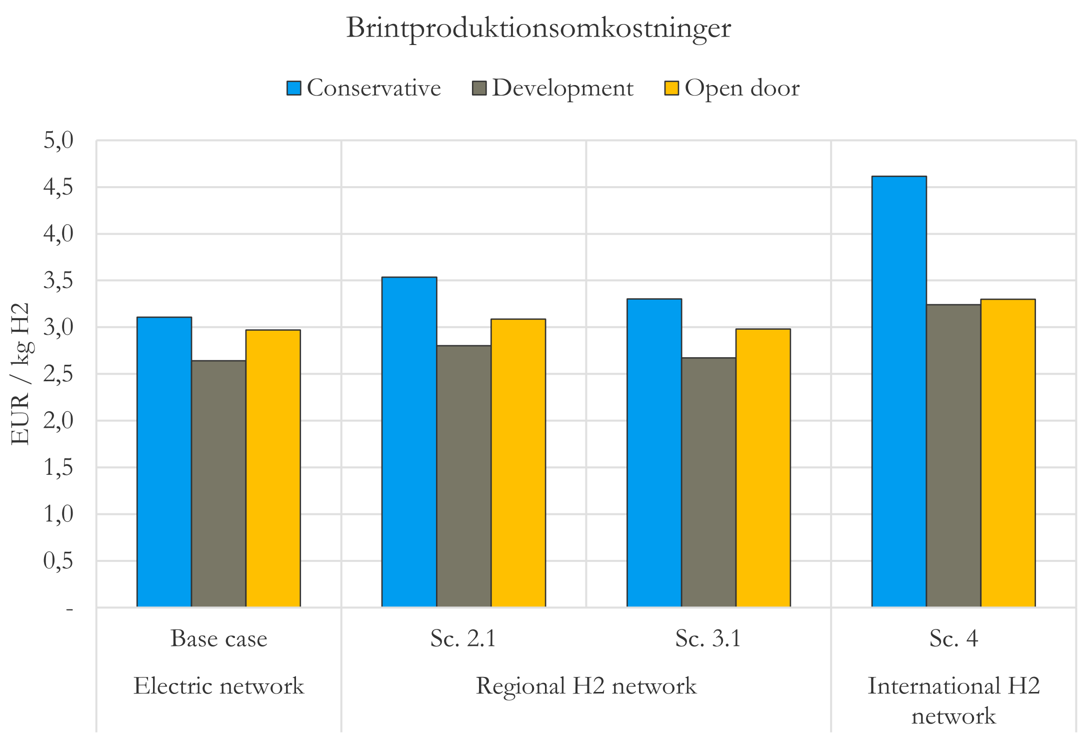


Figure 4 Sammenligning af omkostningerne ved produktion af brint mellem scenarier

Source: Ramboll

1.4.3 Samlet scenarieanalyse

Sammenligningen af scenarier udføres ved at evaluere de årlige omkostninger og indtægter i form af Nettoværdi (NPV) på tværs af følgende fem punkter:

- Investering: Dette omfatter alle investeringer i energiinfrastruktur som vedvarende energi, biogasanlæg, elektrolyse, metanolsynthese osv.
- Drift og vedligeholdelse: Dette inkluderer alle omkostninger forbundet med drift og vedligeholdelse af energiinfrastrukturen.
- CO2-kreditter og lagring: Dette dækker indtægter og udgifter forbundet med udveksling af CO2 til og fra Lolland-Falster. Underjordisk CO2-lagring har fordel af import af store mængder CO2 årligt. Når CO2 fanges og resulterer i en netto positiv årlig mængde, akkrediteres den som solgt på det internationale marked som CO2-kreditter.
- El-salg: Denne værdi afhænger af mængden af elektricitet, der eksporteres til Sjælland fra Lolland-Falster. Når mere PtX-produktion udvikles, falder indtægterne fra el-salg. Desuden forventes markedsværdierne for el-eksport at falde i takt med udviklingen af mere vedvarende energi.
- Brændstofsalg: Dette omfatter salg af metan, brint og metanol.

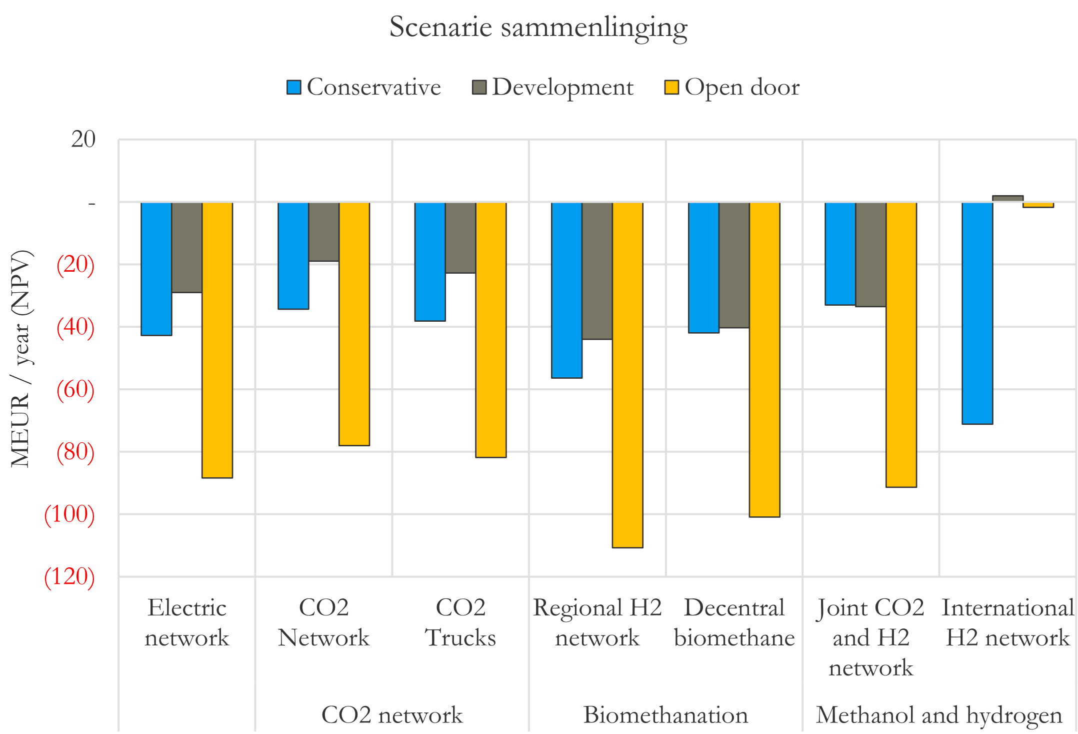


Figure 5 Scenariesammenligning

Source: Ramboll

Resultaterne for alle scenarier viser en negativ NPV, undtagen ved tilslutning til Hydrogen Backbone. Disse resultater er dog følsomme over for el- og brændstofpriser.

Flere konklusioner kan drages fra de forskellige scenarier:

- Konservativt scenario: Hvis udviklingen af vedvarende energi stopper, er det bedst at bevare den eksisterende el-infrastruktur og ikke investere i brintnetværk, men overveje CO2-infrastruktur, hvis CO2-lagring, metanolanlæg og CO2-opsamling etableres. CO2-systemets økonomi er mindre følsom over for vedvarende energikilder end brintsystemet.

- Udviklingsscenario: Her kan det være fordelagtigt at etablere rørledninger frem for kun at bruge el-infrastruktur. Valget mellem brint- og CO2-rørledninger afhænger af, om e-metanproduktion eller CO2-udnyttelse i metanolanlæg er mest fordelagtig. Da elmarkedet kan blive overmættet, kan eksport af elektricitet blive mindre rentabel, hvilket gør et brintnetværk mere fordelagtigt. I udviklingsscenariet er den bedste strategi at etablere et CO2-netværk til at opsamle CO2 til metanolproduktion og lagring. Et regionalt brintnetværk, der forbinder vedvarende energikilder med metanolanlæg, kan også være fordelagtigt, især ved senere tilslutning til Hydrogen Backbone eller udvidelse af metanolsyntesekapaciteten.

- Udviklingsscenario med åben dør projekter: Ved inddragelse af åben dør havvind er det optimalt at udvikle en brintinfrastruktur, både regionalt og til det internationale hydrogen backbone. Hvis det ikke er muligt, kan kapaciteten til metanolsyntese udvides for at eksportere energien som metanol. Et alternativ kan være ammoniak i stedet.

På tværs af scenarierne viser analysen, at udvikling af CO2-infrastruktur, vedvarende energi og metanolproduktion er lovende. CO2-rørledninger fra biogasanlæg er ofte mere rentable end opgraderet biometan, dig afhængigt af certifikater og kreditmarkedet. Et regionalt brintnetværk med lagring er også mere omkostningseffektivt end elektrolyse på biogasanlæg. Brintnetværket er dog meget lig udvidelse at elsystemet omkostningsmæssigt, men kan have andre fordele i et bredere systempersketiv.

De årlige energisalg fra Lolland-Falster varierer fra 250 MEUR (konservativt) til 500 MEUR (med havvind), afhængigt af scenarier og brændstofpriser. At skabe eksportmuligheder ud over elektricitet tillader arbitragehandel med metanol eller brint ved lave elpriser. Overskudsvarme fra PtX-processer kan også dække fjernvarmebehovet, hvilket kræver integration af fjernvarme, termisk lagring og rørledninger, potentielt kombineret med CO2- og H2-rørledninger.

Samlet set ser vi, at ønsker man fortsat at udbygge den vedvarende energikapacitet over de næste årtier, vil det allerede nu være meget fornuftigt at se på anden anvendelse af elproduktionen end eksport med elkabler.

1.5 Anbefalinger og faseplan

Baseret på vores analyse har vi fremsat en række anbefalinger baseret på det potentielle fremtidige energisystem på Lolland-Falster, især vedrørende udviklingen af PtX og tilhørende netværk for kuldioxid og brint. Disse anbefalinger sigter mod at tilføre værdi til energisystemet og samfundet og sikre driften af energisystemet. De er tænkt som støtte til beslutningstagning både lokalt og i bredere national og international sammenhæng. Anbefalingerne fokuserer også på lokal udvikling, herunder jobskabelse og økonomisk vækst.

Med den forventede vækst i vedvarende energi på Lolland-Falster lægger denne rapport vægt på evaluering af rørledningsinfrastruktur for kuldioxid og brint i et fremtidsorienteret scenario med balanceret PtX-udvikling. De følgende anbefalinger gælder kun under forudsætning af, at vedvarende energi kontinuerligt udvikles. Hvis denne udvikling stoppes, er anbefalingen meget forenklet at fortsætte som hidtil.

Lokale anbefalinger

- **Fremme PtX-import og -eksportinfrastruktur ved Rødbyhavn:** Udvikling af CO2-importinfrastruktur ved havnen, underjordisk lagring og eksportinfrastruktur for metanol via skibe, og muligvis fremtidigt eksportinfrastruktur til Rostock med en brintrørledning.
- **Udvikle fælles kuldioxid og brint rørledningsinfrastruktur:** Økonomisk fordelagtig CO2-rørforbindelse mellem Rødbyhavn og Nakskov, mens et brintnetværk afhænger af vedvarende energi og fremtidsplaner for enten brint- eller metanoleksport.
- **Udvikle en detaljeret energisystemplan**: Sikre optimal beslutningstagning og undgå faldgruber såsom vedvarende energiprojekter uden netinfrastruktur eller PtX-anlæg uden nødvendige støttesystemer og elproduktionskapacitet.
- **Udvikle lokalt højtuddannet arbejdskraft:** Skabe en dygtig lokal arbejdsstyrke for energisektoren baseret på langsigtede energiplaner.
- **Anvende Lolland-Falster som et testcenter for ny energiteknologi:** Ideelt set for dansk og tysk energivirksomheder til at teste nye energiteknologier.
- **Integration af fjernvarme:** Udnytte overskudsvarme effektivt i samspil med PtX.
- **Kortlægge det samlede vedvarende energipotentiale på Lolland-Falster:** Vurdere totalt potentiale for vedvarende energiudvikling i området.
- **Energihandel:** Diversificere eksport ved at inkludere metan, metanol og brint og eventuelt ammoniak for at øge robustheden mod prisudsving.
- **Tiltrække industri:** Støtte udvidelsen af vedvarende energi i regionen ved at tiltrække industrier, der kræver billig grøn energi.

Nationale og internationale anbefalinger

- **Øge konkurrenceevnen ved at etablere Lolland-Falster som en separat elmarkedzone:** Lavere elpriser og overholdelse af EU's regler for grøn brændstofsproduktion for at tiltrække industri.
- **Blå brint**: Overveje implementering af grundlastproduktion af brint i en ny brint-infrastruktur via blå brint baseret på naturgas med CO2 fangst og lagring.
- **Grønt kreditsystem:** Et robust kreditsystem er nødvendigt for effektivt at regne bæredygtigheden af forskellige molekyler.
- **Udvikling af brint- og kuldioxidnetværk i Østdanmark:** Fokus på en integreret plan, der særligt omhandler brintinfrastrukturen.

- **Storskalaøkonomi:** Afbalanceret udbygning af både landbaseret- og havbaseret vindenergi er afgørende for at understøtte PtX initiativer.

Faseplan

1. **Energiplan:** Udarbejde en detaljeret, integreret energiplan for energiinfrastrukturen.
2. **Støtteordninger:** Udvikle lokalt forbrug af grøn elektricitet og incitamenter til produktion og brug af grønne brændstoffer samt tiltrækning af industri.
3. **Vedvarende energi og efterspørgsel:** Fokus på udvidelse af vedvarende energiprojekter og regionale elnets forbedringer.
4. **Import- og eksportinfrastruktur til PtX:** Prioritere infrastruktur ved Rødbyhavn.
5. K**uldioxid- og brintrørledningsinfrastruktur:** Etablere CO2 og brintinfrastruktur efter behov over hele Lolland-Falster.
6. **Integration med europæiske netværk:** Forbinde el-, brint- og kuldioxidinfrastrukturudvikling med bredere nationale og europæiske netværk.

2. MARKET ASSESSMENT

Power-to-X (PtX) value chains unlock the potential of renewable energy sources by converting electricity into energy carriers and chemical products that can replace fossil-based products. In a typical PtX value chain, hydrogen is produced through electrolysis for either direct use or conversion into derivatives such as e-ammonia (using nitrogen) or synthetic hydrocarbons like e-methanol, e-kerosene, and e-methane. The production of hydrocarbons requires carbon as a feedstock, which can be captured from industrial point sources or directly from the air through carbon capture technologies. The electricity can in turn come from renewable energy, why it is named e-fuel.

As such, PtX and CCUS are interlinked through key resource flows (see Figure 1) and the coupling of these processes can provide opportunities for synergies.

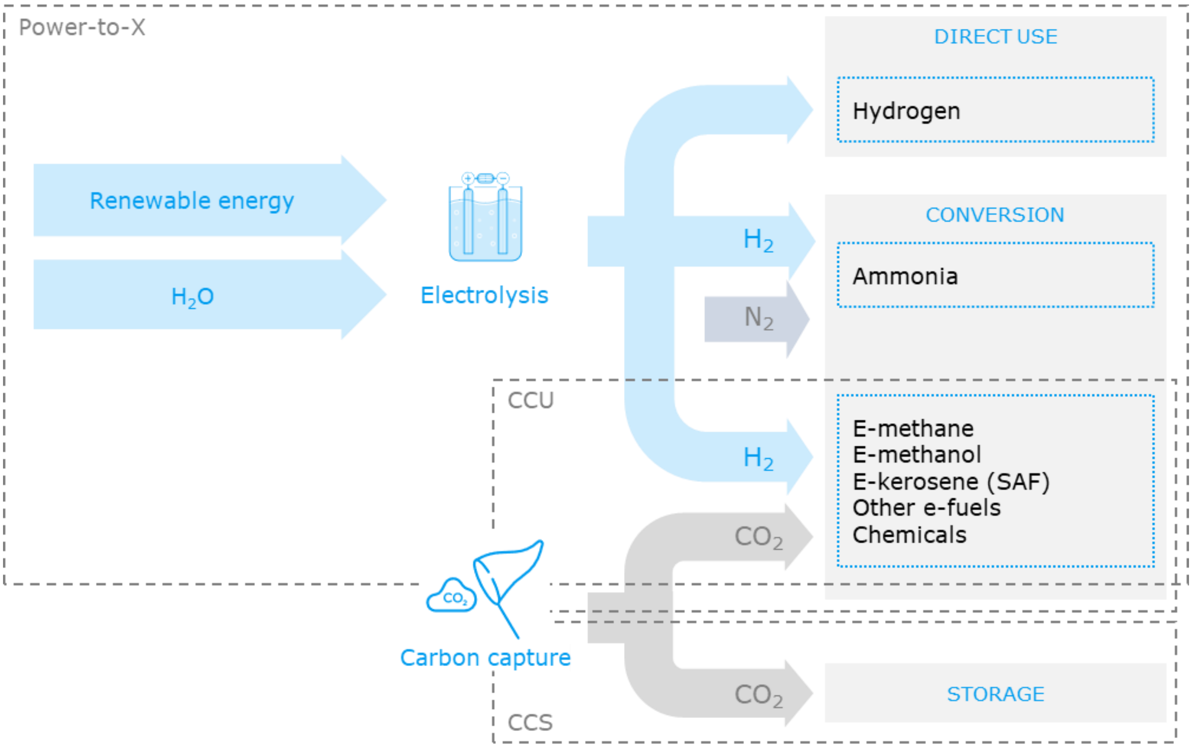


Figure 6 Overview of PtX and CCUS linkages

Source: Ramboll analysis

In this report, the potential for PtX and CCUS value chains is evaluated based on the local availability of renewable energy and CO_2 as well as the energy infrastructure. E-fuel made from CO_2 and H_2 is expected to become an important part of the global transition to renewable energy, particularly for light and heavy transport, shipping, and air traffic. Historically, the price of e-fuel is predominantly determined by the price of electricity.

2.1 Overview of actors on Lolland-Falster

Lolland-Falster is a strategic location for the development of PtX and CCUS value chains, due to the availability of renewable power, biogas production, industrial actors with point sources for CO_2, harbour infrastructure, and the new natural gas infrastructure. Moreover, there are opportunities for CO_2 storage (CCS) and additional development of renewable energy.

There are many public and private sector actors exploring opportunities to engage with PtX and CCUS value chains on Lolland-Falster (see Table 3). This includes actors developing and/or supplying feedstocks like electricity, water, and CO_2, as well as actors operating and maintaining infrastructure (e.g., the methane/natural gas pipeline, electricity grid, harbours) that can be leveraged for transport of energy. Finally, there are developers of potential storage sites present on Lolland-Falster.

Table 3 Overview of key PtX actors on Lolland-Falster

Category	Key actors in Lolland-Falster
Renewables developers Companies operating and/or developing wind and solar projects on Lolland Falster.	European Energy, Better Energy, Copenhagen Energy, Hofor
Biogas developers Companies operating and developing biogas projects on Lolland Falster.	Bigadan, Biofuels Technologies, Danish Agro, Leverandørforening LF Biogas, Nature Energy
Utilities and system operators Companies that supply electricity, gas, and water through operating infrastructure on Lolland Falster.	Andel, Cerius, Evida, Lolland Forsyning, Guldborgsund Forsyning, REFA
Other infrastructure providers/developers Various (other) companies operating or developing infrastructure e.g.: harbours, CO_2 storage, etc.	CarbonCuts, Nakskov Havn, Rødbyhavn
Industry Various companies across agriculture, food, chemical sectors in Lolland Falster, consuming and producing local resources, incl. gas and CO_2.	Alfa Laval, Codan Medical, Crispy Foods, DLG, Hveiti Ingredients, JMA Filtration, JP AirTech, Melitek, Metal Colour, Nordic Sugar, Nordic Air Filtration, Vestas
Public sector	Lolland Municipality, Guldborgsund Municipality

Source: Ramboll analysis

2.2 Overview of resource availability

For PtX and CCUS value chains to be viable, a reliable and efficient supply of essential resources such as electricity, water, and carbon dioxide (CO_2) is important. Moreover, leveraging on other local resource flows and production processes such as biomethane production and heating/cooling systems may improve the cost-effectiveness of projects. The availability and distribution of these resources therefore directly impact the feasibility and scalability of PtX and CCUS projects.

While multiple integration points and synergies can be achieved through the exchange of resources, the resource mapping focuses on two key resource flows including the availability of renewable electricity and the availability of biogenic CO_2 locally.

