Forskningsrådet

Modellering av energisystemet

En oppsummering av resultater fra Forskningsrådets workshop om utviklingsbehov for energisystemmodeller, holdt i Oslo den 25. april 2017.

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Innhold

1 Innledning og avgrensning **3**
2 Modellutvikling og -bruk i Norge i dag **4**
2.1 Modellutvikling 4
2.2 Modellbrukere 5
3 Resultater fra workshopen **6**
3.1 Modeller og utviklingsbehov 7
3.1.1 Fleksibilitet og effekt 7
3.1.2 Forbrukere 8
3.1.3 Usikkerhet 9
3.1.4 Omfang 10
3.2 Organisering av modellene/miljøene 11
3.2.1 Samarbeid mellom miljøene 11
3.2.2 Koblinger mellom modellene 12
3.2.3 Datatilgang og -kvalitet 12
3.2.4 Andre utfordringer knyttet til organisering av modeller/miljøene 12
3.3 Bruk av modellene 13
3.3.1 Brukerinvolvering og -kompetanse 13
3.3.2 Fleksibilitet i modellene 13
3.3.3 Andre utfordringer knyttet til bruk av modeller 14
4 Oppsummering av forslagene **15**

Vedlegg

Vedleggene finnes som separate dokumenter

1. Modelloversikt
2. Program og deltakerliste fra workshopen
3. Presentasjoner fra workshopen

1 Innledning og avgrensning

Den 25. april 2017 arrangerte Forskningsrådet en workshop på Lysaker om forskning knyttet til langtidsmodellering av det norske, nordiske og europeiske energisystem. Forskningsrådet ønsker et bedre samspill mellom de offentlige brukernes behov for politikkutvikling og hva forskningsmiljøene kan modellere. Hensikten med workshopen var derfor å skape en felles forståelse for energisystemmodellering og en synliggjøring av hva som må utvikles for å møte fremtidens behov.

I senere år har den offentlige finansieringen av modellutvikling i Norge skjedd gjennom enkeltprosjekter og forskningssentre finansiert av Forskningsrådet. Et grovt anslag viser at rundt 15 mill. NOK (3 %) av finansieringen i ENERGIX-programmet i 2017 gikk til prosjekter eller arbeidspakker i prosjekter knyttet til modellering av energisystemet. Forskning om korttids driftsmodeller sto for ytterligere 18 mill. NOK. De samfunnsvitenskapelige Forskningssentre for Miljøvennlige Energi (FME) CenSES, CREE og CICEP har bidratt vesentlig til finansiering og strukturering av modellutviklingen siden de ble etablert i 2011.

Forskningsrådet ønsker å innrette den offentlige forskningsfinansieringen på dette området slik at den mest mulig effektivt dekker nasjonens behov for analyseredskaper. Workshopen var avgrenset hovedsakelig til forskningsbaserte langtids modelleringsaktiviteter som adresserer hele energisystemet, og som kan informere politikkutforming. Workshopen dekket ikke korttidsmodeller for drift av energisystemet, selv om slike modeller kan spille en viktig rolle i å danne kunnskap om teknologienes begrensninger med hensyn til økende problemstillinger som fleksibilitet og effektsikkerhet. Modeller utviklet av andre aktører enn forskningsinstitusjoner, blant annet analysefirmaer, var heller ikke dekket. Deltagelse var begrenset til representanter fra forskningsinstitusjoner, myndigheter og andre sentrale brukere av modellene.

Presentasjoner og gruppearbeid under workshopen avdekket en rekke utfordringer som modellutviklingen må håndtere for å bedre imøtekomme brukerens behov. Utfordringene og noen forslag til tiltak er sammenfattet i denne rapporten. Rapporten er skrevet av Forskningsrådet og med formål om å oppsummere synspunktene og forslagene som kom fram under workshopen. Rapporten er ikke ment å oppsummere Forskningsrådets prioritering av forskningsfinansiering.

Rapporten er kortfattet med utfyllende detaljer tilgjengelige i vedleggene. Inndelingen som følger om modellutvikling og -bruk suppleres med *Vedlegg 1. Modelloversikt*. Takket være et initiativ fra miljøene i etterkant av workshopen er oversikten et steg i retning av å svare på et av behovene påpekt på workshopen – en modellkatalog for brukerne. Forskningsrådet takker for fremmøtet og engasjement, og ønsker å bruke innspillene fra workshopen og rapporten til å forsterke samarbeidet om energisystemmodellering fremover.

2 Modellutvikling og -bruk i Norge i dag

2.1 Modellutvikling

Kompetansen innen modellering av kraftsektoren i Norge er høy, med utgangspunkt i flere tiårs erfaring med detaljert modellering av vannkraft og kraftmarkedet. Kompetanse om modellering av det bredere energisystemet er geografisk og organisatorisk spredt blant flere modelleringsmiljø i norske forskningsinstitusjoner og universiteter. Miljøene har både utviklet egne modeller og tatt i bruk modeller med åpne kilde for kalibrering med norske, nordiske og europeiske datasett. Dette har resultert i at flere titalls ulike modeller har vært i bruk i en eller annen form i Norge, men ofte med et fåtall eksperter som bruker/utvikler hver enkelt modell.

Sentrale miljøer inkluderer blant andre IFE, NMBU, NTNU, SINTEF, SSB, TØI og UiO (Frischsenteret). Flere av miljøene er samlet i de samfunnsvitenskapelige FMEene med fokus på modellering (CenSES og CREE). Modellutvikling foregår også hos analysefirmaer. På workshopen var CenSES og CREE bedt om å gi presentasjoner om modellutviklingsaktivitetene sine, mens andre miljø fikk mulighet å gi replikk. Presentasjonene finnes i *Vedlegg 3*.

Som det framgår i *Vedlegg 1. Modelloversikt*, er modellene bygget på ulike måter og derfor egnet til ulike formål. Eksempelvis (og forenklet) gir teknologirike "bottom-up" energimodeller mer innsikt over det fysiske energisystemet, mens "top-down" likevekts økonomimodeller gir mer innsikt i markedene og atferd. I motsetning til deterministiske modeller bruker stokastiske modeller sannsynlighetsfordelinger for å bedre representere klimatisk, økonomisk eller politisk usikkerhet. Korttidsmodeller har horisonter fra uker til flere år og analyserer drift av systemet uten nye investeringer. Langtidsmodeller analyserer utviklingen av systemet over flere tiår med endogene investeringer.

Noen energimodeller "backcaster" fra et gitt utslippsnivå i fremtiden og optimaliserer energisystemet til å oppnå utslippsreduksjonen til lavest systemkostnad. Disse modellene viser den ideelle sammensetning og bruk av teknologier (som kan være i strid med hva som er politisk sannsynlig) og er derfor ikke ment å predikere fremtiden. Andre modeller "forecaster" fra dagens situasjon og simulerer utvikling i energisystemet, gitt ulike forutsetninger. Et fåtall av disse simuleringsmodellene lager prognoser og skal predikere den virkelige utviklingen.

Et høyt aggregeringsnivå på geografi, tidsoppløsning, teknologi eller andre faktorer forenkler modellen slik at det egner seg for hyppige kjøringer til mindre detaljerte analyser. I den andre enden av skalaen kan svært detaljerte modeller ta flere dager å kjøre, noe som begrenser fleksibiliteten i analyser som krever flere titalls kjøringer. For at en analyse skal dekke hele energisystemet, flere land, kort- og langtids perspektiver, eller både teknologiske og økonomiske utviklinger, må enten modellen være veldig stor og kompleks, eller flere ulike modeller må kobles sammen under like forutsetninger. Modellkobling brukes ofte i pågående forskningsprosjekter og gjøres enten "hard-linked" i programvaren eller "soft-linked" med manuell dataoverføring.