2.2.1 Renewable electricity production

Current electricity production on Lolland-Falster consists of a mix of offshore and onshore wind, solar PV and combined heat and power (CHP) plants. Lolland-Falster has a large share of renewables, which constitute over 97% of the electricity production capacity. This includes Rødsand, an offshore wind farm south of Lolland with a capacity of approx. 380 MW.

While the current electricity system is already heavily reliant on wind and solar power – with renewable electricity being exported from Lolland-Falster to Zealand – future plans are even more ambitious. As we will demonstrate later, these ambitious plans are necessary to develop the PtX economy, which requires a substantial amount of energy.

Over the next decade, a substantial increase in total electricity production is expected on Lolland-Falster, from approx. 1,000 MW to over 4,500 MW by 2034 (see Figure 7), in the development scenario. This is based on planned renewable projects and excludes a potential reinstatement of the open-door policy[1], which allows developers to propose unsolicited renewable energy projects without waiting for specific government calls for proposals. The projected development in production capacity in the development scenario, as seen on Figure 7, is driven by[2]:

- A large build out of solar PV projects, particularly by European Energy in 2027-29
- A build out of onshore wind in 2032-34, particularly in eastern and southern Lolland, including the Nakskov Fjord Cluster, Rødby Fjord Cluster and Tunnelfabrikken[3]
- Replacement/repowering of old wind turbines, which is assumed for 30% of onshore turbines and 100% of offshore turbines. Onshore wind is ongoing during the period depending on end of life on turbines, whereas offshore wind at Rødsand is in 2040 and Nysted in 2034.

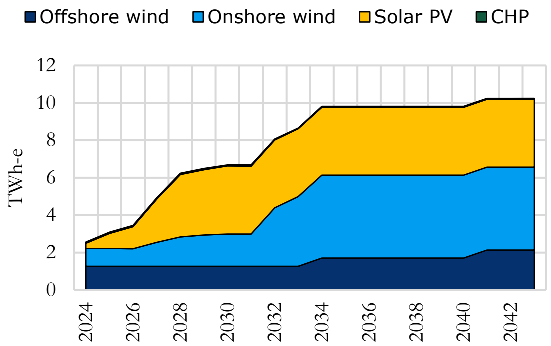
If these projects are realised, electricity production capacity on Lolland-Falster will increase by 4x within the decade. As repowering old wind turbines becomes a viable business case, we believe there is significant potential in this approach, especially since locations for renewable energy have already been established. However, the prospects for offshore repowering are more uncertain due to the continuously evolving landscape of offshore wind. Despite this, repowering offshore sites could be an efficient way to maintain and increase installed renewable capacity. A relevant example is the repowering of the onshore wind farm site at Bogø Inddæmningen on Lolland.

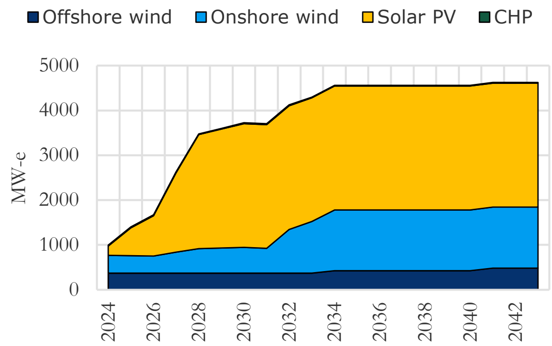
[1] Open door projects: Lolland Syd 260 MW, Femern Bugt 275 MW, Lolland Nord 253 MW, Guldborgsund 500 MW

[2] See a full overview of the assumptions in Appendix 1.

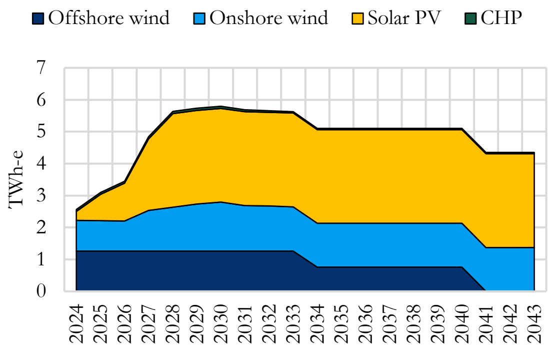
[3] SWECO, Energiøer på Lolland (2022)

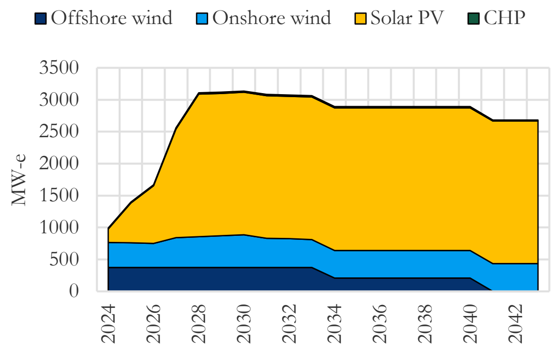
Development scenario



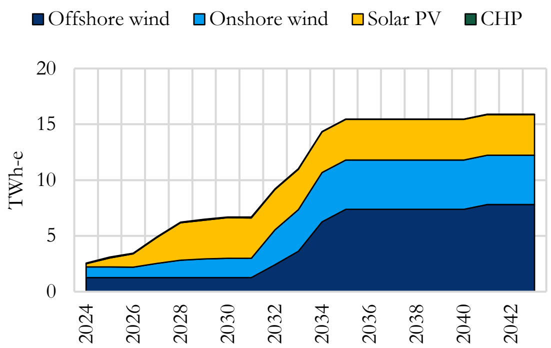


Conservative scenario





Development scenario (incl. open door projects)



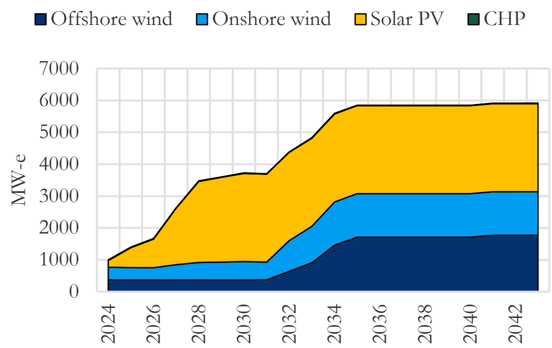


Figure 7 Annual electricity production and capacity over time per scenario (TWh and MW)

Sources: Ramboll analysis; Gate21 Ressourcekortlægning (2023); Sweco Energiøer på Lolland (2022)

2.2.2 Electricity consumption

While existing electricity consumption (see Figure 7) is expected to remain stable over the upcoming decades, planned PtX projects will significantly increase total electricity consumption. Additionally, there will be a rise in electricity use for district heating and new demands such as the electrification of transport and individual heating, though these are minor compared to the demand from PtX plants.

Several PtX projects are under development on Lolland (see Table 2), including four projects: two in Nakskov and two in Rødby by European Energy and Copenhagen Energy. The methanol plant in Nakskov, developed by European Energy, is the most likely to become operational. The other projects are still in preliminary stages. For the two hydrogen plants by Copenhagen Energy to become feasible, a hydrogen pipeline to Germany or Zealand is required.

For the Copenhagen Energy hydrogen plants to be realisable, either more local demand has to be developed (methanol or ammonia plants or industry) or alternatively to establish the hydrogen pipeline to Zealand and Germany. Otherwise, it is not relevant to develop additional hydrogen production on Lolland-Falster.

Table 4 Overview of PtX projects in development

Owner	Location	Electricity demand	Electricity capacity	COD[4]
European Energy	Nakskov, Lolland	~ 1.200 GWh	240 MW	2027-28
European Energy	Rødby, Lolland	~ 1.200 GWh	240 MW	Unknown
Copenhagen Energy	Nakskov, Lolland	~ 2.500 GWh	500 MW	Unknown
Copenhagen Energy	Rødby, Lolland	~ 2.500 GWh	500 MW	Unknown

Sources: Ramboll analysis

The PtX projects create a significant demand for renewable electricity, which can be matched by the expected future renewable production capacity if all projects are realized as planned (see Figure 8). Note that the exact timelines for three of the four PtX projects remain uncertain. In the forecast, it is assumed that these projects will develop incrementally, with commercial operation dates in 2032 (500 MW), 2034 (500 MW), and 2035 (240 MW).

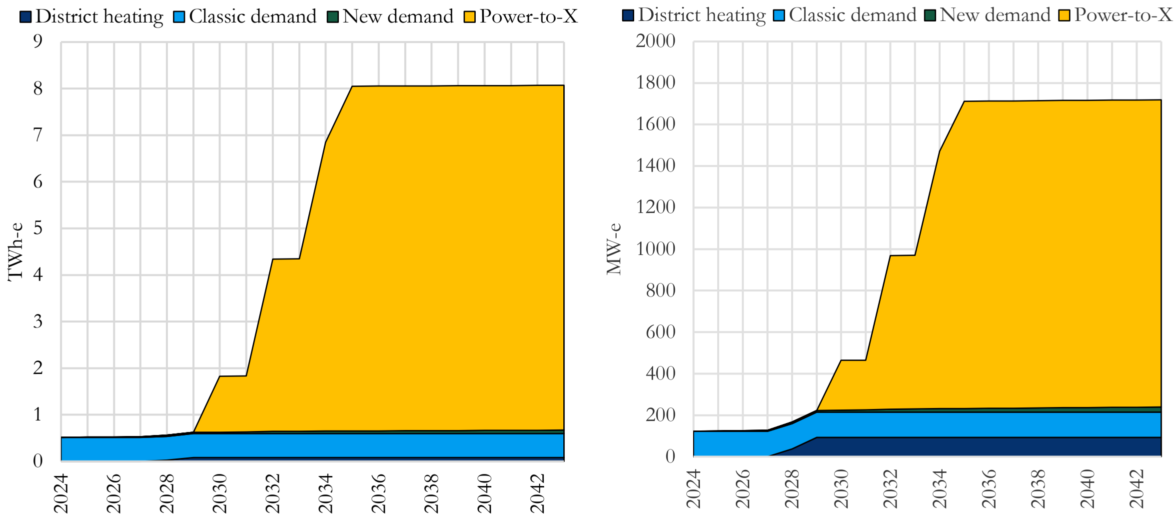
If production of upgraded biomethane through electrolysis for bio methanation is preferred over capturing CO2 for methanol production, this additional electrolysis capacity will be in addition to the planned PtX capacity.

We compare the projected electricity demand, including the addition of PtX technologies, to the anticipated electricity production in the development scenario.

It is important to distinguish between energy and capacity, as renewable energy sources typically have lower capacity factors. Consequently, large amounts of renewable capacity are required to generate the energy needed for PtX plants. However, the mismatch between production and demand can lead to undesirable electricity exchange patterns. In the subsequent energy and economic analysis, we will use an hourly energy system model to assess production and demand. Therefore, the energy demand figures presented here may not match those analysed later.

[4] Commercial Operations Date.

Electricity demand development



Demand and production development (development scenario)

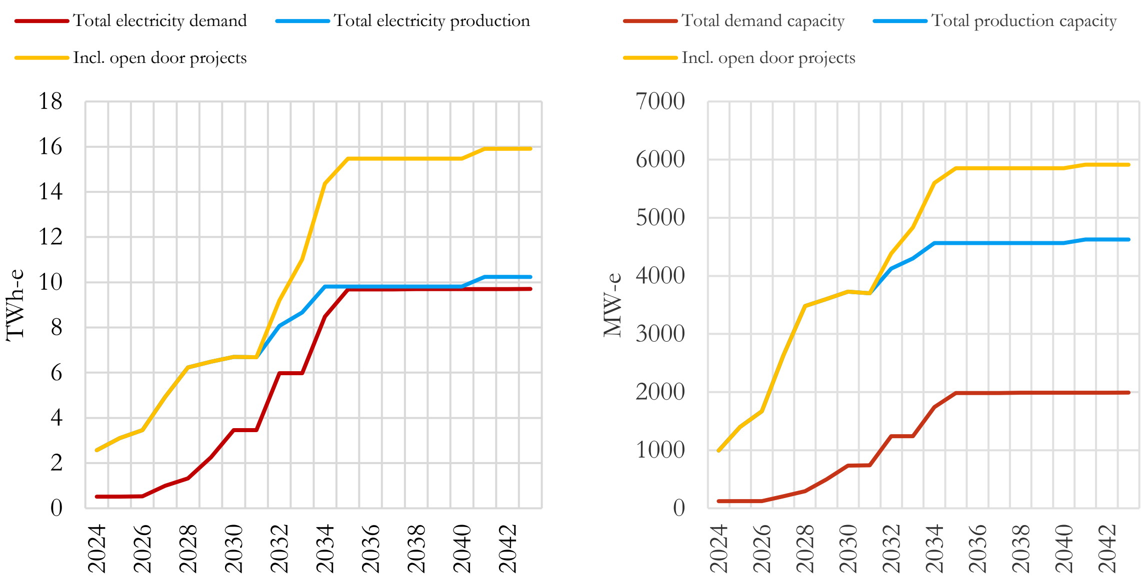


Figure 8 Overview of annual electricity consumption and production over time (TWh and MW)

Source: Ramboll analysis.

2.2.3 Carbon dioxide

2.2.3.1 CO_2 emissions

PtX projects aimed at producing hydrocarbons such as e-methanol or e-methane will require biogenic CO2 as a crucial input to market e-fuels as renewable fuels of non-biological origin (RFNBOs) under the EU's Renewable Energy Directive (RED). Starting in 2026, several planned biogas plants are expected to become operational, upgrading and injecting biogas into the gas grid (see Table 5). Insights from Biogas Denmark indicate that these projects include one existing biogas asset in Kettinge, previously used for electricity production, and three new projects on Lolland. The Falster project remains uncertain.

The development of biogas assets will increase the availability of CO2 on Lolland-Falster (see Figure 10). Our subsequent analysis will determine whether it is preferable to use this CO2 for methanol production or to produce more biomethane at the biogas plants by injecting hydrogen from electrolysis into the process.

Table 5 Overview of biogas development on Lolland-Falster

Owner	Location	Volume (CH_4)	COD
Nysted Bioenergi (Bigadan)	Kettinge, Lolland	10 mil. m^3 (current) 15 mil. m^3 (future)	In operation, adding extended capacity in 2026
Nature Energy	Abed, Lolland	20-25 mil. m^3	2026
Nature Energy	Nørre Alslev, Falster	20-25 mil. m^3	Unknown/uncertain
LF Biogas & Danish Agro	Midt-Østlolland	20-25 mil. m^3	2028-2029
Biofuels Technologies	Nakskov, Lolland	50 mil. m^3	2028-2029

Source: Ramboll analysis; Biogas Danmark.

As shown in Figure 9, approximately 60% of the CO_2 on Lolland-Falster is currently biogenic. By 2029, the share of biogenic CO_2 is expected to increase to 100% due to the planned biogas development and the potential for sugar factories to use this same biogas. CO_2 from district heating comes from small biomass boilers used in smaller district heating systems. The only CO_2 available for capture and utilization will be from biogas plants and sugar factories.

On Lolland-Falster, there are today approximately 500 ktons of CO_2 available from district heating and industrial sources (see Figure 9). This amount is expected to decrease to about 300 ktons due to reduced operational hours and the decommissioning of district heating assets, such as the waste-to-energy plant in Nykøbing. Furthermore, we also expect that the excess heat from PtX facilities and heat pumps and electric are used to produce district heating reducing the CO2 emissions. We have assessed each district heating system, and the only remaining biomass boiler operation is in smaller district heating systems where heat pumps and electric boilers cannot supply the entire district heating demand. Additionally, there may be an extra 30 kton of new industrial activity in Nakskov starting in 2030, which has not been included in the current assessment due to uncertainties. However, any additional CO2 emissions from new industries can be relatively easily integrated into the planned CO2 system.

The CO_2 demand from the methanol plants is projected to be around 300 ktons per year. However, it is important to consider the temporal mismatch between production and consumption, which demands a need for CO2 storage to balance this temporal mismatch. The industrial CO_2 emissions primarily originate from the two sugar factories located in Nakskov and Nykøbing, which operate from September to January. The monthly CO2 balance is later shown.

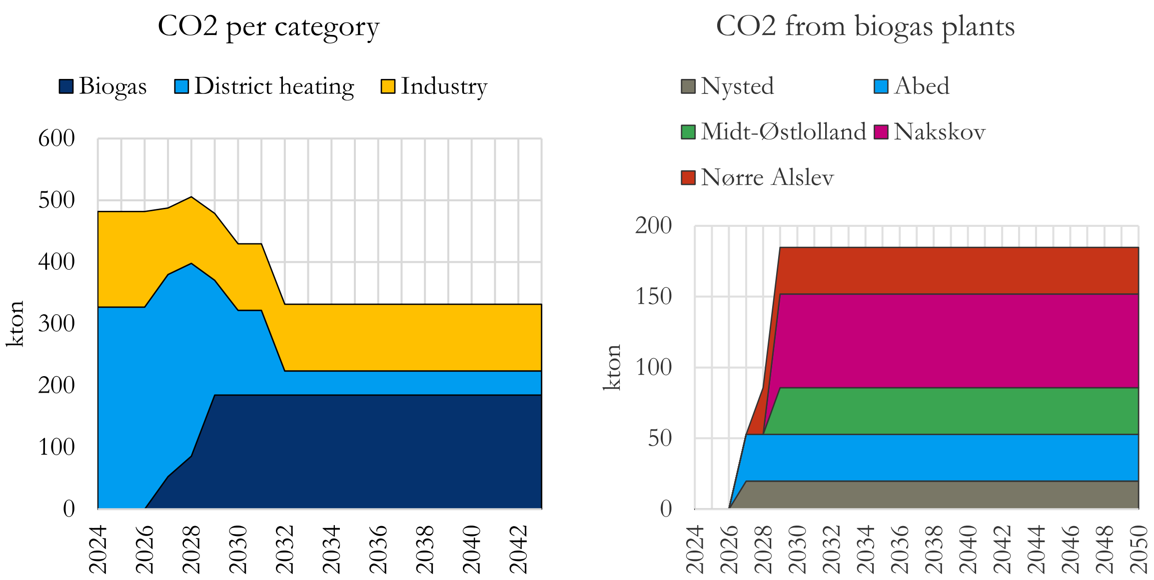


Figure 9 Available CO2 over time and by category (kton)

Source: Ramboll analysis

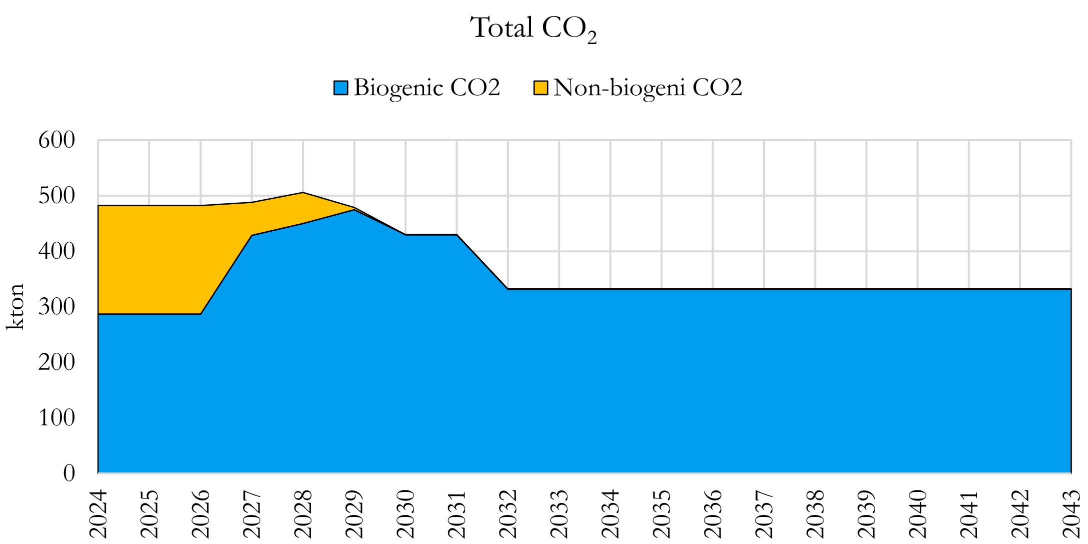


Figure 10 Annual CO_2 on Lolland-Falster over time

Source: Ramboll analysis

2.2.3.2 Demand for CO_2 from PtX projects

The demand for CO_2 for PtX projects depends on the fuel that will be produced. For the two European Energy projects, the PtX assets are expected to be used for methanol synthesis.