Se også:

Vedlegg 1. Modelloversikt – En detaljert oversikt over sentrale modeller i bruk i Norge

2.2 Modellbrukere

Modellbrukere kan inkludere forskere, konsulenter, bedrifter og myndigheter. Derimot forståes brukere i denne rapporten som myndigheter og sentrale statsforetak med direkte påvirkning på politikkutviklingen som enten kjører modellene selv, eller bestiller modellbaserte analyser. Disse brukere har et selvstendig ansvar for å sikre at det finnes et godt nok modellverktøy til å kunne understøtte en forsvarlig forvaltning av energiressursene og en oppnåelse av politiske målsetninger rundt energi og klima.

OED, NVE, Statnett, Enova og Miljødirektoratet deltok på workshopen og er sentrale brukere av energisystemmodellering i Norge. Disse ga hver sin presentasjon på workshopen, se Vedlegg 3.

OED, Enova og Miljødirektoratet er primært indirekte brukere av modellene gjennom bestillinger til forskningsmiljøene og konsulenter for å vise konsekvenser av ulike politiske grep, deltagelse i styringsgrupper i forskningsprosjekter eller bruk av analyser publisert av modelleringsmiljøene. OED bestiller også analyser fra NVE. OED har behov for modellbaserte analyser for å følge utviklingen i energi- og kraftmarkedene, i vurderingen av aktuelle tiltak på energiområdet og i utformingen av den langsiktige energipolitikken. Koblinger mellom norsk, nordiske og europeiske energimarkeder og -politikk, og mellom energisektoren og den øvrige økonomien er viktige i denne sammenhengen. Eksempler på konkrete spørsmål hvor OED kan ha behov for å trekke på modelleringskompetanse inkluderer blant annet maksimering av verdiskapning fra norske vannkraftressurser, håndtering av fremtidig kraftoverskudd, utbygning av overføringskapasitet til kontinentet og design av et velfungerende kraftmarked. I tillegg til OED er flere andre departementer viktige brukere av modellanalyser, blant annet finans-, samferdsels- og klima- og miljødepartementene.

NVE har mange modelleringsbehov ut ifra de mange rollene organisasjonen har som regulator av energisektoren og vannressursforvaltningen. NVE har bygget opp modelleringskompetansen internt over de siste fire år til et relativt høyt nivå for blant annet å kunne utgi selvstendige analyser av det fremtidige kraftmarkedet. Seks ulike modeller er i bruk internt og hver modell er egnet til å studere en bestemt del av energisystemet. NVE samarbeider med modelleierne om funksjonalitetsutvikling, som for eksempel IFE for TIMES-Norway, SINTEF for Samkjøringsmodellen og Thema Consulting for TheMA modellen.

Statnetts rolle som kraftsystemoperatør gjør at de har avanserte modeller med stort behov for oppdaterte data om fysisk infrastruktur. For å forstå konsekvens av begrensningene og restriksjoner i kraftsystemet kreves modellering på et veldig detaljert nivå og dermed også relativt høy intern kompetanse på modellbruk og -utvikling. Statnett bruker flere modeller for ulike elementer i kraftsystemet, som er ofte "soft-linked" gjennom en iterativ prosess.

Se også:

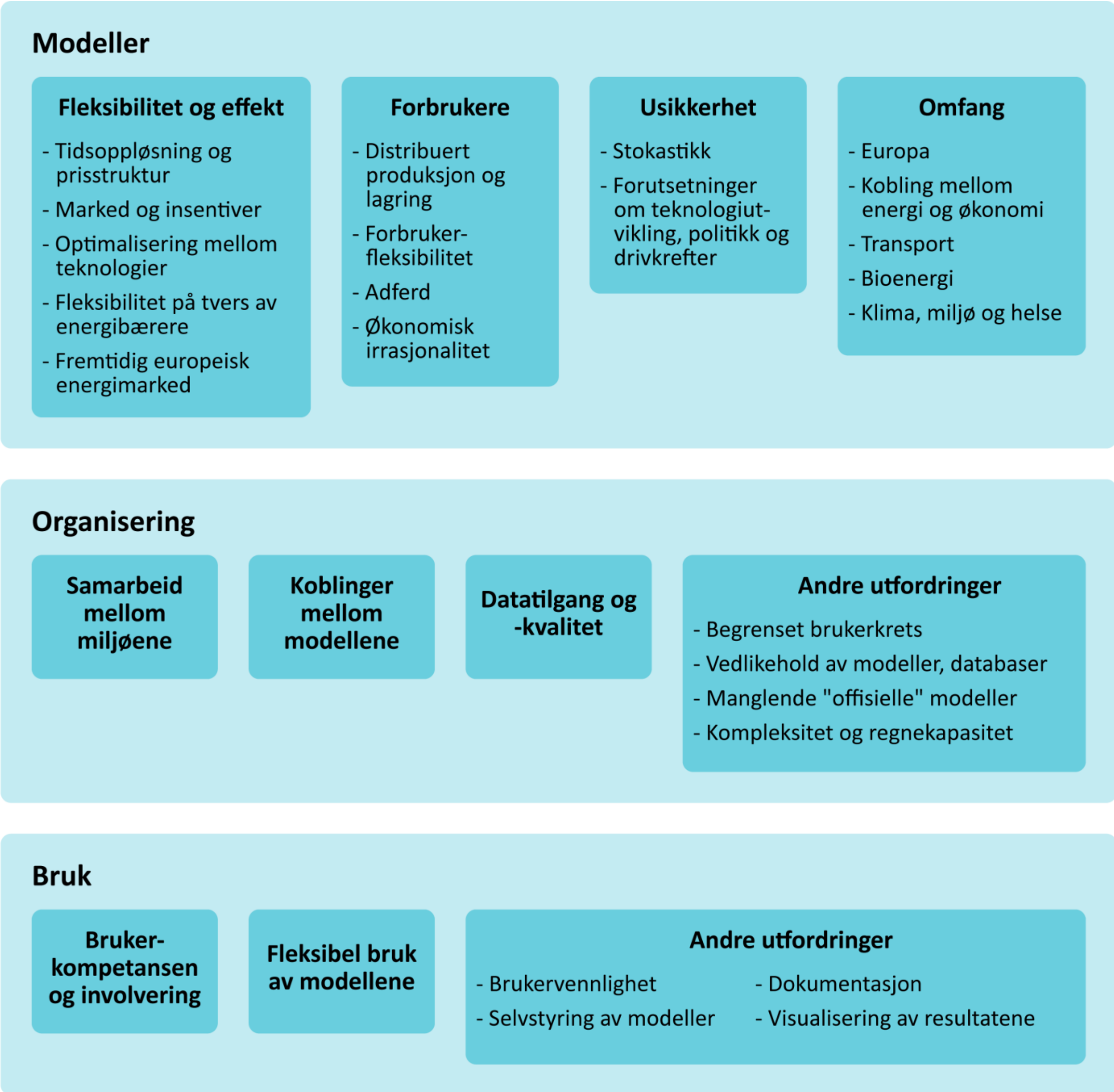
Vedlegg 2. Program og deltakerliste fra workshopen

Vedlegg 3. Presentasjoner fra workshopen

3 Resultater fra workshopen

Disse resultater er basert på flere kilder fra workshopen den 25. april 2017: Presentasjoner fra brukere og forskningsmiljø, individuelle innspill til gruppearbeidet, presentasjoner fra gruppearbeidet og diskusjoner i plenum. I tillegg er deltakernes kommentarer til en foreløpig versjon av rapporten innarbeidet i teksten. Resultatene er hovedsakelig i form av utfordringer og forbedringer, med et fåtall forslag til helt nye tiltak. En oppsummering av forslagene finnes på slutten av rapporten. Resultatene er kategorisert i tre områder: Modeller, som omfatter utviklingsbehov for modellverktøy; Organisering, som handler om hvordan miljøene og modellene organiseres; og Bruk, som dekker bruk av modellene i analysearbeid og politikkutforming.