Table 6 Overview of PtX projects in development

Owner	Location	Asset type	CO_2 consumption	COD
European Energy	Nakskov, Lolland	Methanol synthesis	140.000	2027-28
European Energy	Rødby, Lolland	Methanol synthesis	140.000	Unknown

Sources: Ramboll analysis

With the currently available CO_2 on Lolland-Falster, there is theoretically enough biogenic CO_2 for methanol synthesis at the two European Energy plants. Starting in 2026, the available CO_2 will increasingly come from biogas production and industry, particularly the two sugar factories. Larger volumes of CO_2 can be captured at single sites, making this approach more attractive. From biogas alone, approximately 185 ktons of biogenic CO_2 is expected to be available, with an additional 100 ktons from the sugar factories.

However, given the volumes required and the possibility that not all CO_2 will be captured for methanol production, developers will need to explore additional methods for sourcing CO_2.

2.2.3.3 CO_2 subsurface storage

The import infrastructure for CO_2 can be facilitated by developing the subsurface CO_2 storage site at Rødby by Carbon Cuts, which in June 2024 received a license to examine the storage potential.

In addition to the planned storage facilities, Carbon Cuts plans to establish an import infrastructure for CO_2 from ships and trains. Trading within the local CO_2 network using credits for biogenic CO_2 will enable the import of CO_2 to the methanol plants at a lower cost than if they had to establish their own import infrastructure. This can create significant synergies.

Table 7 Overview of CO2 subsurface storage in Rødby

Owner	Location	Asset type	CO_2 storage	COD
Carbon Cuts	Rødbyhavn, Lolland	CO2 subsurface storage	1 Mt per year	2030

There are currently eight onshore locations that have been identified by the Geological Survey of Denmark and Greenland (GEUS) for CO_2 storage. Five sites were selected in the Danish Energy Agency's tendering round for exploration licenses[5] (December 2023), including the Rødby structure (see Figure 11) which in June 2024 was appointed to CarbonCuts.

[5] Commercial access to the Danish CCS market is provided through the awarding of exploration licenses, which provide preferential access to storage licenses (Undergrundsloven).

Figure 11 Potential storage site for CO2 at Rødbyhavn

Source: Business Lolland Falster

CarbonCuts is planning to develop and operate 'Project Ruby,' a CO_2 storage facility. While the capacity of storage site is currently unknown, CarbonCuts is aiming at storage of 1 million tons of CO_2 per year. Several concepts for transport to and storage at the Rødby structure are under development, including:

1. **Rail-based import of CO_2** from Germany (once Fehmern link is completed) or from Sweden, with a terminal at Rødby for a key intake point.
2. **"Northern Lights"-concept** utilising buffer tanks at the port (or nearby), where CO_2 carriers can dock to offload CO_2, followed by transport to injection sites.
3. **Floating hub** within or outside the harbour, where CO_2 carriers can offload CO_2, before transport to injection sites.

For all concepts, a substantial amount of infrastructure for the transport of CO_2 to the Rødby structure can be expected. This provides opportunities for using this infrastructure for transport of CO_2 for PtX/e-fuel production. Moreover, the storage operator may be able to facilitate import of CO_2 to alleviate local sourcing constraints.

2.2.3.4 CO2 network plans in Europe

There are numerous plans to develop CO2 infrastructure across several European countries. The EU's Joint Research Centre has explored multiple potential pathways for this development. One of these plans involves constructing a major CO2 pipeline from Germany to Denmark via Lolland-Falster to utilize the planned Danish subsurface CO2 storage facilities.

The anticipated expansion of the European CO2 transport network begins in Belgium, the Netherlands, and Denmark, with significant growth expected by 2030. Most storage projects are located in the North Sea and Eastern Denmark. However, in southern Europe, limited storage capacities necessitate long transport routes. By 2040, the network is projected to extend to 15,400 km, with increased CO2 capture and storage capacity due to new storage sites being developed closer to capture locations. By 2050, the network will span 21 countries, capturing 250 Mtpa of CO2 and featuring 22 cross-border connections. To optimize costs, some underutilized network segments, originally built for limited storage options, may be repurposed with alternative transport methods or deferred. The map below illustrates the planned CO2 network in Europe for 2040 under one of the development scenarios. The key difference for Denmark across these scenarios is whether the connection to Germany will pass through Eastern or Western Denmark.

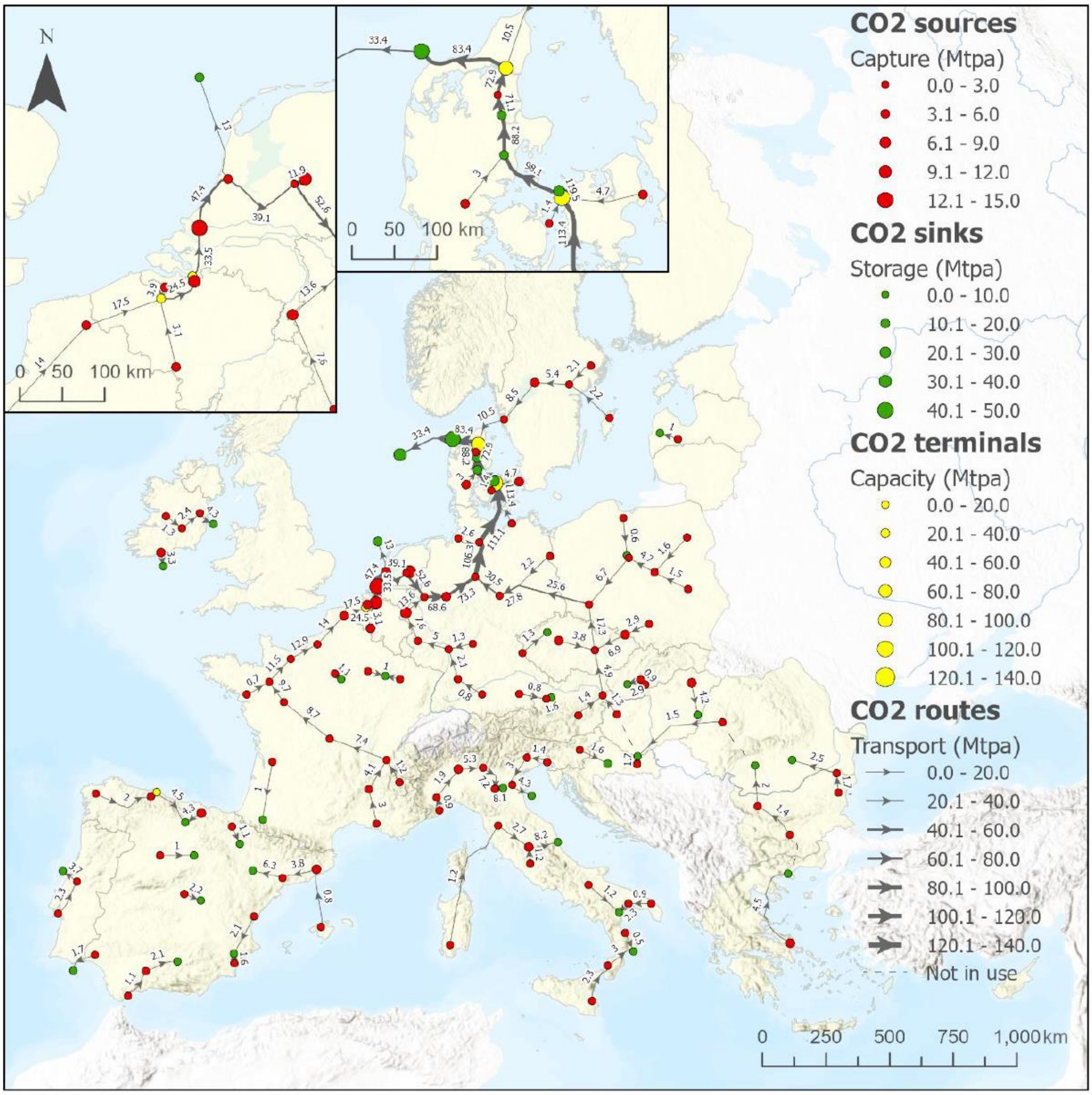


Figure 12 Potential CO2 network in Europe in 2040

Source: Joint Research Centre (https://publications.jrc.ec.europa.eu/repository/handle/JRC136709)

2.2.4 Other resources

Other resource flows on Lolland-Falster are integrated into CCUS and PtX value chains, including water and heat. Actors like utility Lolland Forsyning are eager to explore opportunities to engage with PtX value chains through different ways, including:

- Utilizing excess heat from PtX operations and integrating it into the district heating network
- Utilizing oxygen from PtX operations in Lolland Forsyning's wastewater treatment plants, which can enhance the biological process in the treatment facilities.
- Supplying technical water to PtX plants.

Lolland Utility pumps approx. 1,850,000 m^3 of drinking water annually, and the Nakskov wastewater treatment plant processes approx. 2,500,000 m^3 of wastewater annually. There is currently no production of technical water, but this could be established at the Nakskov wastewater plant. From 2028 (at the earliest), the potential for technical water in Nakskov is as follows:

- Approx. 300,000 m^3 for European Energy's PtX project
- Approx. 300,000 m^3 for Copenhagen Energy's PtX project
- An additional 400,000 m^3 for other projects

For Rødby, the potential for technical water (from 2028) is:

- Approx. 300,000 m^3 for the Fehmarn facility (Note: Fehmarn is currently permitted to use 450,000 m^3 of drinking water, but this will cease once their production ends).
- Approx. 300,000 m^3 for Copenhagen Energy's PtX project

The use of water for PtX is currently under regulatory review at the environmental authorities.

In addition to leveraging excess heat from PtX project for district heating, there is also an opportunity for utilising excess cooling from the CO_2 conditioning facilities linked to CCS at Rødby. The CO_2 will be received in a pressurized and cooled state (-15-20 °C), which needs to be heated before injection. Possible users of excess cooling could include server farms, cold storage warehouses, and data centres, i.e., processes requiring temperatures from -15/-20 °C up to 0 °C.

2.3 National and international perspectives

When developing local value chains for complex industries like PtX and CCUS, opportunities at national and international levels can be pivotal for successful projects. Opportunities could include sourcing feedstocks in nearby regions, leveraging on infrastructure, availability of offtakers, as well as access to partners or funding opportunities.

Due to its geographic positioning, Lolland-Falster can access both Zealand (Denmark) and continental Europe, capitalising on the broader Danish and European political ambitions for development of PtX. The EU Commission aims to scale up PtX in Europe to 40 GW of electrolysis capacity and 10 million tons of hydrogen production by 2030. Denmark is seeking to position itself as a frontrunner within these European ambitions, targeting large-scale PtX production by 2030 with 4-6 GW of electrolysis capacity[6]. These policies set the foundation for a supportive regulatory framework that drives market development, including:

- Establishment of offtake for hydrogen and derivatives, e.g., EU regulations such as the RefuelEU Aviation and FuelEU Maritime are increasingly putting pressure on end use sectors to switch to decarbonised fuels such as e-methanol, e-ammonia, and sustainable aviation fuels (SAF).
- Development of infrastructure, e.g., the European Hydrogen Backbone (EHB)

[6] Agreement on development and promotion of hydrogen and green fuels (March 15, 2022)

- Availability of funding and support schemes, e.g., the European Hydrogen Bank

2.3.1 Offtake

The e-fuels market in Denmark has local offtake in industry but is expected to be export-driven once technologies are at scale. In Figure 13, the expected European demand or hydrogen, e-methanol, e-ammonia, and SAF has been indicated for 2025 and 2040.

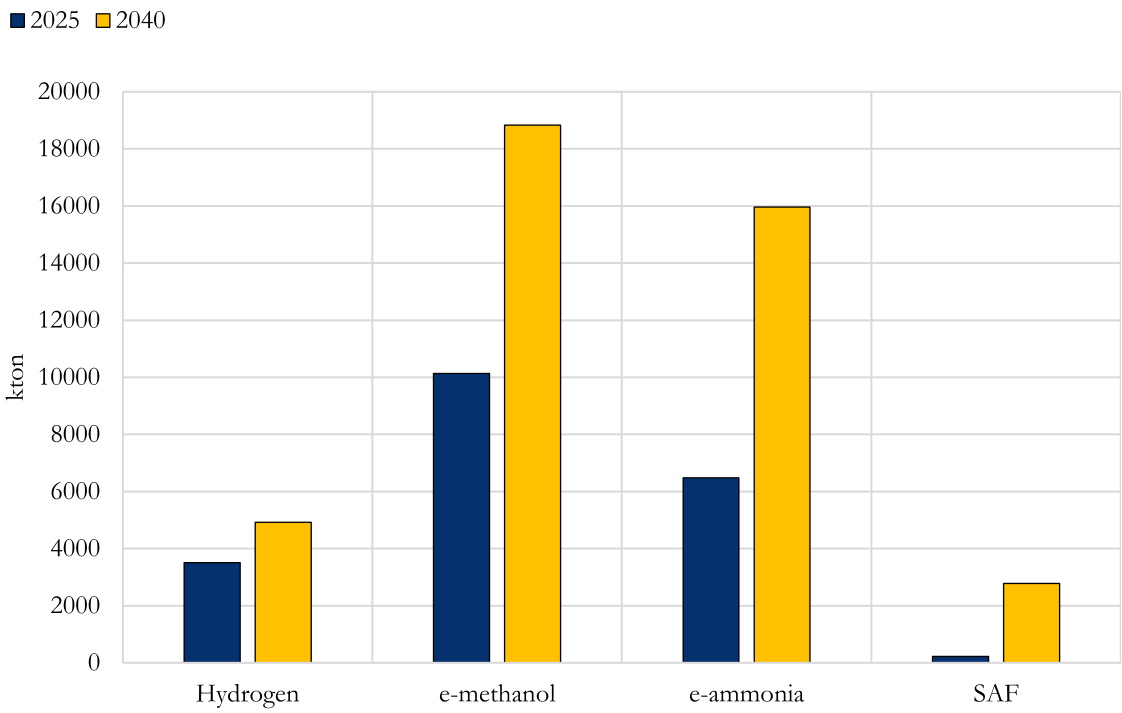


Figure 13 Demand for hydrogen and derivatives in Europe

Source: Ramboll analysis.

Hydrogen

The predominant market for green hydrogen within Denmark is anticipated as the intermediary for production of other e-fuel derivatives. There is insufficient scale at industrial operation to utilise large volumes of hydrogen as domestic product. A larger accessible market can be identified in neighbouring countries e.g., Germany, Netherlands, France, and Belgium, and thus, most green hydrogen production is anticipated for export.

Central Europe hosts a wide variety of manufacturing and industrial processing companies, including over 50% of European steel production. Germany has the largest chemical and steel production, and the highest industrial hydrogen demand (55 TWh / year, with expectations for this to increase).

At a recent German-Danish Green Hydrogen Summit (November 2023), key industry players published a joint statement on agreed industry cooperation between Danish producer/suppliers of green hydrogen, and German industrial off takers, citing German National strategy reliance on an imported volume of 1.5 – 3 million tons of green hydrogen by 2030.

The planned European Hydrogen Backbone (EHB) network will facilitate such export. Alternatively, in a less efficient use case, green hydrogen can be sold to the natural gas grid. The considerations on the Green Gas Lolland-Falster pipeline with regards to hydrogen conversion and blending is described in Section 3.2.1. Another alternative is to transport hydrogen as a liquid fuel. However, most developers are opting to use ammonia as an intermediate energy carrier for this purpose.

E-methanol

Methanol is a fundamental component for chemicals, plastics, gasoline substitutes and biodiesel. The chemical industry accounts for 96-97% of the total EU demand (~10.8 Mton MeOH) for methanol, with the remaining 3-4% going towards fuel blending for the land-transport industry and is only utilized in negligible volumes in the maritime industry (demonstration projects only). Demand from the maritime sector is expected to increase exponentially, as fuel blending and emission reduction targets are implemented at an EU level.

Maritime ports represent the dominant offtake pathway for e-methanol, through the dual opportunities of providing bunkering services for marine traffic, and as a gateway to broader export markets via marine shipping. Major bunker hubs in Denmark include Copenhagen, Aarhus, Frederikshavn and Esbjerg. Some ports have more advanced targets for incorporation of e-fuels than others, however the regulatory implications of e.g., FuelsEU Maritime will mandate increased uptake long-term.

E-Ammonia

The fertiliser industry is heavily reliant on ammonia and presents high demand for green ammonia as a substitute. The demand for ammonia in the fertiliser sector will primarily centre around countries with robust fertiliser production. An estimated 630,000 tons of ammonia-based fertiliser product is imported annually, to supply Denmark's agricultural industry. Export is primarily sourced from Germany, Spain, Poland, and the Netherlands. Establishment of domestic production facilities can replace the reliance on import of ammonia and other chemicals produced abroad. Near-shore export to large fertiliser producers in Germany can also present an attractive market, e.g., Yara.

Demand for ammonia in the maritime industry is projected to expand long term, as the technology for ammonia-fuelled vessels is improved. Ammonia is a well-established global commodity, with over 120 ports globally with existing import/export operations and relevant facilities. There are around 170 ammonia transportation ships in operation. This existing network can enable an accelerated transition to large scale trade of green ammonia across a global network.

SAF

E-kerosene, also known as Power-to-Liquid Sustainable Aviation Fuel (PtL-SAF, or SAF) is relied upon by the aviation industry as a critical element of decarbonisation targets. The aviation sector cannot be electrified, and there are currently no known available alternatives. The current usage of SAF in Europe is currently almost non-existent in comparison to the total volumes of fossil jet-fuel used. However, the EU's "Fit-for-55" package introduced mandatory SAF targets to increase the uptake of SAF by the aviation industry. Individual countries (e.g., in central Europe and the Nordics) have also set blending mandates that go beyond the EU Fit-for-55 targets.

Furthermore, the Danish government has announced ambitions to be operating all domestic routes on 100 percent green fuels by 2030, with an allocation of 1.8 billion DKK towards increasing the demand for sustainable aviation fuels. An initial target is the establishment of a 'green domestic flight route', such as the recent collaboration between Norwegian and Aalborg Airport has facilitated.

Copenhagen Airport operates as a transport hub for international connectivity of northern Europe and will continue to grow in this position. As part of the Aviation Climate Partnership, Copenhagen Airport has committed to driving the sustainable transition of the aviation sector through e-fuel development.

2.3.2 Infrastructure for hydrogen

The transportation of e-fuels via pipelines is an essential and efficient component of the e-fuel supply chain. Pipelines offer advantages in terms of cost-effectiveness, safety, and the ability to transport large volumes of e-fuels over extended distances. This makes them particularly valuable for connecting production facilities with distribution hubs and end-users. The European Hydrogen Backbone (EHB) is an initiative to support the development of the European hydrogen market through a hydrogen transport network consisting of new and repurposed pipelines. Following recent geopolitical developments, the EHB has accelerated its planned infrastructure to a total of approx. 53,000 km of (mostly repurposed) pipelines by 2040.

The development of the EHB (see Figure 14), can offer Lolland-Falster the necessary infrastructure to trade and transport hydrogen efficiently to demand centres like Germany. In the first phase, planned for 2030, EHB focuses on western Denmark and connection to Germany, while the second phase, planned for 2040, includes an eastern pipeline that connects Zealand to Germany via Lolland-Falster. Locating production facilities within these predetermined hydrogen corridors will facilitate access to the pipeline when it develops, and thus, access to an extended domestic and cross-border consumer base.

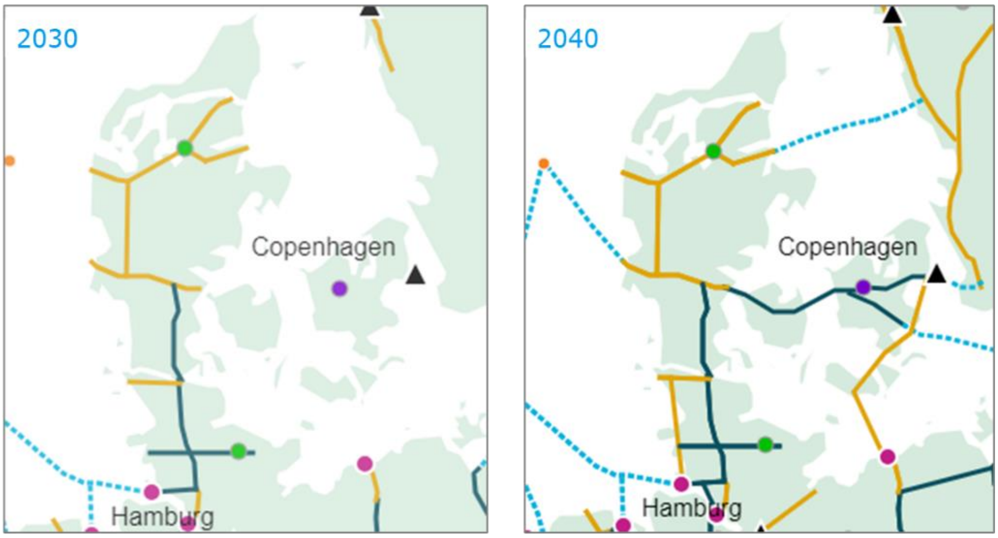


Figure 14 Overview of the 2030 and 2040 European Hydrogen Backbone

Source: European Hydrogen Backbone

2.3.1 Infrastructure for electricity

The electric grid infrastructure development plans from Energinet at Lolland-Falster are not aligned with the plans for renewable energy development. If local electricity demand does not increase as expected, the planned renewable energy projects may be deemed unfeasible.

The figure below shows the planned increase in electric grid capacity from Lolland-Falster to Zealand. Since a significant capacity increase is not expected for another 15 years, alternative solutions for managing the electricity need to be considered in the meantime.

In the development scenario, the installed electrical capacity on Lolland-Falster is projected to reach 4.5 GW by 2035. With further offshore wind expansion, this could approach 6 GW, while the expected peak demand is around 1.8 GW.

However, delays in the development of supply, demand, and infrastructure are likely. This underscores the importance of creating a comprehensive energy plan to effectively manage these dynamics.

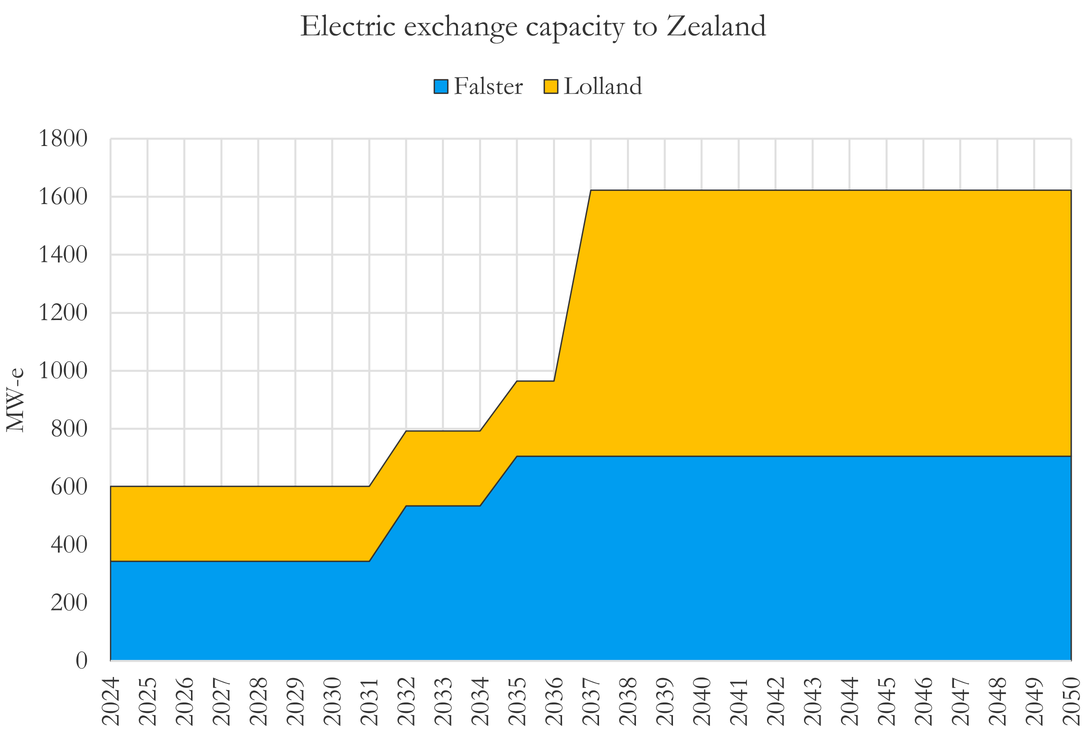


Figure 15 Development of electric transport capacity from Lolland-Falster to Zealand

Source: Energinet (planned construction projects)

2.4 Summary from market assessment

The following is a summary of the findings in the market assessment:

- PtX and CCUS are interlinked through key resource flows and the coupling of these processes can provide opportunities for synergies.
- Renewables developers, point sources, grid operators, and other infrastructure providers are present or exploring opportunities on Lolland-Falster, creating a potential for the development of local PtX and CCUS value chains.
- If planned renewables projects are realised on Lolland-Falster, electricity production capacity on Lolland-Falster will increase by 4x within the decade to >4,500 MW. This will also be necessary to realise the four planned PtX projects, which result in an electricity consumption of almost 1500 MW of capacity.
- Notably, planned PtX projects are located on Lolland rather than Falster, likely due to the prevalence of and access to CO_2 and renewables.
- There are currently 500kton of CO_2 available on Lolland-Falster which will decrease slightly to approx. 300kton by 2032, of which 100% are biogenic. However, the CO_2 must be captured from a mix of biogas and industrial sources, which may be costly. If sourcing only from biogas assets, there is about 180kton available, which is about sufficient for one of the two planned methanol synthesis PtX projects, requiring 140kton of biogenic CO_2.
- There are opportunities for storage of CO_2 through the Rødby CO_2 storage structure, which is currently being examined by Carbon Cuts. Should a CO_2 storage site develop, this would require the establishment of harbour and CO_2 transport infrastructure which may be leveraged for utilisation cases (CCU) as well.
- Pipeline infrastructure for hydrogen is not currently planned for Lolland-Falster but may be developed as part of the second phase of the European Hydrogen Backbone build out in 2040. This would provide access to international markets and demand centres like Germany.

Scenarios for the subsequent techno-economic analysis:

- **Conservative development scenario:** Only announced solar PV projects are developed and onshore and offshore wind is not repowered. The renewable energy development basically goes towards a full stop.
- **Development scenario:** Substantial increase in total electricity production capacity approx. 1,000 MW to over 4,500 MW over the coming years. This is based on planned renewable projects and excludes a potential reinstatement of the open-door policy.
- **Development scenario including open door projects:** In this variation scenario we include the *open-door* offshore wind projects around Lolland-Falster.

3. CARBON DIOXIDE AND HYDROGEN INFRASTRUCTURE

This section presents potential networks for carbon dioxide and hydrogen. The technical details for calculating pipe sizes and related process equipment are available in the Technical Report. Key technical aspects for operationalizing such pipeline networks on Lolland Falster are described here. The strategic considerations for determining the routes and sizes of the pipelines, along with other relevant details, are presented. To minimize environmental impact, the same pipeline corridors are repeatedly utilized. For example, the pipeline layouts designed for transporting H_2 can also be used for CO_2 transport.

Although we recognize that the pipeline layout and sizes may differ if either or both networks are implemented, our analysis reveals a list of findings, which will be clarified in the economic assessment. We have developed the networks to operate on a regional level and, for the hydrogen and biogas network, also on an international level. Regional scenarios encompass the geography of Lolland Kommune and Guldborgsund Kommune, while international scenarios consider infrastructure extending to Germany and Zealand.

The subsequent economic assessment considers the pipeline transportation of CO_2, H_2, and biomethane between industries, storage sites, or external infrastructures such as the European Hydrogen Backbone pipeline or the Green Gas Lolland-Falster pipeline. The infrastructure analysed includes the initial conditioning (to achieve the desired pressure and temperature) of the transported substances and the pipeline infrastructure itself.

3.1 Technical design assumptions

The following assumptions were applied to calculate the pipe and equipment sizes. Although operational patterns might slightly differ, marginal changes to these assumptions have minimal impact on the results, making them a good starting point:

- The design pressure for CO_2 pipelines is 30 bar.
- The design pressure for hydrogen pipelines is 30 bar.
- The design pressure for biomethane pipelines is 55 bar.
- Sugar factories operate continuously for 5 months per year.
- Biogas plants operate continuously throughout the year, except for maintenance.
- Methanol and hydrogen plants have a predetermined maximum flow rate.

The flow rates for the assumed production or demand rates of CO_2, H_2, and biomethane for biogas plants, considered under different scenarios, can be found in the Technical Report.

3.1.1 Routing

Routing of pipelines in the ground consider several aspects, including:

- Densely populated areas and narrow streets with associated safety concerns and challenges during construction.
- Vast existing underground infrastructure (power lines, telecommunication cables, transport infrastructure, water and sewage lines, various utilities, etc.)
- Roads and railways, and to minimize crossing of these.
- Restricted areas and safety distances.

- Areas of natural protection.
- Limitations imposed by municipality local plans (planned housing and infrastructure development).

Focus on the routing scenarios has been (priority order):

- Safety, during operation and execution.
- Existing infrastructure, roads, metro
- Environment, protected nature and cultural heritage etc.
- Crossings, bridges, railways, water
- Other utilities, major piping, critical infrastructures

3.1.2 Environmental Restrictions

Lolland-Falster contains zones with environmental restrictions, which prohibit pipeline routing in these areas. Consequently, pipeline layouts for various scenarios have been designed to avoid these restricted zones. The environmental restrictions are categorized into several zones, including areas such as lakes and buildings. Figure 19 provides an overview of these environmental restrictions.

However, a strict adherence to these zones has not been maintained due to the reliance on class 5 cost estimation (refer to Section 4.5).

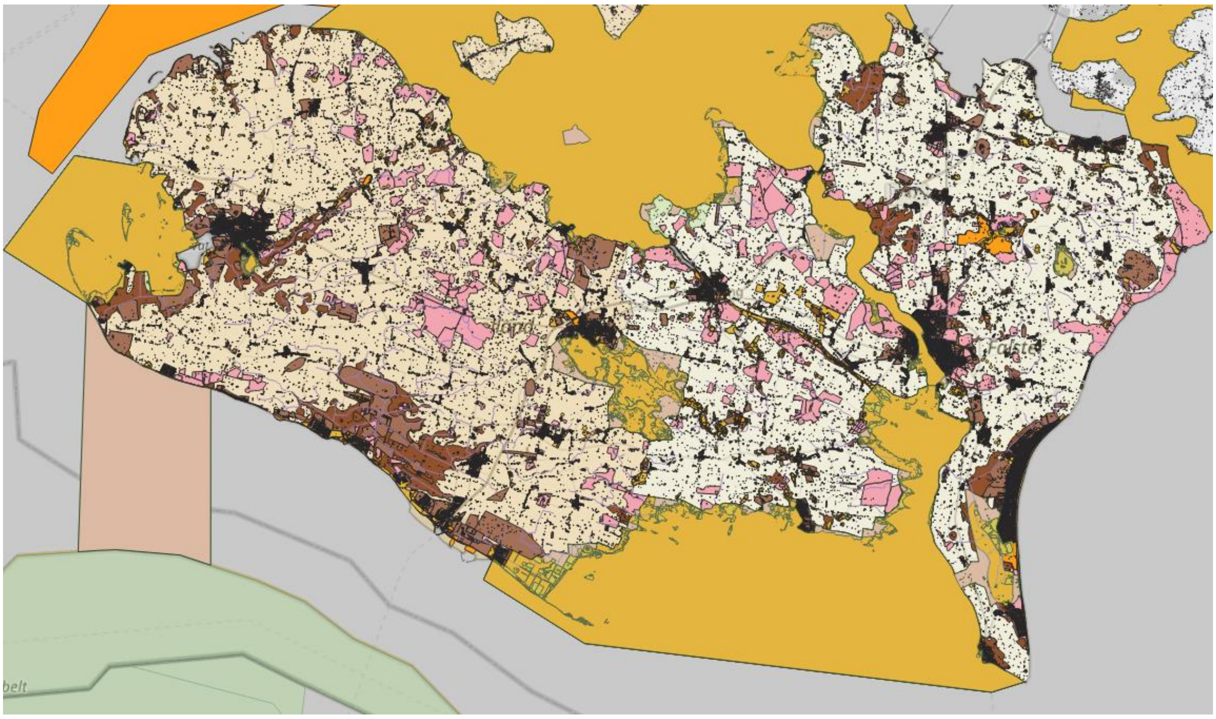


Figure 16 Environmental restrictions at Lolland-Falster

Source: Ramboll

3.2 Regional network

When designing regional networks, we only include the infrastructure (e.g., CO_2 capture, methanol plants, biogas plants) that fits within the regional scope. For instance, a large hydrogen production plant, like the one planned by Copenhagen Energy, is intended solely for hydrogen export due to insufficient local demand. Therefore, the production of substantial hydrogen quantities will be addressed in the international network assessment in the next section.

3.2.1 Green gas Lolland-Falster pipeline

In some scenarios, we will analyze whether it is preferable to produce upgraded biomethane at the biogas plants compared to using the CO_2 for methanol production. However, our analysis will also assume that the biogas is upgraded to meet injection standards for the new natural gas pipeline. Once upgraded, the biogas is compressed to 55 bar and transported via pipeline to the new natural gas pipeline.

In the economic analysis, we assume that the biogas plants are connected to the Green Gas Lolland-Falster pipeline and can produce upgraded biogas for this pipeline. The production of upgraded biomethane will result in even higher gas output. The map below illustrates the pipeline and biogas plant locations, along with their connections.

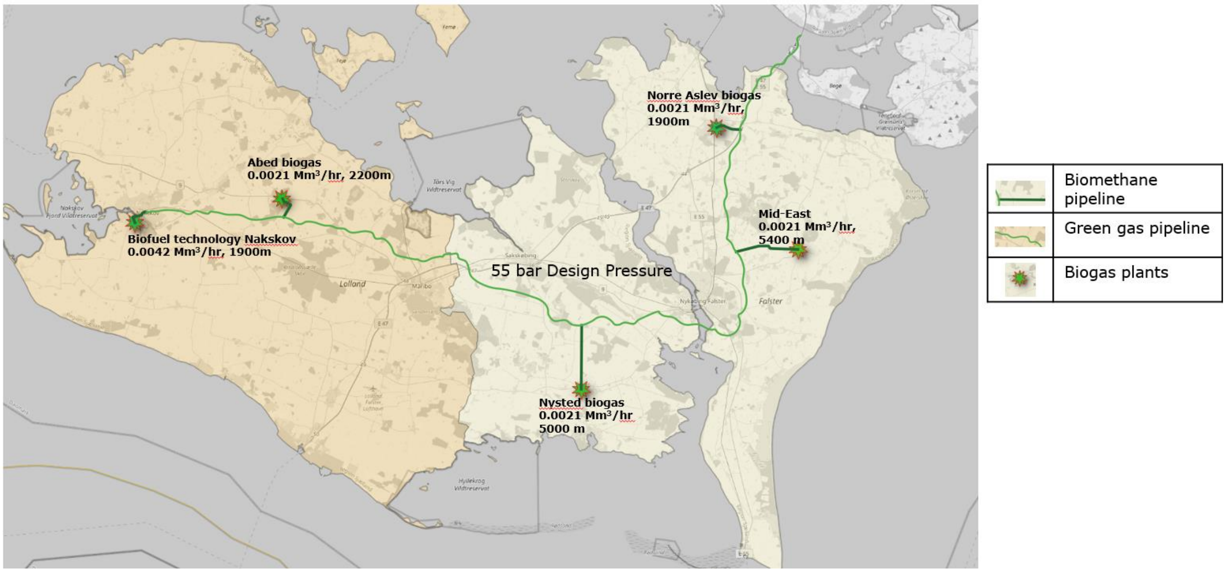


Figure 17 Green Gas Lolland-Falster pipeline with connection to the biogas plants

Source: Energinet, Ramboll

We do not anticipate that converting the new natural gas pipeline to hydrogen transport is feasible. However, the pipeline can be retrofitted to also transport hydrogen in two ways.

<u>Complete retrofit to a hydrogen pipeline</u>

- Requires recommissioning, including purging, which is not advisable.

- Hydrogen certification for the pipeline was discussed in the green gas Lolland-Falster project but did not progress. Energinet has shown no intention to retrofit to hydrogen.
- The pipeline is designed and commissioned for 2024 with the scope limited to gas import/export only.
- Changes required in testing and monitoring requirements.
- Pressure levels are limited by the pipeline design pressure.

Maintaining the current scope of gas transport with a mix of biogas and hydrogen

- Blending up to 2% hydrogen (EU limits for hydrogen content without modifications to equipment and deblending) or above 2%, which would require deblending.
- Testing and monitoring depend on the blending percentage.
- Blending could provide some value for the hydrogen based on its burning value.

As shown in Figure 18, the Green Gas Lolland-Falster pipeline can be extensively used for exporting green gas from Lolland-Falster to Zealand. The local production of biogas, and potentially upgraded biomethane, is able to meet the demand from the sugar factories and other industries, and export biogas to Zealand.

The growing interest in developing biogas plants at Lolland-Falster suggests that the area is well-suited for such projects, given its local agricultural resources and the newly available gas pipeline. This also indicates that the pipeline, originally intended to supply the sugar factories, can create new business opportunities and drive economic growth at Lolland-Falster.

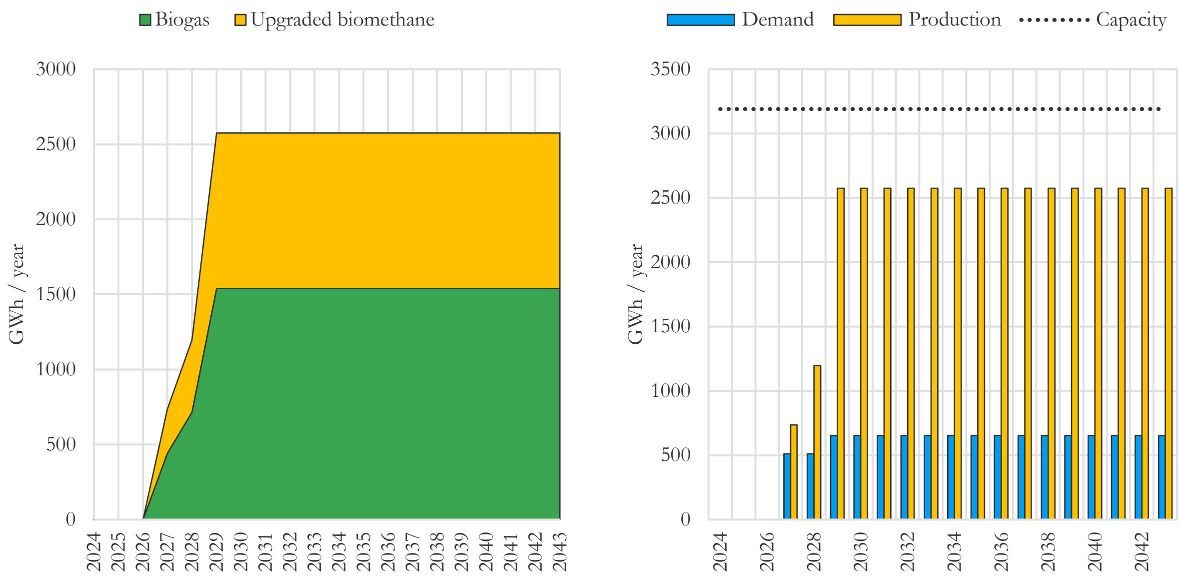


Figure 18 Gas production and comparison to demand and pipeline capacity.

Source: Ramboll

3.2.2 Carbon dioxide pipeline network

The CO_2 network has been designed to connect various point sources of carbon dioxide with demand centers such as methanol plants and subsurface CO_2 storage. The following elements are connected within this network:

- Biogas plants as sources of CO_2 production connected to the network.
- Sugar factories as sources of CO_2 production connected to the network.
- Methanol plants as CO_2 demand centers connected to the network.
- CO_2 subsurface storage site at Rødbyhavn for CO_2 import, buffer storage, and permanent subsurface storage.

The subsurface storage site plays a crucial role in the network's economy, as we will see later. It establishes the necessary CO_2 import infrastructure, which would otherwise need to be constructed at the methanol plants. Additionally, it provides temporary buffer storage for biogenic CO_2 needed for green methanol production via credits trading with imported CO_2. This subsurface site is the central hub and likely the enabler of the CO_2 network, creating significant synergies with methanol production and could well be the key differentiator for Lolland-Falster.

The primary objective is to establish a central import infrastructure with adjacent CO2 storage facilities. If CO2 subsurface storage as a buffer is not feasible, CO2 exchange or local carbon capture at are alternatives. If the Rødbyhavn storage site is unavailable, on-site storage capacity, assuming truck transport instead of pipelines, is required at the carbon capture sites.

CO_2 produced at the biogas plants and sugar factories is transported via CO_2 pipelines to the PtX assets. Any surplus CO_2 is sent to the subsurface storage through the CO_2 pipeline.