Figur 1. Utfordringer ved modellering av det fremtidige energisystemet



3.1 Modeller og utviklingsbehov

Det er bred enighet om at modellverktøyene må utvikles for å kunne adressere fremtidige behov. Eksisterende modeller vil møte store utfordringer i de kommende år, som vist i figuren og utdypet under. Eksisterende modeller kan forbedres, utvikles med ny funksjonalitet og kobles til andre modeller for å imøtekomme behovene. Dette vil skje samtidig som modelleringsmiljøene tar i bruk ny teknologi som for eksempel økt beregningskapasitet, forbedret algoritmer og bruk av maskinlæring i modellene. Det er uklart hvorvidt det er tilstrekkelig med videreutvikling av eksisterende modeller eller nødvendig med utvikling av nye modeller. Noen brukere uttrykker et ønske om et fåtall gode og fleksible modeller som spiller godt sammen fremfor utvikling av nye modeller. Utviklingsbehovene kan deles i fire områder: Fleksibilitet og effekt, Forbrukere, Usikkerhet og Omfang.

3.1.1 Fleksibilitet og effekt

Fleksibilitet i energisystemet blir mer verdifullt og effekt blir en viktigere vare i fremtidens elektrisitetssystem (i forhold til mengde energi). Behovet for fleksibilitet forårsakes av en økende andel av elektrisitet produsert fra variable fornybare kilder som vind og sol i Norge og særlig i nabolandene, samt (og til en mindre grad) mer effektkrevende forbruksmønstre fra for eksempel elbiler og induksjonstopper. Fleksibilitetsbehovet kommer til å øke mest i Europa, og markedsendringene som følge av dette blir noen av de viktigste premissgiverne for den framtidige verdien av norske energiressurser. Foreløpig henger langtidsmodellene etter i denne utviklingen mens driftsmodeller er i større grad bygget for å representere effekt i tillegg til energi. Langtidsmodellene må derfor bli bedre til å representere verdien av effekt og fleksibilitet for å kunne gi svar på flere spørsmål som er sentrale i politikkutformingen. Eksempler inkluderer hvordan maksimere verdien av norsk regulerbar vannkraft, hva er lønnsomheten av utenlandskabler, nettforsterkninger, lagring og forbrukerfleksibilitet.

- **Tidsoppløsning og prisstruktur**
  Høyere tidsoppløsning er essensielt for å modellere variasjoner i produksjon og forbruk, og ut ifra det generere en detaljert prisstruktur. Noen få timer med høye priser kan være avgjørende for lønnsomhet i investeringer i fleksibilitet. Hvis ikke volatiliteten representeres i modellen, gir den feil grunnlag for investeringer. I tillegg er høyere tidsoppløsninger viktige for å ta hensyn til flere stokastiske faktorer. Dagens modeller har tidsoppløsninger fra en titalls aggregerte representative tidssteg per år til timenivå med 8760 tidssteg per år. Noen korttidsmodeller har enda kortere tidsoppløsninger. En modell blir fort veldig kompleks hvis den skal ha en høy tidsoppløsning sammen med en tidshorisont over flere tiår og en bred geografisk dekning. En av metodene brukt i dag er å supplere en langtidsmodell med en annen modell med høyere tidsoppløsning for å analysere fleksibilitetsbehov for utvalgte år eller uker i analyseperioden. Det er enighet om at dagens modellverktøy ikke fanger opp hele fleksibilitetsbehovet og derfor trenger modeller høyere tidsoppløsning der det er relevant.

- **Marked og insentiver**
  Med en viktigere rolle for effekt kan fleksibilitetstjenester bli en større inntektskilde for vannkraftprodusentene og andre aktører som kan tilbyde fleksibilitet i energisystemet (lagring, forbrukerfleksibilitet, osv). Modellene må bli bedre til å analysere hvordan markedet og andre insentiver kan utløse fleksibilitet, hva virkninger blir av ulike markedsdesign, og hvordan samspillet blir mellom spotmarked, reguleringsmarked og kapasitetsmarked. Her er det viktig at modellene tar hensyn til markedsutviklinger i Norden og spesielt i Europa.