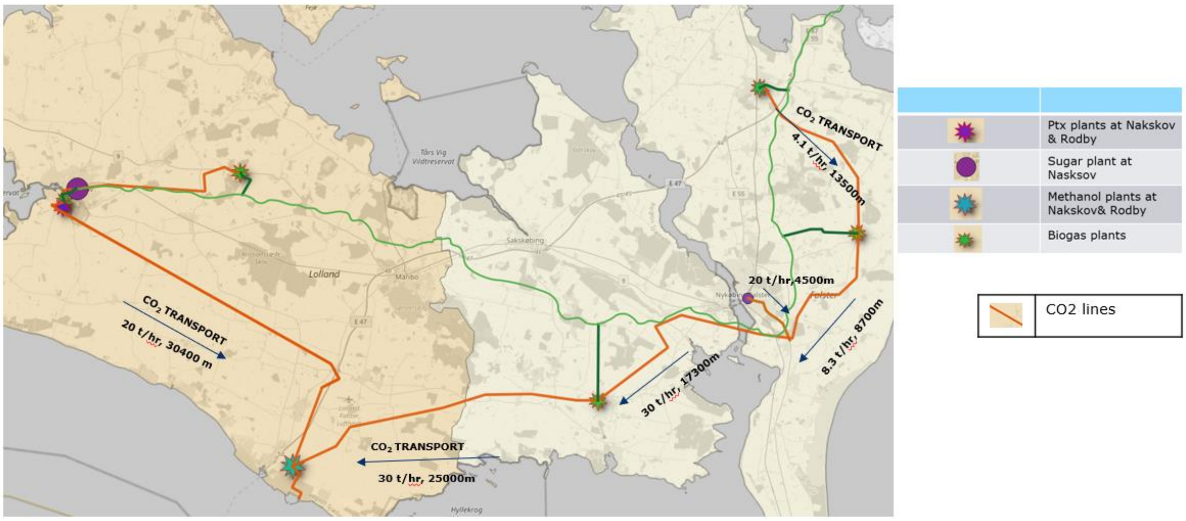


Figure 19 Carbon dioxide pipeline network layout

Source: Ramboll

The carbon dioxide is received in liquid form from the harbor, and it is stored near the storage tanks near the methanol plant. It is transported at the rate of 200 t/ hour. The CO_2 is stored in six storage tanks with 2500 m^3 capacity.

3.2.3 Hydrogen pipeline network

A regional hydrogen network can serve various purposes depending on future regional demand. Currently, there is no significant demand for hydrogen, so the network's viability hinges on the development of future demand, such as biomethane upgrading at biogas plants or hydrogen requirements at methanol plants.

Assuming such demand emerges, the regional hydrogen system could serve several purposes:

- Producing hydrogen at optimal locations close to the renewable energy and distributing it for bio methanation upgrades at biogas plants or methanol production.
- Producing hydrogen at optimal locations to increase local electricity demand and reduce potential bottlenecks in the electricity grid.
- When including a hydrogen cavern storage, it is possible to produce even higher amounts of renewable hydrogen due to storage over time.

We have not examined how a subsurface hydrogen cavern storage affects the potential CO2 storage with regards to the subsurface and displacement of ground water. There is a potential for hydrogen cavern sites in the underground salt structures at Lolland-Falster. We have assumed that it is located at Øllebølle, yet more examination is required.

This means that the hydrogen network for once competes with local hydrogen production at biogas plants if bio methanation is pursued with associated electric grid connection, but it also means that it stands in comparison to establish a CO_2 network for methanol production and exchange on the international market, depending on whether it is more advantageous to produce methanol or biomethane.

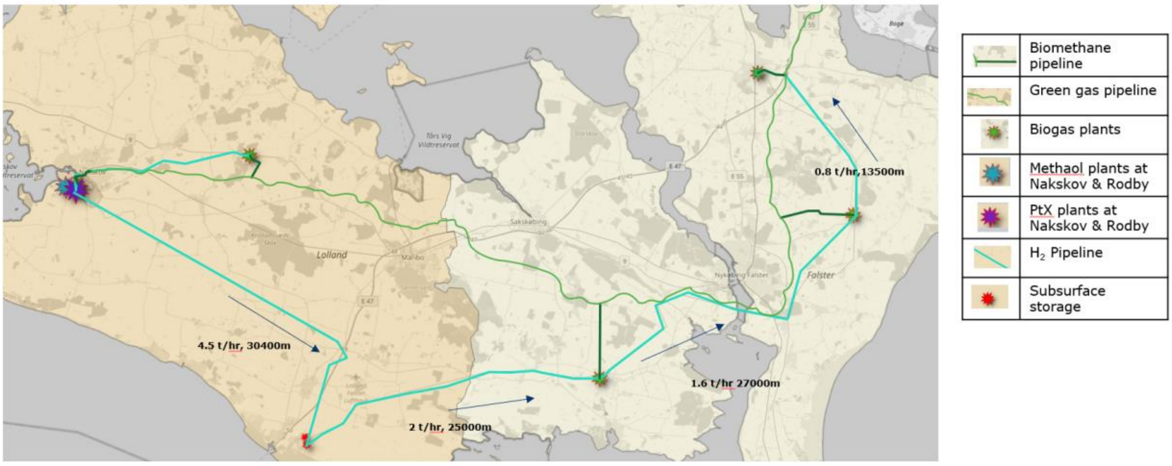


Figure 20 Regional hydrogen pipeline network layout

Source: Ramboll

Furthermore, and most importantly when assessing the hydrogen network, it stands in competition with expansion of the electricity grid. Future regional bottlenecks in the electricity grid are challenging to analyse, making it difficult to compare the real benefits of a regional hydrogen network with reinforcing the local electricity grid without a comprehensive DSO electricity network analysis paired with information on renewable energy locations.

Considering the same units in operation, the regional hydrogen network will follow the same route as the carbon dioxide network, as seen on the map.

3.3 International network

We have only analysed an international hydrogen pipeline connection. It can also be argued that the CO_2 network is inherently international, as it is connected via import infrastructure at the subsurface site in Rødbyhavn. However, we have not conducted any calculations for a CO_2 pipeline extending to Germany or Zealand. Methanol export is also assumed to be via ship.

3.3.1 Hydrogen pipeline network

We size the hydrogen pipeline to match the pipeline dimensions of the European Hydrogen Backbone, stretching across Falster, down to Rødbyhavn, and onwards to Rostock in Germany.

This approach helps us in understanding the marginal cost increase associated with over-dimensioning the pipeline for international hydrogen trade with Germany and import from Zealand. Essentially, it allows us to determine how much of the additional cost will be borne by the expected hydrogen export from Lolland.

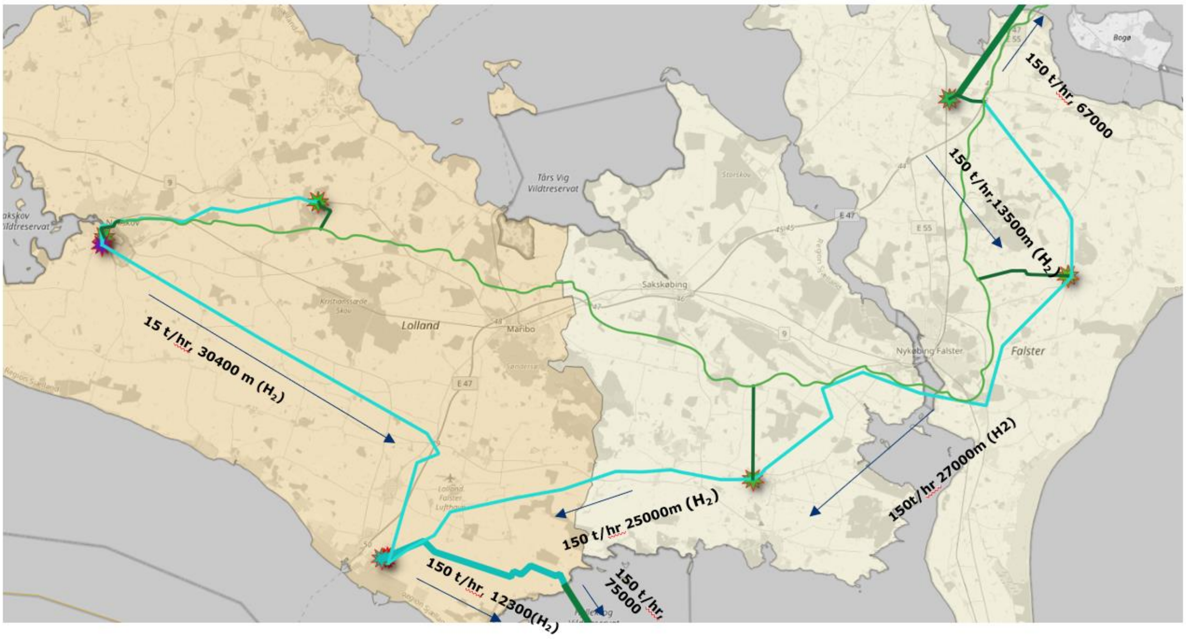


Figure 21 International hydrogen pipeline network layout

Source: Ramboll

3.4 Process facilities

Process facilities have been evaluated from a high-level perspective, which is consistent with CAPEX estimations Class 5. Process assumptions, descriptions and simulation flow sheets are presented in the Technical Report. The assessment is undertaken for the hydrogen, CO2 and methane process facilities required for the operation of the various networks.

4. TECHNO-ECONOMIC EVALUATION

This section presents the techno-economic evaluation of hydrogen and carbon dioxide networks. We assess the scenarios based on economic results, where NPV values reflect all investment and operational costs adjusted to today's price levels. Similarly, the levelized costs, which encompass total adjusted costs over total demand or production, are used to calculate the balancing energy price or operational cost.

For the implementation of both hydrogen and carbon dioxide networks, certain assumptions must be met. These assumptions will be discussed in the subsections for each respective network. Generally, the continuous development of renewable energy sources, PtX plants, and CO_2 subsurface storage are crucial elements to ensure the necessary production and demand.

We have structured the analysis using updated costs and what we believe are realistic price projections wherever possible. However, as with all large infrastructure projects, cost assumptions over the next 35 years are inherently uncertain. Despite these uncertainties, we believe the analysis yields several useful results and comparisons.

One clear conclusion is that if Lolland-Falster aims to increase its renewable energy capacity and become an energy-exporting hub (or energy island), hydrogen and carbon dioxide infrastructures will be crucial. Continuing to rely solely on the electric infrastructure, as it stands today, is an option but not advisable due to potentially significantly higher costs and poorer conditions for integrating renewable energy. Without exploring alternative approaches, the electrical grid will become a bottleneck, hindering further renewable energy expansion in the Lolland-Falster area.

Another crucial aspect of the analysis is the necessity to develop a demand side for renewable electricity production on Lolland-Falster. It is unrealistic to assume that all excess electricity can be exported to Zealand due to the sheer volume of electricity produced. To address this, the demand can be generated through the establishment of methanol plants or electrolysis plants that produce hydrogen for export, primarily to Germany. However, the feasibility of this last option depends on the Hydrogen Backbone connection to Zealand and Germany via Lolland-Falster.

The pipeline infrastructure for carbon dioxide and hydrogen is highly relevant when considering these needs. The carbon dioxide network will transport the carbon dioxide feedstock to the methanol plants, while the hydrogen network can serve as an alternative to electricity transport. Developing a hydrogen cavern storage would enhance flexibility, enabling better utilization of locally produced renewable electricity for methanol production or export.

The techno-economic analysis is structured in the following way:

- First, we present an analysis of constructing a CO_2 pipeline infrastructure and evaluate its economic aspects compared to truck transportation. This analysis assumes that CO_2 will be required at methanol plants and that CO_2 subsurface storage will serve as an import/export hub (intermediate storage) for CO_2 trading. We then assess the network expansions to include carbon capture at sugar factories and biogas plants.
- Next, we present the operational aspects of a hydrogen network and the economic evaluations for the entire future energy system on Lolland-Falster.

4.1 Assumptions

4.1.1 Cash flow analysis and levelized cost of energy

The economic model is structured as a cost-benefit analysis to assess the costs and benefits associated with each scenario and the corresponding sensitivity analyses. Our cost-benefit analysis method relies on forecasted fuel prices, electricity prices, and other costs, primarily based on Ramboll's assumptions unless otherwise stated. The investment plan covers the timeline for investments and subsequent operations for the following:

- Capacities for renewable energy with a focus on wind and solar, or the purchase of electricity.
- Electrolysis.
- Energy storage with a focus on hydrogen cavern storage.
- Energy networks for hydrogen, CO_2, and electricity.
- Methanol synthesis plants.
- CAPEX (Capital Expenditure) and OPEX (Operational Expenditure).

The energy system analysis employs a time-series approach without detailed cost-based optimization of asset operation timing. We opted for this method to maintain model simplicity and reduce simulation time. Future work could delve deeper into such analysis.

To compare the scenarios, we will analyze the export and import of energy (hydrogen, CO_2, electricity) through the energy system model and calculate CAPEX, OPEX, and other costs for each scenario. This includes considering alternative investments in the electrical system to assess the value of a hydrogen network compared to conventional electrical systems. The economics of the CO2 and hydrogen networks will be evaluated separately in a larger assessment for all of Lolland-Falster.

The Levelized Cost of Energy (LCOE) calculation compares the total costs of each concept to the total energy production over the project's lifetime. However, the LCOE approach has certain limitations, as it assumes costs are evenly distributed annually without accounting for short-term price fluctuations in fuel and electricity.

4.1.2 Energy system analysis assumptions

The energy system analysis for the area is based on an hourly time series analysis by using duration curves for the expected electricity production from renewable energy.

4.1.3 Economic analysis assumptions

The CAPEX and OPEX assumptions are in the Technical Report for the relevant energy technologies analysed as well as the hydrogen and carbon dioxide networks which are also described in detail in the previous section, as these are the focus points of this analysis.

We have assumed that the CAPEX costs are placed in the beginning of the project evaluation period even as some projects will be realised later. A phased implementation will have some influence on the results per scenario, but can distort the comparison between scenarios.

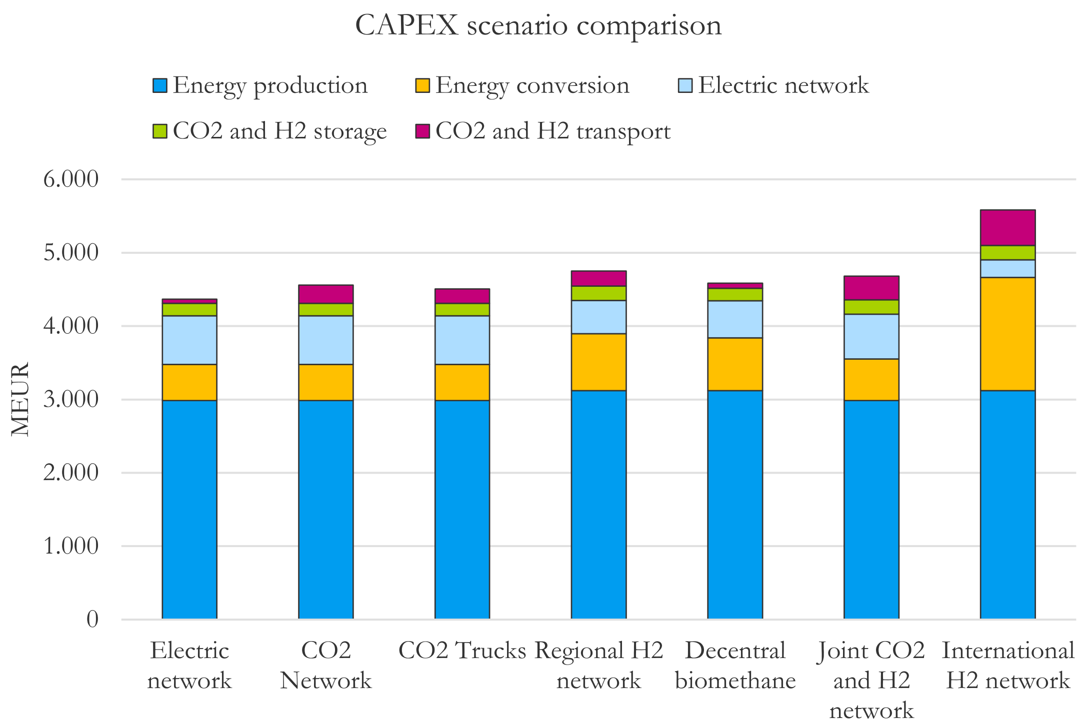


Figure 22 CAPEX comparison (development scenario)

Source: Ramboll

The figure above compares the CAPEX estimates in the development scenario. As shown, the CAPEX for carbon dioxide and hydrogen storage and transport is relatively modest compared to energy production CAPEX.

Additionally, as the system transitions to a more hydrogen-based one, the CAPEX for the alternative electric grid infrastructure decreases. However, the CAPEX for energy conversion, including electrolysis and synthesis plants, increases simultaneously.

4.1.4 Scenario structure

In the scenario analysis, we will be comparing six scenarios against the base case scenario of continuing to rely on the electricity grid only. The six scenarios are the following:

- Base case: Electricity grid only
  - No PtX development. This serves as the base case scenario against which the other scenarios will be compared.
- Sc. 1.1: Regional carbon dioxide network
  - CO_2 will be captured from various point sources (e.g., sugar factories and biogas plants) and exchanged with CO_2 subsurface and import facilities in Rødbyhavn via a CO_2 network.
- Sc. 1.2: Regional carbon dioxide trucks

    - CO_2 will be captured from various point sources (e.g., sugar factories and biogas plants) and exchanged with CO_2 subsurface and import facilities in Rødbyhavn via CO_2 trucks.
- Sc. 2.1: Regional hydrogen network
    - A regional hydrogen network with cavern storage will facilitate long-term hydrogen storage, enabling increased local hydrogen production for methanol production and bio methanation. CO_2 will still be imported to the methanol plant in Nakskov via Rødbyhavn, similar to scenario 2, but the remainder of the CO_2 network will not be included.
- Sc. 2.2: Decentral biomethane production (using the electricity grid)
    - The hydrogen network will be excluded, and hydrogen will instead be produced on-site at the biogas plants and methanol plants using the electricity grid.
- Sc. 3.1: Joint hydrogen and carbon dioxide network
    - This scenario assumes that CO2 is captured on the biogas plants and fed into the CO2 network. For the hydrogen network we assume that it is only connected to the methanol plants and optimal location of electrolysis units in relation to the renewable energy production to utilize the flexibility as before.
- Sc. 3.2: International hydrogen network
    - This scenario builds on scenario 3 by including two hydrogen plants from Copenhagen Energy and assumes a connection to the European Hydrogen Backbone, linking Lolland-Falster to Zealand and Germany. Hydrogen can be exported via this pipeline.

Based on this outline of scenarios, we can assess the different development paths for Lolland-Falster under the three different renewable energy development scenarios outlined in the market assessment.

4.2 Carbon dioxide network

We assume that the development of the CO2 network will proceed in stages, starting from the planned subsurface storage facility in Rødby. Initially, the focus will be on supplying CO2 for the methanol production, followed by the integration of CO2 capture at the sugar factories and biogas plants. Identifying the sweet spot and determining the most economically viable approach is crucial. Therefore, we will compare the CO2 network with the import of CO2 via trucks and the necessary short-term storage facilities.

We consider the captured biogenic CO2 a revenue source for Lolland-Falster, either through the sale of carbon credits or the potential export of CO2. This revenue consideration is essential for assessing the overall economic feasibility and benefits of the CO2 network expansion.

4.2.1 Carbon dioxide transportation

The first comparison we undertake is to determine whether it is preferable to transport CO2 via pipelines or trucks. The main differences between these two transportation modes are as follows:

- Pipelines: These will be connected to the Rødbyhavn storage site (Carbon Cuts), serving as a buffer in the system to balance fluctuations between demand and supply.
- Trucks: Intermediate CO2 storage is needed at both the capture sites and the demand sites to balance import/export with demand and supply.

For both pipelines and truck transportation, onsite process facilities are required to ensure compliance with operation parameters. However, these facility costs are not included in the transportation cost comparison as they are the same for both modes.

We have assumed a cost of 30 EUR per ton of CO2 for truck transportation.

When examining the results of the CO2 transportation cost assessment between pipelines and trucks, several conclusions are evident:

- West Lolland: If the CO2 storage site in Rødbyhavn and the methanol plant in Nakskov are operational, it is cost-effective to have a pipeline connection between the two. This pipeline would also facilitate the connection of the sugar factory in Nakskov and biogas plants, enabling them to deliver CO2 into the same network. Therefore, West Lolland should have an operational CO2 pipeline infrastructure rather than use trucks for CO2 transportation.
- East Lolland and Falster: For East Lolland and Falster, where CO2 is transported from sugar factories and biogas plants to the storage site in Rødby (and potentially to methanol plants), the economy of a pipeline infrastructure is more challenging compared to truck transportation. However, if all sources are connected, the pipeline infrastructure is beneficial as a stand-alone solution for this area as well.
- Overall network: When considering the entire Lolland-Falster area, assuming all demand and supply points are connected to the network, the pipeline infrastructure is preferable to truck transportation. A possible solution can be to establish a West-Lolland pipeline infrastructure and base the East-Lolland and Falster area on trucks.

The next task is to understand the costs associated with CO2 capture, demand, and storage to determine the market price for CO2 in Lolland-Falster.

Table 8 Comparison between CO2 pipelines and truck transportation

Area	Location	Unit	CO2 pipelines	CO2 trucks
West Lolland	**Rødbyhavn – Nakskov (only methanol plant)**	EUR / ton CO2	19	42
	Rødbyhavn – Nakskov (all)	EUR / ton CO2	15	45
	Rødbyhavn-Nakskov-Abed	EUR / ton CO2	16	45
	Nakskov-Abed	EUR / ton CO2	18	38
East Lolland and Falster	**Rødbyhavn-Nysted**	EUR / ton CO2	69	38
	Rødbyhavn-Nysted-Nykøbing	EUR / ton CO2	40	40
	Rødbyhavn-All	EUR / ton CO2	35	39
Overall network		EUR / ton CO2	**23**	**43**
Combination (Pipelines on West Lolland and Trucks on East Lolland and Falster)		EUR / ton CO2		**26**

4.2.2 Carbon dioxide capture

Like the transportation cost assessment, we evaluate the carbon capture cost for the various point sources included in the network assessment. Unlike the transportation cost differences observed between the eastern and western parts relative to Rødbyhavn, capture costs do not vary as significantly.

The carbon capture costs are derived by considering the process facilities and carbon capture units at the sugar factories. We expect that CO2 is already being stripped from the upgraded biogas at the biogas plants, so we only include additional costs for process facilities related to network operation.

Overall, we find that CO2 can be made available more cheaply from biogas plants compared to sugar factories, which operate only during a limited part of the year.

The capture costs should be compared to alternative capture costs at power plants or large industrial facilities in countries like Sweden, Denmark or Germany, including the associated transport and import costs through the planned CO2 terminal in Rødbyhavn.

Table 9 Comparison of CO2 capture costs

Area	Location	Unit	CO2 capture
West Lolland	Sugar factory Nakskov	EUR / ton CO2	92
	Abed biogas	EUR / ton CO2	30
	Nakskov biogas	EUR / ton CO2	23
East Lolland and Falster	Nysted biogas	EUR / ton CO2	35
	Sugar factory Nykøbing	EUR / ton CO2	92
	Midt-Falster biogas	EUR / ton CO2	31
	Nørre Alslev biogas	EUR / ton CO2	31
Overall		EUR / ton CO2	**52**

4.2.3 Carbon dioxide system operation

To optimize the CO2 system at Lolland-Falster, an intermediate CO2 storage facility is essential. This storage will interact with the subsurface CO2 storage in Rødbyhavn (Carbon Cuts), allowing for the storage of excess CO2 and the utilization of large import streams to supply methanol plants when needed. While the assurance that the CO2 is green can be provided using credits, the actual CO2 molecule used in the process may not necessarily be green. The subsurface storage cannot be used for short-term storage, but credits can be used instead to ensure the green certification.

As shown in the figure, capturing all CO2 from industrial sources (such as sugar factories) and biogas plants will meet the CO2 requirements of the two methanol plants planned by European Energy at Lolland. However, due to variations between demand and supply, there will be instances where CO2 is utilized directly, stored as excess, or sourced from storage to meet deficits. In the scenario presented, there will be an excess of CO2 for the year, which will be stored and generate tradable credits (a positive economic outcome). In case of a deficit, CO2 can be purchased from the storage site.

The capture price at the sugar factories can be compared to the import price at Rødbyhavn from power plants in Germany for example. The power plants in Germany and elsewhere will also "suffer" from not having a high number of annual full-load hours (like the sugar factories) due to renewable energy integration, why the CO2 capture cost at the sugar factories can be competitive.

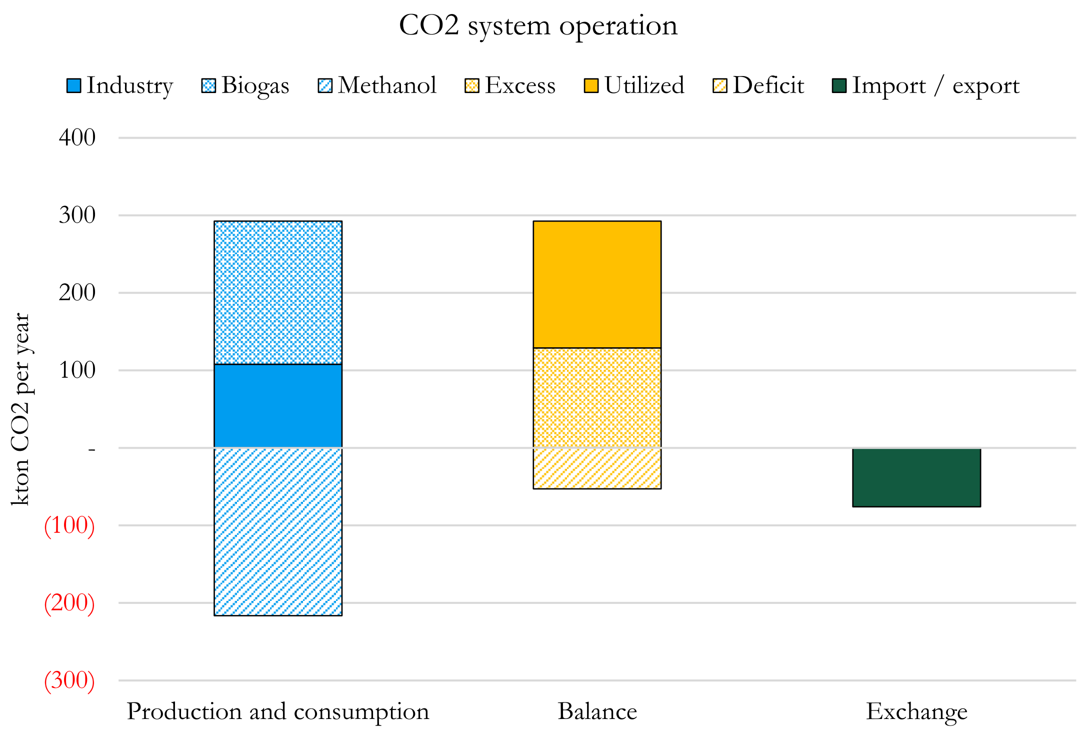


Figure 23 CO2 system operation at Lolland-Falster (at full expansion)

Source: Ramboll

By applying an exchange price of CO2 at 100 EUR per ton for both import and export, we find the NPV as shown in the table. When converted to EUR per ton of CO2, this results in a relatively justifiable CO2 price compared to the exchange price.

- The levelized CO2 price without CO2 exchange is **89 EUR per ton of CO_2**.
- The levelized CO2 price with CO2 exchange is **65 EUR per ton of CO_2**.

Table 10 Economic breakdown (central concept)

	Unit	CAPEX	PM, DEVEX, design, engineering, etc.	OPEX	Residual value	CO_2 import / export	NPV
Result	MEUR	(194)	(19)	(69)	12	73	(164)

On a stand-alone basis, it is economically beneficial to develop a CO_2 network with pipelines at Lolland-Falster. This assumes that the import facilities and subsurface storage facilities will be built at Rødbyhavn and that the methanol plants will be operational in Nakskov and Rødbyhavn. While carbon capture from sugar factories and biogas plants positively contributes to the network, it is not the determining factor for its economic viability.

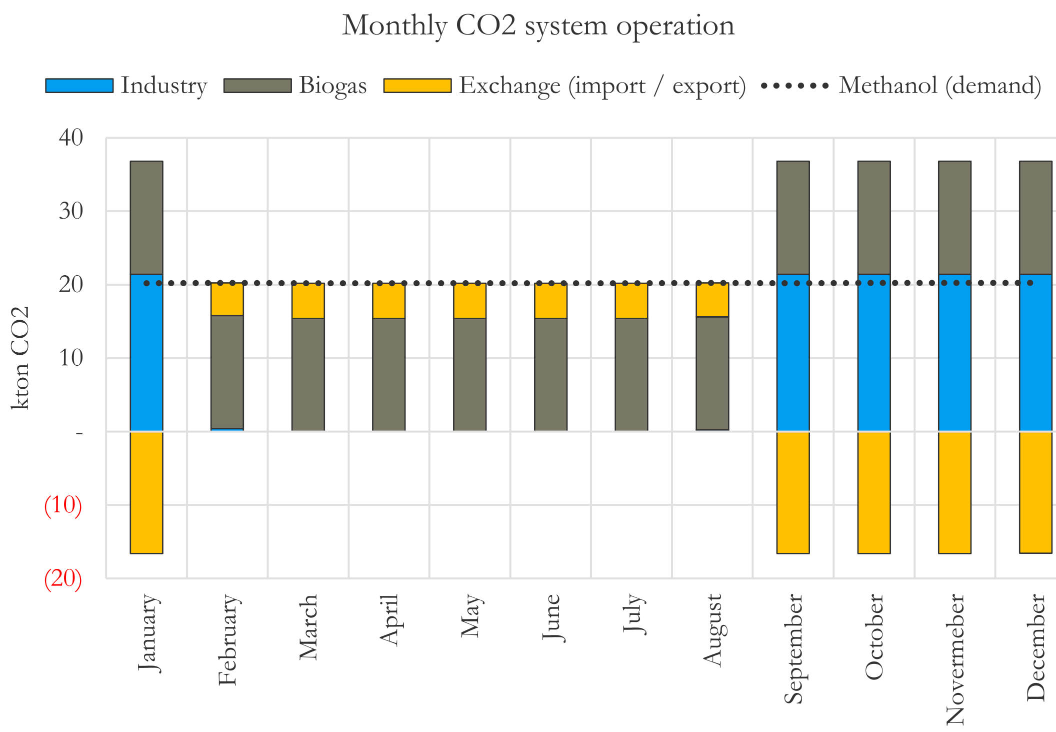


Figure 24 CO2 system operation on a monthly basis (assuming possible exchange with CO2 storage)

Source: Ramboll

The monthly operation of the CO2 system is depicted in the figure above. It illustrates the operation over a year, capturing CO2 from biogas plants and sugar factories (industry). As shown, there will be a deficit during the spring and summer when the sugar factories are not operational. This deficit can be covered with imports from the potential subsurface storage site at Carbon Cuts. However, during periods when the sugar factories are operational, there will be a substantial amount of excess CO2 that cannot be utilized by the methanol plants. This excess can be stored in the subsurface storage and traded as green CO2 credits. Thus, the subsurface storage can function as a CO2 bank for exchanges on Lolland-Falster and with the wider international market.

4.3 Hydrogen network

The regional hydrogen network has a slightly different comparison base than the CO2 network. The regional hydrogen network may provide several benefits, such as balancing fluctuations from renewable energy through potential subsurface storage and line packing (around 100 MWh for the regional hydrogen system) within the network. Utilizing the local hydrogen network for storage can support the continuous operation of methanol synthesis.

Another relevant comparison involves either producing upgraded biomethane using locally produced hydrogen or using centrally produced hydrogen distributed to biogas plants. This comparison would shift the focus to central electrolysis, requiring reinforcement of the electrical grid. Additionally, developing both CO2 and hydrogen networks could offer an advantage by allowing arbitrage between producing upgraded biomethane via hydrogen or capturing CO2 for methanol production, depending on market prices at the time.

We will furthermore assess the potential for expanding the regional hydrogen network to an international hydrogen network, connecting to the planned European Hydrogen Backbone via Zealand and Germany. In this scenario, the two planned hydrogen production plants by Copenhagen Energy could produce hydrogen for export to Germany.

The figure below illustrates the challenges of operating the electricity system on Lolland-Falster in 2035. It is highly likely that the electricity system will be unable to manage these challenges effectively. Therefore, converting the energy into molecular form can significantly help the electricity system integrate renewable energy more efficiently.

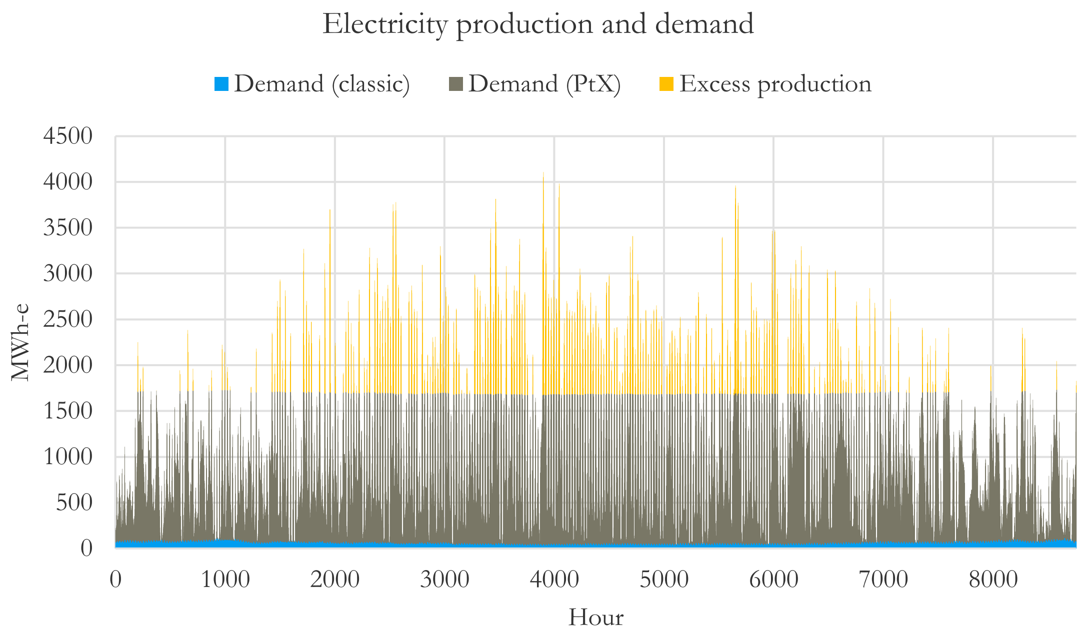


Figure 25 Electricity system operation (development scenario 2035)

Source: Ramboll

4.3.1 Hydrogen network operation

Comparing hydrogen transportation costs is distinct from comparing CO2 transportation costs, as the alternative for hydrogen is not truck transportation but rather using the electric grid instead of a hydrogen network.

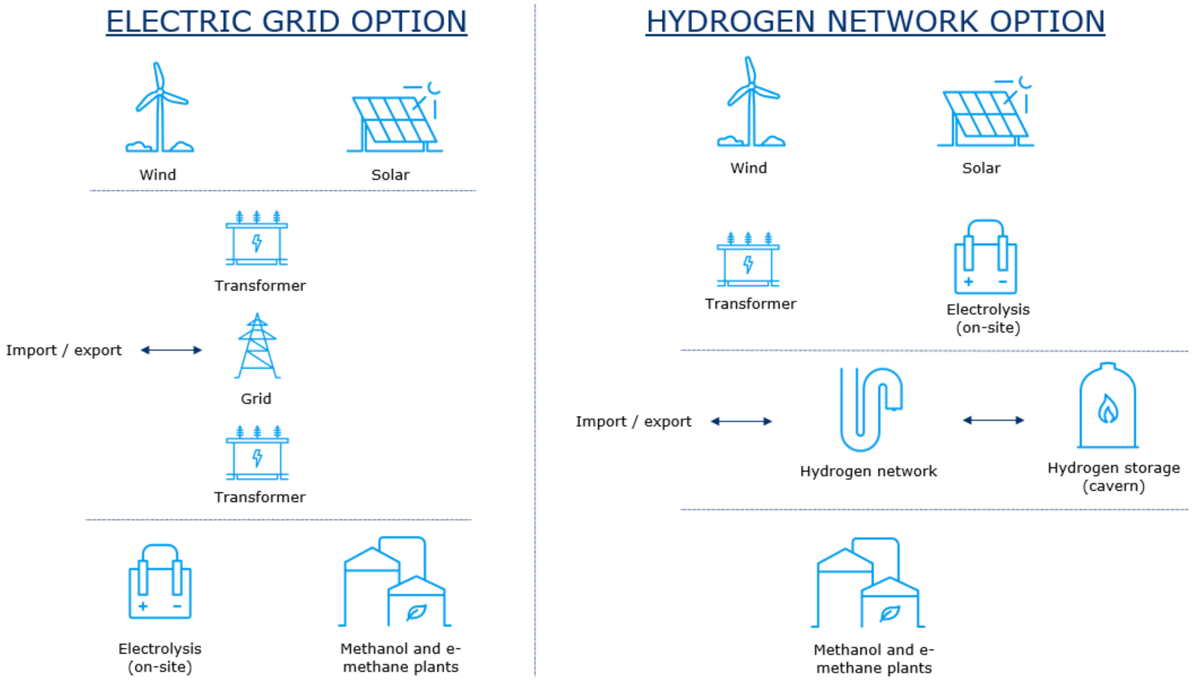


Figure 26 Electric grid and hydrogen network options for energy transport.

Source: Ramboll

The two options for energy transport, either as electricity or hydrogen, are shown in the figure above. This comparison is only relevant if the demand side requires hydrogen for their production or industrial facilities. If the end use is electricity, the hydrogen option is too expensive due to significant energy losses during conversion.

However, on Lolland-Falster, a demand for hydrogen can be established at the biogas (e-methane) and methanol plants. This can enable the use of a hydrogen network instead of the electric grid, offering greater flexibility and better integration of renewable energy. The import and export of electricity and hydrogen will be possible through connections to broader electricity and hydrogen networks in the future.

The regional hydrogen networks can provide a constant supply of green hydrogen to methanol synthesis and bio methanation processes at biogas plants. This would enable the conversion of more renewable electricity to hydrogen throughout the year compared to a scenario without the hydrogen network. Without this infrastructure, methanol production would need to operate flexibly to integrate renewable energy or import electricity at higher prices during periods without renewable energy in the system. We assume that a hydrogen cavern storage facility is established in Øllebølle to balance these fluctuations.

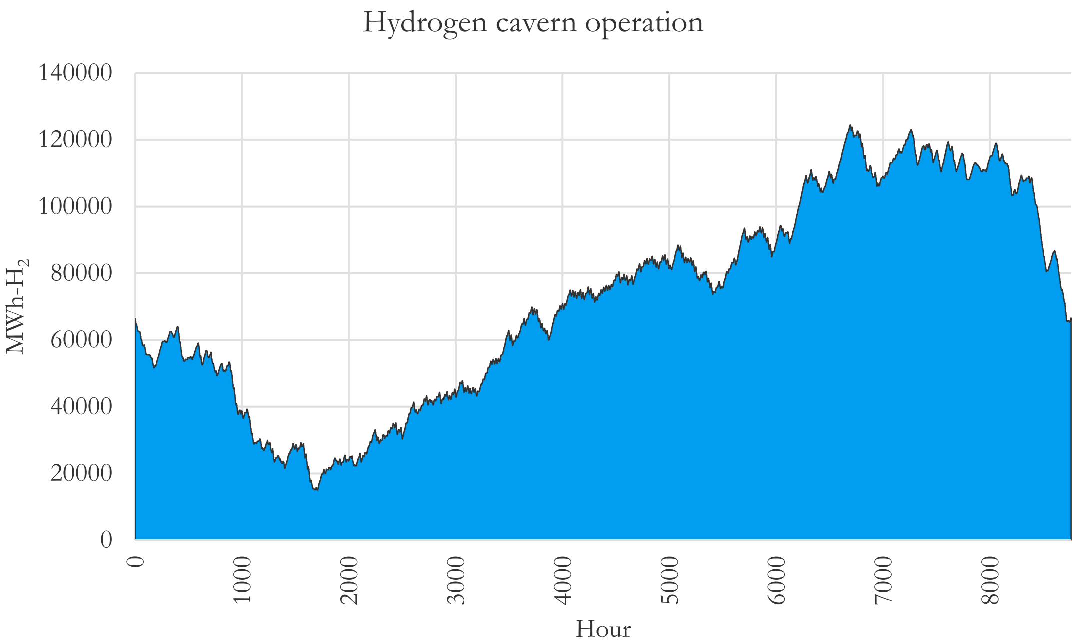


Figure 27 Hydrogen cavern operation (development scenario 2035, sc. 2.1)

Source: Ramboll

As shown in the figure, the hydrogen cavern, when operated optimally, can help balance the hydrogen system by storing excess electricity/hydrogen generated from solar PV during the summer for use during the winter.

However, the cavern storage can, as shown, only balance the relatively modest hydrogen system on Lolland-Falster. If a larger system is created, the number of caverns needed will need to increase accordingly.

The operation of the hydrogen system is best understood by comparing it with alternative scenarios. The figure below illustrates how electricity produced from renewable energy sources is utilized for electricity export, hydrogen, e-methane, e-methanol, and excess heat production.

In all scenarios, methanol production is assumed. However, in Scenario 2.1, it is possible to slightly increase the production of methanol and e-methane, as the hydrogen system can function as an intermediate buffer storage. This flexibility is not available in Scenario 2.3, where hydrogen is assumed to be produced at the location of the biogas and methanol plants. Additionally, this scenario results in increased excess heat production. In Scenario 3.2, where there is a connection between the hydrogen production plants of Copenhagen Energy and the potential Hydrogen Backbone, the amount of excess heat also increases substantially.

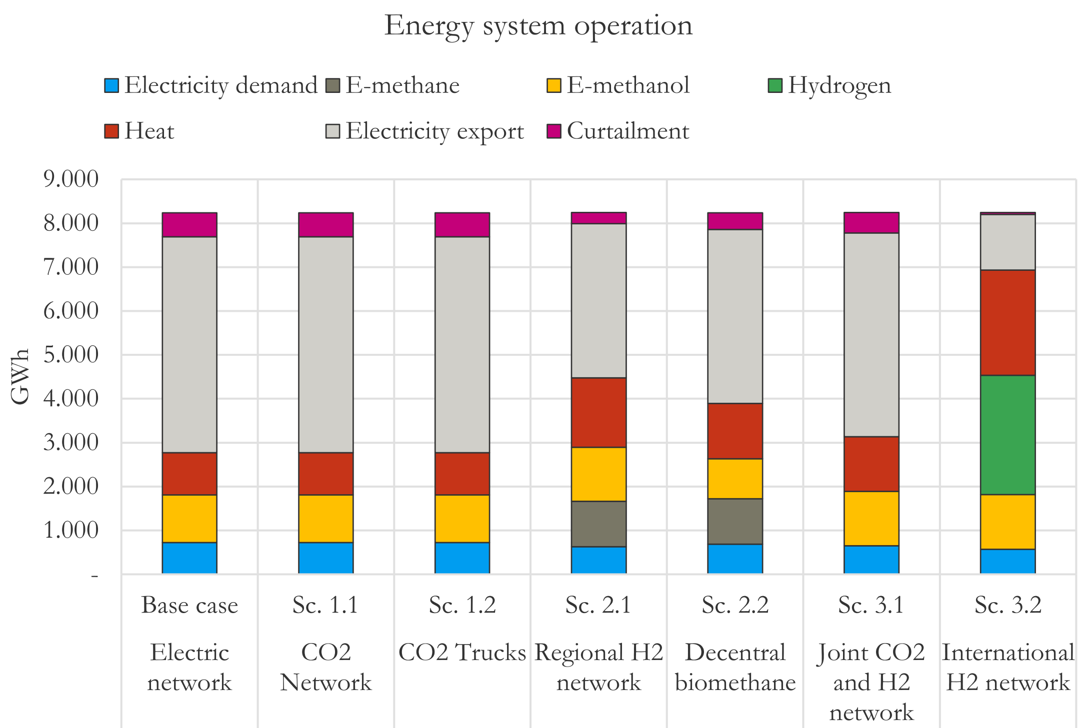


Figure 28 Energy system operation on Lolland-Falster (development scenario 2035)

Source: Ramboll

Table 11 Comparison between electric and hydrogen transport for production costs

Area	Location	Unit	Electric network	Regional hydrogen network		International hydrogen network
				Incl. biomethanation	Methanol only	
Lolland-Falster	Electricity transport	EUR / MWh	6	-	-	-
	Hydrogen transport	EUR / MWh	-	8	8	12
	-	EUR / kg H2	-	0.3	0.3	0.4
	Hydrogen production	EUR / MWh	79	84	80	97
	-	EUR / kg H2	2.6	2.8	2.7	3.2

The hydrogen production costs presented reflect the price of hydrogen at the receiving end of the pipeline or, alternatively, the production costs when using the electric grid. These prices relate exclusively to the hydrogen system and do not account for the broader energy system perspective.

The costs encompass all relevant expenses related to electricity or hydrogen transport. Essentially, these are the costs at which hydrogen can be produced on Lolland-Falster. From the perspective of the end product cost, the expenses of using the electric grid or a hydrogen network for energy transport are relatively similar. However, system integration aspects may make the hydrogen network a more favorable option.

Compared to other projects, such as those focused on offshore wind to hydrogen production, the production costs here are lower. Typically, offshore projects cost 3.5 EUR/kg H2 and upwards. The lower production costs in this case are due to the cheaper establishment of onshore wind and solar PV, which also show complementarity across different seasons.

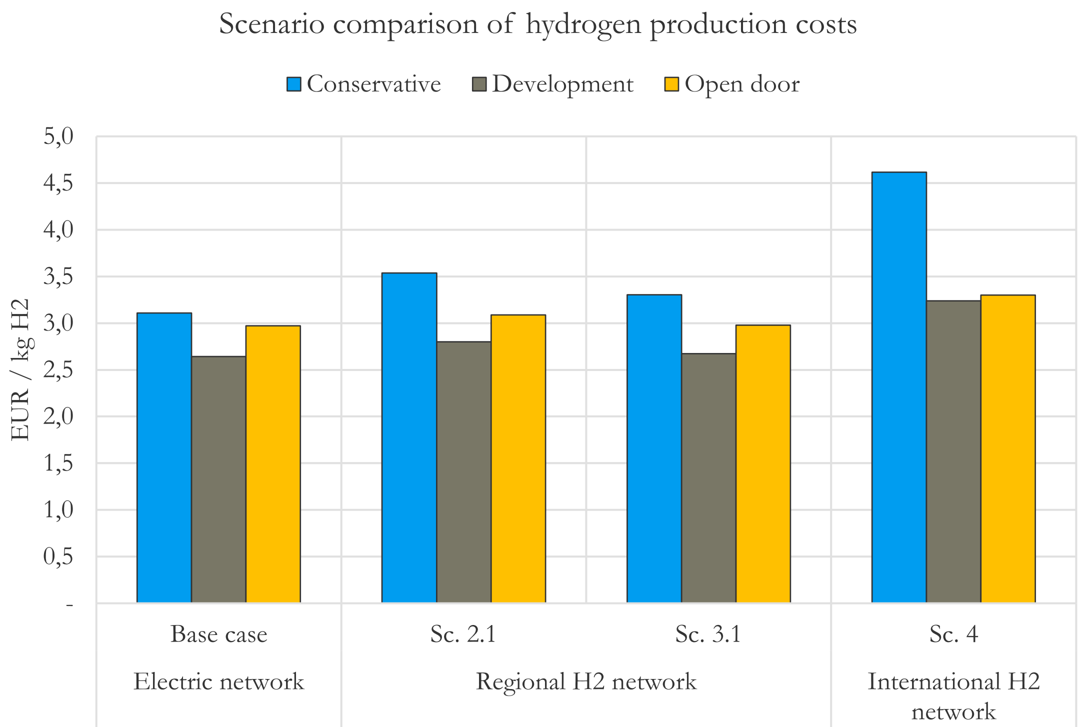


Figure 29 Comparison of hydrogen production costs between scenarios

Source: Ramboll

If the open-door projects are established, hydrogen production for export or methanol production could exceed expectations from the two Copenhagen Energy hydrogen plants. It is likely preferable to double the hydrogen production capacity with an additional 1 GW of electrolysis capacity.

4.3.2 Hydrogen pipeline regulation

4.3.2.1 Danish political agreement

Before analyzing the hydrogen network transportation costs on Lolland-Falster and potentially across Eastern Denmark, it's important to outline the key points from the Danish political agreement on hydrogen infrastructure regulation[7], as these are highly relevant to our analysis.

The political agreement include the following:

- Adoption of regulated third-party access for hydrogen infrastructure.
    - Users are required to pay tariffs, based on a methodology from Forsyningstilsynet, with no exemptions.
    - Companies (system operators) can defer part of their tariff revenues to reduce initial user risks, with the opportunity to recover accumulated deficits later.
    - A portion of the infrastructure capacity is reserved for short-term contracts (10 % of the total pipeline capacity).

- Hydrogen infrastructure companies are expected to operate as natural monopolies and will be subject to economic revenue regulation.
    - The regulation will initially have two-year periods and will be flexible to accommodate the uncertainties of the emerging market.
    - Efficiency measures will not be imposed during the initial phase due to the significant uncertainties.
    - Forsyningstilsynet is responsible for the regulation of the economic framework related to hydrogen pipeline operation.

The agreement is a political commitment where parties agree to support necessary legislation and funding, setting the framework for potential investment decisions.

Related to the Hydrogen Backbone in Jutland, the state may take on part of the risk in establishing the hydrogen backbone, particularly with Energinet's potential investment, estimated at around 2 billion EUR. Specific conditions must be met before the state commits to financial support, including long-term user commitments and agreements with German partners. The state requires a binding agreement on use of 1.4 GW out of 3 GW of capacity for the next 10-15 years from companies intending to use the pipeline for hydrogen transport to Germany. Furthermore, the Danish state is also requiring commitment from the German offtake to guarantee the risk taking.

The financial structure involves a distribution of risks and costs among stakeholders, including agreements on managing cost overruns, revenue delays, or market changes. The pipeline will operate within a regulated market where the government sets rules on safety, tariff structures, and competition, impacting how revenue is generated and distributed. Furthermore, Energinet is requires to establish a wholly owned subsidiary that is legally and financially separate, without parent company liability, to manage activities related to the possible establishment, financing, and operation of the hydrogen system.

[7] https://www.kefm.dk/Media/638204311368810699/Aftaletekst%20-%20mulighed%20for%20etablering%20af%20brintinfrastruktur.pdf

4.3.2.2 Comparison of ownership models

There are essentially three potential ownership models for a hydrogen infrastructure: public, private, and public-private. The Danish political agreement primarily lays the groundwork for the hydrogen backbone in Jutland. However, other ownership models for hydrogen infrastructure, or parts thereof, could also be relevant, as outlined below.

Public Ownership

- Public ownership offers stable, long-term funding, independent of short-term private investment goals. It ensures regulatory compliance and fair access through tariff adjustment, with usually lower financing costs due to the state's borrowing advantage. Nonetheless, it may face budget constraints and bureaucratic delays, and while it provides reliable revenue, it could limit project agility, with profits varying based on political will and public endorsement.
- This type of ownership has today been preferred in Denmark for the onshore electricity, gas, and district heating systems. This ownership model ensures that the energy transportation infrastructure is under public control.

Private Ownership

- Private entities are driven to enhance efficiency and innovation for higher returns. They operate without public fiscal restrictions, which may allow for quicker decision-making. However, this comes with higher financing costs due to increased risk and could potentially compromise public welfare for profit.
- An example of this type of ownership is the British and Italian TSO´s, National Grid and Enel, which are privately owned and operated under a regulatory framework set by the government. The Danish offshore oil and gas pipelines are also privately owned.

Public-Private Partnership (PPP)

- PPP leverages a mix of public stability and private investment to mitigate risk and boost project funding. Despite its potential, PPPs often involve intricate negotiations and might incur higher costs and delays, with a risk of conflicting interests between public and private entities in changing economic or political climates.
- Examples of this type of ownership include offshore wind projects in Germany, but also the envisioned ownership model for the Energy Island in the North Sea and the six current offshore wind tenders in Denmark, where the Danish state will co-ownership 20 %.

4.3.3 Hydrogen transportation costs

Developing a regional hydrogen pipeline system on Lolland-Falster is likely most effective as a distribution network. In contrast, the larger hydrogen backbone system planned for Eastern Denmark will function as a transmission network, connecting to Sweden, Germany, and Western Denmark via Funen. In this analysis, we have not evaluated the costs of establishing the entire hydrogen backbone in Eastern Denmark. Our assessment has focused solely on the costs associated with the pipeline section connecting Lolland-Falster with Germany and Zealand.

We have not conducted a detailed financial analysis of the three ownership models. However, the differences can be illustrated through a simplified example that highlights how ownership models primarily impact costs through variations in financing rates and profit margins.

- Public Ownership: With state-financed loans, a lower interest rate can typically be secured. The project would focus solely on cost recovery, without incorporating a profit margin. Assuming a 4.0% discount rate, the transportation cost for hydrogen in the international scenario is approximately 0.35 EUR/kg.
- Private Ownership: In this scenario, a higher interest rate of 8% can be assumed due to the risk premium associated with private funding. Additionally, a profit margin of around 10% on costs is assumed. With an 8.0% discount rate, including a 10% profit margin, the transportation cost for hydrogen in the international scenario is approximately 0.55 EUR/kg.
- Public-Private Partnership: Here, a mid-range interest rate can be assumed due to the shared risk, along with a moderate profit margin of around 5%. Assuming a 6.0% discount rate, including a 5% profit margin, the transportation cost for hydrogen in the international scenario is approximately 0.45 EUR/kg.

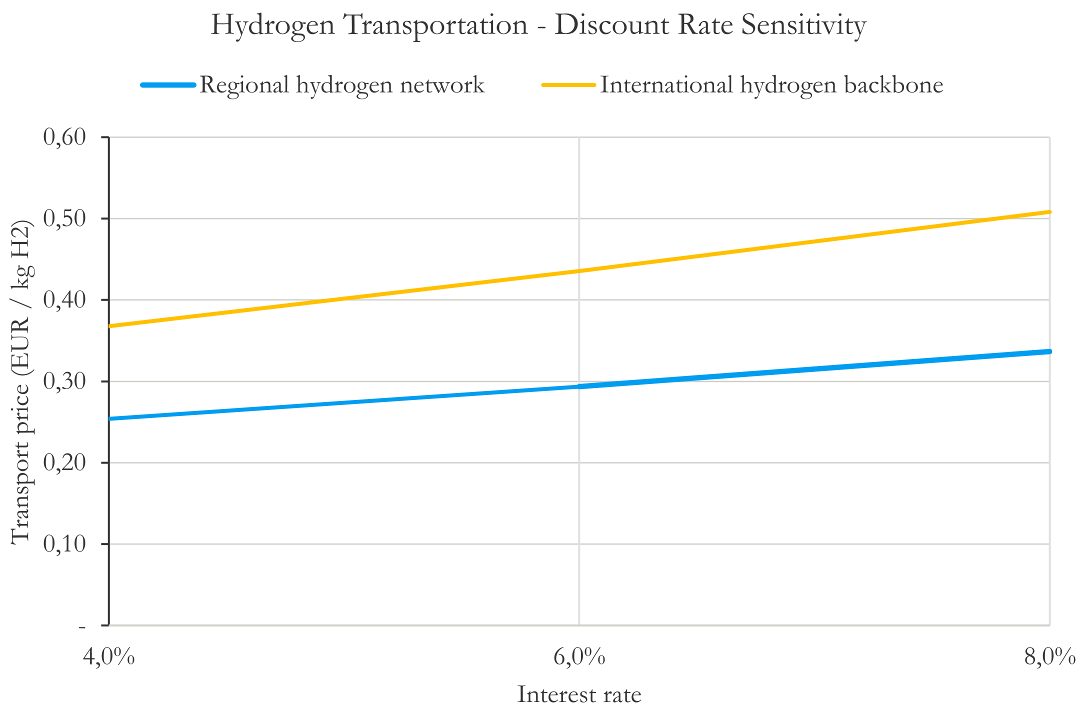


Figure 30 Comparison of hydrogen transport costs varying the interest rate

Source: Ramboll

As demonstrated, everything has its cost. Private ownership of the hydrogen infrastructure may lead to faster development compared to a public ownership model, particularly if financing can be secured more quickly. However, this speed may come at a premium for users of the network. On the other hand, the financial risk is borne by the private investor rather than the state.

Challenges related to potential bankruptcy and pipeline decommissioning must be addressed through regulation, which could require additional time. A public-private partnership (PPP) offers a middle ground, combining private sector development and part-financing with shared public ownership, thereby distributing the risk.

4.3.4 Hydrogen production potential in Eastern Denmark

As we will explore in the following section, it generally appears more advantageous to utilize electricity for purposes other than export in the renewable development scenario and beyond on Lolland-Falster. This conclusion will be the same for all of Eastern Denmark.

Connecting to a hydrogen system seems to be a promising option, though alternative fuels like methanol or ammonia could also be viable, depending on market trends. The electricity generated from renewable energy sources will only be necessary if there is simultaneous development on the demand side, such as in industry or PtX applications. Otherwise, it may seem excessive to develop such a large amount of electricity production solely to meet Eastern Denmark's electricity demand. Export opportunities will likely be to markets abundant in renewable energy, which could lower expected profit margins and reduce the utilization of energy production. Denmark´s neighboring countries are also implementing decarbonization strategies centered on renewables, carbon capture, and nuclear power. These baseload technologies require numerous full-load hours (excluding solar PV) to be economically feasible.

Currently, there are ambitious plans for the development of renewable energy in Eastern Denmark. This development could support onshore hydrogen production primarily for export, as further refining plans are not yet in place.

However, the feasibility of connecting to the hydrogen backbone depends on its establishment in Eastern Denmark, along with the associated challenges of securing offtake agreements from German industries and binding contracts from producers, similar to those faced by the planned hydrogen pipeline in Jutland.

To illustrate the potential energy input into the hydrogen pipeline and its possible origins, Table 10 provides an overview for Eastern Denmark. Assuming the same capacity booking requirements as in Jutland, this would account for 2.3 GW of the planned 5 GW hydrogen backbone pipeline (equivalent to 150 tons per hour).

However, investing in this infrastructure—both the production and transportation—carries significant risk if not fully utilized. In the competitive hydrogen market, Germany might opt to import liquefied hydrogen from Northern Africa and the Middle East if it proves more cost-effective. Additionally, recent findings from the European Hydrogen Bank auction indicate that hydrogen production on the Iberian Peninsula is currently the most economical in Europe.

Considering the scheduled commissioning years for renewable energy production—and likely the associated PtX plants—the timelines are very optimistic. Thus, it's important to undertake a realistic assessment of the Eastern Danish energy system development and the competitiveness of a hydrogen system to prevent high curtailment rates and extreme volatility in electricity prices.

The alternative to developing the demand side or enabling alternative fuel exports is to accept that energy production assets may remain idle for extended periods. One approach to making the hydrogen system viable from the outset could be to produce blue hydrogen for baseload supply, establishing a consistent offtake while also supporting subsurface carbon storage. This approach is similar to how the natural gas system is currently being supplemented with biogas.

Table 12: Development of renewable energy and associated PtX in Eastern Denmark

	Infrastructure	Unit	Capacity	Unit	Energy	Establish-ment (year)	Price (EUR / kg)
Transportation	Hydrogen Backbone (Eastern Denmark)	ton H_2 / hour ($GW-H_2$)	150 (5)	$TWh-H_2$ / year	40	2040	-
Production	Hesselø	$GW-H_2$	0.6	$TWh-H_2$ / year	3.5	2029-2031	~4
	Kriegers Flak	$GW-H_2$	1.0	$TWh-H_2$ / year	6.0	2030-2032	~4
	Energy Island Bornholm I	$GW-H_2$	0.6	$TWh-H_2$ / year	3.5	2030-2032	~4
	Energy Island Bornholm II	$GW-H_2$	1.5	$TWh-H_2$ / year	9.0	2030-2032	~4
	Onshore renewables Zealand	$GW-H_2$	0.7	$TWh-H_2$ / year	4.0	2030-onwards	~3
	Onshore renewables Lolland-Falster	$GW-H_2$	0.7	$TWh-H_2$ / year	4.0	2030-onwards	~3
	Offshore renewables Lolland-Falster	$GW-H_2$	0.7	$TWh-H_2$ / year	4.0	2032-2034	~4
	Blue hydrogen	$GW-H_2$	0.7	$TWh-H_2$ / year	5.5	2030-onwards?	~2
Demand	Methanol Lolland-Falster	$GW-H_2$	0.2	$TWh-H_2$ / year	1.5	2028-2030	-
	Green Fuels Avedøre	$GW-H_2$	0.4	$TWh-H_2$ / year	3.0	2030?	-
	Vordingborg e-fuels	$GW-H_2$	0.2	$TWh-H_2$ / year	1.5	2030	-
Balance	Import (-) (likely from Sweden)	$GW-H_2$	Unknown	$TWh-H_2$ / year	Unknown	-	-
	Export (+) (likely to Germany)	$GW-H_2$	+ 5.7	$TWh-H_2$ / year	+ 33.5	-	-

4.4 Techno-economic energy system evaluation

The scenario comparison is conducted by evaluating the annual costs and revenues in terms of Net Present Value (NPV) across the following five points:

- Investment: This includes all energy infrastructure investments such as renewable energy, biogas plants, electrolysis, methanol synthesis, etc.
- Operation and maintenance: This involves all costs related to the operation and maintenance of the energy infrastructure.
- CO2 credit and storage: This includes revenues and costs associated with the exchange of CO2 to and from Lolland-Falster. The CO2 subsurface storage benefits from importing large quantities of CO2 annually. When CO2 is captured and results in a net positive annual amount, it is accredited as sold on the international market as CO2 credits.
- Electricity sales: This value depends on the amount of electricity exported to Zealand from Lolland-Falster. As more PtX production is developed, revenue from electricity sales decreases. Additionally, market values for electricity exports are likely to decrease as more renewable energy is developed.
- Fuel sales: This covers the sales of methane, hydrogen, and methanol.

The economic breakdown of the economic analysis in the development scenario is shown in the figure below.

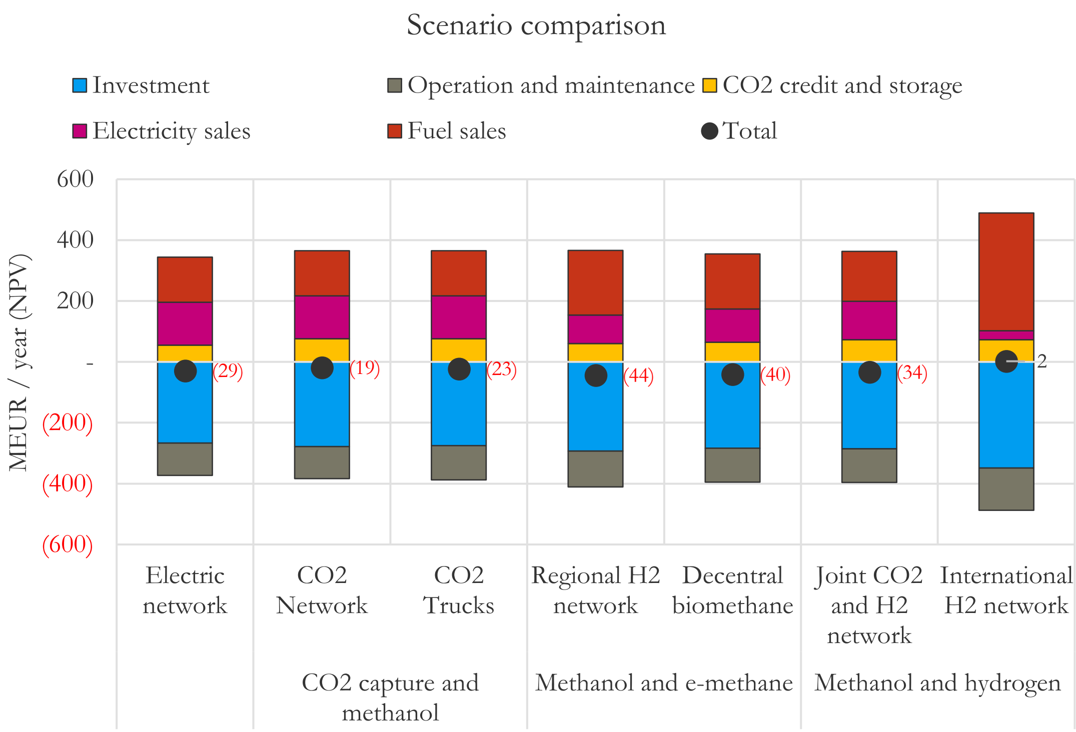


Figure 31 Scenario comparison of the development scenario (NPV)

Source: Ramboll

The results for all scenarios show a negative NPV except for the connection to the Hydrogen Backbone. However, these results are highly sensitive to the assumed electricity and fuel prices.

The figure below presents the scenario comparison for the three renewable energy scenarios, shown as total NPV. The open-door results would significantly improve if additional hydrogen electrolysis capacity is built, as too much electricity is available for the current plans.

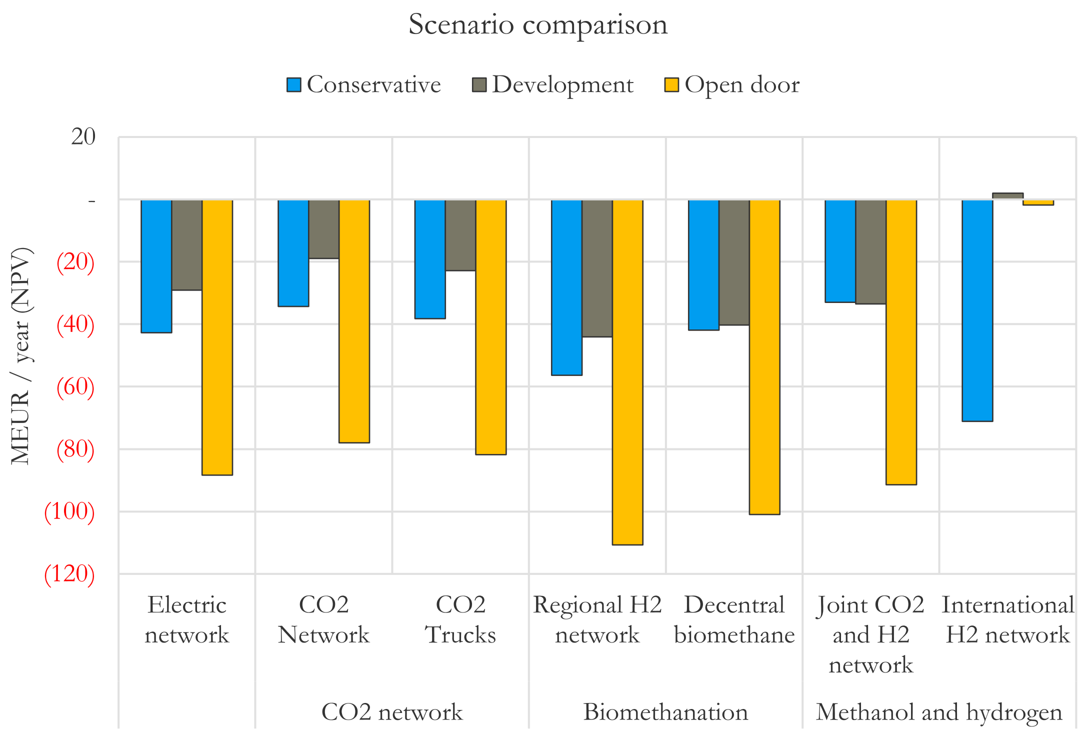


Figure 32 Scenario comparison of the development scenario (NPV)

Source: Ramboll

Under the development scenario, the optimal regional strategy is to establish a CO_2 network to capture CO_2 from point sources for methanol production and storage exchange. Furthermore, a regional hydrogen network connecting the renewable energy to methanol plants also seems preferable in a setting where the goal is to either connect to the Hydrogen Backbone or build additional methanol synthesis capacity.

Albeit that it might be hidden in the underlying numbers there are several conclusions that can be drawn from the results presented for each renewable energy scenario:

- Conservative development scenario: If renewable energy development on Lolland-Falster halts due to local opposition, diminishing market returns, or other factors, the best option is to maintain the current electric infrastructure and avoid building any hydrogen networks. Essentially, continue with the existing setup and consider establishing the CO2 infrastructure presented earlier, if CO2 subsurface storage, methanol plants and CO2 capture is established, regardless of the renewable energy developments. The economy of the CO2 system is less sensitive to the renewable energy development than the hydrogen system.

- Development scenario: In this scenario, establishing pipelines instead of relying solely on electric infrastructure appears beneficial. The choice between hydrogen or CO_2 pipelines depends on whether it is preferable to produce e-methane or utilize CO_2 in methanol plants while selling the excess on the CO_2 market. An argument against solely electric development is that electricity exported to Zealand would likely need to be used in a PtX plant there instead, as the electricity market will be oversaturated. The benefit of electric grid development thus relies on external investments in PtX infrastructure. Our evaluation may even be overly optimistic related to electricity exports, as electricity would be exported into the saturated DK2 market, likely resulting in lower-than-expected revenues from electricity sales. Our results indicate that it can be beneficial to build a regional hydrogen network connected to the methanol plants and a CO2 network connecting point sources to the same methanol plants.
- Development scenario including open door projects: When including the development of offshore wind projects, the optimal choice is to develop a hydrogen infrastructure, both regionally and connected to the international hydrogen backbone. If the international hydrogen network is not yet in place, an alternative is to expand methanol synthesis capacity to export energy as methanol instead of hydrogen. The most significant improvements in economic benefits as renewable energy increases are seen in the hydrogen scenarios, where higher energy export needs lead to greater advantages.

It is important to note that in the international hydrogen network scenario, we still develop the regional hydrogen network. The primary difference lies in whether the remaining excess electricity is exported as electricity or converted to hydrogen. The analysis shows that it is economically beneficial to export products other than electricity as renewable energy shares increase.

Furthermore, there are several general conclusions across scenarios:

- Analysis shows a promising alignment between CO2 infrastructure, renewable energy development, and methanol production. CO2 pipelines from biogas plants are more economically viable than upgraded biomethane, although depending on e-methane's green certification and credit sales.
- A regional hydrogen network with storage is more cost-effective than electrolysis at biogas plants for e-methane production.
- Annual energy sales on Lolland-Falster are estimated at 250 MEUR (conservative), 400 MEUR (development), and 500 MEUR (including offshore wind), depending on scenarios and fuel prices.
- Building an export pathway besides electricity enables arbitrage trading with methanol or hydrogen during low electricity prices.
- Excess heat from PtX processes could meet the 0.75 TWh annual district heating demand on Lolland-Falster. Future PtX developments will generate significant excess heat, necessitating a plan for district heating integration, long-term thermal storage, and new pipelines, potentially combined with CO2 and H2 pipelines.

4.5 Local job creation

We have estimated the potential for local job creation under the renewable energy development scenario outlined in the table below. These high-level figures suggest that a significant workforce will be required to operate such a renewable energy system.

People currently employed in the energy sector will continue to be essential. The numbers indicate how many additional workers will be needed on Lolland-Falster to support the energy sector. The construction workforce will be spread out over the next 15-20 years, resulting in an annual employment of approximately 400 people.

The proportion of these jobs filled by residents of Lolland-Falster will depend on the required skill levels and local availability. Therefore, we recommend starting today to educate and train skilled workers to meet the demands of this development.

Table 13 Estimated job creation (development scenario)

Scenario	Location	Unit	Construction	Operation
Development	Methanol plants	# of persons	400	100
	Hydrogen plants	# of persons	300	50
	Onshore wind	# of persons	1500	200
	Offshore wind	# of persons	300	50
	Solar PV	# of persons	1500	200
	Electric grid	# of persons	1200	200
	CO2 storage	# of persons	300	40
	Biogas plants	# of persons	1000	150
	CO2 network	# of persons	200	30
	CO2 capture	# of persons	150	30
	H2 network	# of persons	200	30
Overall		# of persons	**8050**	**1080**

5. OUTLOOK AND RECOMMENDATIONS

This section presents a set of recommendations based on the analysis of the potential future energy system on Lolland-Falster, particularly regarding the development of PtX and associated networks for carbon dioxide and hydrogen. These recommendations aim to bring value to the energy system and society on Lolland-Falster and ensure operability of the actual system. They are intended to support decision-making at both the local level on Lolland-Falster and within the broader context of national and international energy markets. Our recommendations also focus on local development, including job creation and economic growth.

Although the recommendations are presented clearly, further analysis will be required to determine how each recommendation can or should be implemented. Given the expected growth in renewables on Lolland-Falster, this report emphasizes evaluating pipeline infrastructure for carbon dioxide and hydrogen in a future scenario with balanced PtX development.

The following set of recommendations are only relevant under the assumption that renewable energy is continuously developed (development scenario and up). If this development is stopped, the recommendation is simply to do business as usual.

Local recommendations

- **Enable PtX import and export infrastructure at Rødbyhavn:** Differentiating PtX production on Lolland-Falster from other places hinges on the development of import and export infrastructure at Rødbyhavn. Key components include CO2 import infrastructure at the harbour, the subsurface storage and export infrastructure for methanol via ships. In the future, an export infrastructure to Rostock with a hydrogen pipeline may also be established. This infrastructure is a key prerequisite for the continuous growth of renewable energy on Lolland-Falster.
- **Develop a joint carbon dioxide and hydrogen pipeline infrastructure:** To establish PtX as a major industry on Lolland-Falster, our analysis indicates that a pipeline infrastructure for carbon dioxide and hydrogen is economically beneficial. Although based on a range of uncertain projects (size, location, etc.), the general finding is that such infrastructure can enhance the area's competitiveness. The CO2 pipeline connection between Rødbyhavn and Nakskov is economically beneficial, whereas the hydrogen network relies on a continous development of renewable energy and the future plans for either hydrogen or methanol export.
- **Develop a detailed energy system plan:** With the planned expansion of renewable energy production on Lolland-Falster, it is crucial to develop an integrated energy plan encompassing all current and future energy vectors. This plan must ensure optimal decision-making and to avoid pitfalls such as renewable energy projects lacking grid infrastructure or PtX plants without necessary support systems. Lolland-Falster has significant potential for renewable energy supply, and avoiding suboptimal sector focused solutions without the integrated system in mind is key to enable this potential.
- **Develop local high-quality labour supply:** Since the PtX and renewable projects are coming sometime in the future, a development of skilled local labour force for the energy sector based on the long-term energy plans are necessary.

- **Utilize Lolland-Falster as a test centre for new energy technology:** With its good location, relatively sparse population, and the opening of the Femern tunnel, Lolland-Falster is an ideal site for Danish and German energy companies to test new energy technologies in a highly renewable environment. Examples of successful developments in similar contexts include GreenLab in Skive, and the test center for large wind turbines in Østerild. Projects focused on energy storage and PtX could be established on Lolland-Falster.
- **District heating integration:** Building on the integrated energy plan it is essential that the district heating sector is utilizing the vast amounts of excess heat. The interplay with PtX may become the new combined heat and power integration.
- **Conduct a mapping of the total onshore renewable energy potential on Lolland-Falster:** To grasp the full potential of PtX development on Lolland-Falster, a mapping of the total potential for renewable energy development in the area is needed (mainly Guldborgsund Kommune) considering the technology development in renewable energy technologies. The conclusions in this report rely on stated plans for renewable energy and PtX development.
- **Energy Arbitrage:** With the anticipated increase in renewable energy production, Lolland-Falster will become a major energy exporting area. In this context, it is crucial not to rely solely on a single energy vector, such as electricity, for exports. Instead, diversifying to include methane, methanol, and hydrogen will enhance robustness against price fluctuations in any one type of energy.
- **Attract industry:** Attracting new industries to Lolland-Falster that rely on affordable, green energy—such as data centres with high electricity demand—can significantly support the ongoing expansion of renewable energy in the region.

(Inter) national recommendations

- **Improve competitiveness by establishing Lolland-Falster as a separate electricity market zone:** Enhancing the competitiveness of PtX projects and attracting industries to Lolland-Falster requires low electricity prices and compliance with EU´s rules for green fuel production. The region's renewable energy development can provide such prices, but the connection to the DK2 market area keeps prices high due to demand centres in and around Copenhagen. In contrast, the proposed DK3 electricity market zone at Bornholm is projected to have an annual offshore wind production of 15 TWh, whereas Lolland-Falster, under the development scenario with offshore wind, will have around 12 TWh. Creating a separate market zone for Lolland-Falster would highlight the major bottleneck issues in the electricity grid towards Zealand, which are expected to worsen in the future. It would also simplify compliance with green electricity standards for hydrogen and methanol production.
- **Blue hydrogen:** Consider the enablement and production of baseload hydrogen into a new hydrogen infrastructure via blue hydrogen based on natural gas with carbon capture and storage. The CO_2 storage site in Rødbyhavn, the new gas pipeline to Lolland-Falster and the close location to the planned Hydrogen Backbone to Germany can enable such development. Furthermore, this could also enable the hydrogen offtake and accelerate the hydrogen network earlier than using green hydrogen by production volume and lower prices. An examination of the Danish hydrogen production competitiveness compared to countries with different political visions is needed at this stage to avoid stranded investments.
- **Green credit system:** For the carbon dioxide and derivative fuels trading system to function effectively, a robust credit system is needed to account for the sustainability of

various molecules. For example, when carbon dioxide is exchanged between fossil and biogenic sources at storage sites, which serve as buffers for later use in methanol production, accurate accounting is essential to ensure the system's integrity.

- **Development of a hydrogen and carbon dioxide network in Eastern Denmark:** The carbon dioxide and hydrogen networks can be developed in clusters, particularly around synthesis plants. However, the continuous expansion of renewable energy in Eastern Denmark would benefit from an integrated plan, focusing especially on the hydrogen infrastructure. This plan should also address the capture and distribution of carbon dioxide for storage and PtX applications.
- **Economy of scale:** The development of both onshore and offshore wind energy on Lolland-Falster is crucial to supporting PtX initiatives. Unlike solar PV, which offers limited full-load hours and requires higher ramping, wind energy provides a more stable source for supplying PtX and industrial electricity demands. Therefore, expanding wind power is essential.

Phase plan

Many of the planned developments outlined in this report are interdependent, creating a classic "chicken-and-egg" scenario. The key question is which steps need to be taken first to enable subsequent developments and prevent stranded assets. Some parts can be developed in tandem, but commitment on the first parts is necessary for the subsequent parts. Our proposal is as follows:

1. **Energy plan:** Before building infrastructure, create a detailed, integrated energy plan to guide decisions and ensure efficient use of renewable energy resources.
2. **Support policies:** Develop local offtake for green electricity to balance supply and demand. Implement clear policies and incentives to encourage the production and use of green fuels from PtX processes and attraction of industries. Focus on developing local demand for renewable electricity by supporting facilities for methanol and hydrogen production. To develop the necessary infrastructure and make the plants economically viable, public support is essential. Just as economic support schemes were crucial in launching the renewable energy industry, similar mechanisms are needed to establish the PtX economy. A relevant example is the Dutch support scheme for electrolysis and the country's plans for a national hydrogen infrastructure.
3. **Renewable energy and demand:** Focus on expanding renewable energy projects, such as onshore and offshore wind, in parallel with regional grid improvements, as they are crucial for green PtX production. At the same time, focus on the development of methanol plants. Other industry demand should also be in focus. Without a continuous increase in wind at Lolland-Falster, the PtX plants will not be feasible. The current PtX plans can be supported by the projected onshore wind and solar PV capacity. However, to achieve a significant increase in PtX capacity, the development of offshore wind open-door projects is essential.
4. **Import and export PtX infrastructure:** Prioritize infrastructure at Rødbyhavn, including facilities for CO2 import, subsurface storage, and methanol export. The carbon dioxide infrastructure can grow from such a hub.
5. **Carbon dioxide and hydrogen pipeline infrastructure:** Develop dual-use pipelines on Lolland-Falster to address both current and future needs. A carbon dioxide network should first be established in West Lolland, while connecting biogas plants to either carbon dioxide or hydrogen infrastructure will depend on the feasibility of methanol versus biomethane

production. The establishment of a regional hydrogen network should be considered within a broader European context, as connecting major centres of carbon dioxide and hydrogen demand and production is generally advantageous. Currently, carbon dioxide networks appear more economically viable on a smaller scale, whereas hydrogen networks are more beneficial at a larger scale.

6. **Integrate with European networks:** The development of electric, hydrogen, and carbon dioxide infrastructure should be integrated with broader European networks to maximize regional and international economic benefits. This approach allows for dedicated hydrogen production plants on Lolland-Falster for hydrogen export. The additional cost of preparing the pipeline on Lolland-Falster for export via the European Hydrogen Backbone, compared to a purely regional system, is approximately 120 million EUR—a relatively small figure considering the much larger total investment. Thus, it is crucial to plan the regional hydrogen network with future international expansions in mind to avoid unnecessary double investments.