- **Optimalisering mellom teknologier**
  Fleksibilitetsspørsmålet lan løses på mange måter. Behovet for fleksibilitet kan begrenses gjennom tariffering som fremmer reduksjoner i forbruksvariasjoner, eller "system friendly" variabel fornybare ressurser (øst/vestvendt solkraft og lav vindhastighets turbiner). Fleksibiliteten kan da hentes fra flere ulike kilder i energisystemet; fra store sentraliserte kilder til lokale og distribuerte. Eksempler inkluderer fleksibel vann- og termisk kraft, reservekapasitet, transmisjon og distribusjon, ulike former for lagring, aktiv lastflytting hos forbrukere og industri, CHP og elkjeler i fjernvarmenettet, samt fleksibel produksjon av hydrogen og biodrivstoff. Modellene må kunne fange samspill mellom ulike fleksibilitetsløsninger og optimalisere for å gi et helhetlig bilde. I tillegg må modellene representere nettet, som i de fleste tilfeller kobler sammen fleksibilitetsbehov med fleksibilitetsløsning, på en nyansert måte. Europeiske kraftmarkeder forventes å bevege seg mot en flytbasert markedsklarering, som betyr at handel mellom budområdene blir implisitt prioritert. Flaskehalser og andre fysiske begrensninger i nettet som påvirker energiflyten blir derfor enda viktigere i modelleringen.

- **Fleksibilitet på tvers av energibærere**
  Ofte er analyser av fleksibilitet begrenset til kraftsystemet, da kraftsektoren ha en veldig stor betydning i Norge. I Europa må fleksibiliteten hentes fra andre kilder enn vannkraft, og derfor må modellene bli bedre til å analysere fleksibilitet på tvers av energibærer, sektorer og energimarkeder. En tettere integrasjon mellom elektrisitet, varme, gass og transport kan utløse mye fleksibilitet og effektivitet i energisystemet. Dette kan modelleres bedre gjennom bedre koblinger mellom sektormodeller og bruk av såkalte "multi-scale" modeller.

- **Bedre representasjon av fremtidig europeisk energimarked**
  Det er behov for utvidet modellering av europeiske forhold og økt samarbeid med europeiske modelleringsmiljøer. Forventet økninger i overføringskapasitet til Tyskland og Storbritannia fører til at utenlandske energimarkeder kommer til å prege det norske i enda større grad enn i dag. Europeiske fleksibilitetsbehov og -kilder er annerledes enn de norske. Kontinentet har blant annet mindre regulerbare vannkraft, mer variable fornybar og kapasitetsmarkeder. Disse forholdene må modelleres bedre for å forstå implikasjonene for norske fleksibilitetsbehov og -kilder.

3.1.2 Forbrukere

Teknologivalg, forbruk og atferd hos sluttbrukeren er ikke godt nok representert i dagens modeller. Eksempelvis blir energieffektive atferd/investeringer og innføring av "prosumers" ofte basert utelukkende på eksogene antagelser og lite integrert i modelleringen. Tettere integrasjon av disse faktorene blir viktigere fremover med den forventede aktive rollen for forbrukeren i fremtidens energisystem. Modellering av forbruk og forbrukeradferd vil også få økt relevans og ny muligheter etter at store datamengder med kort tidsoppløsning gjøres tilgjengelig fra AMS-målere, samt innføring av Elhub for tilrettelegging av AMS-data.

- **Distribuert produksjon og lagring**
  Prosumers som selger solkraft tilbake til nettet, muligens kombinert med lagring i elbilen, blir et vanligere syn i fremtidens energisystem i Europa og kanskje også i Norge. Rivende kostnadsreduksjoner innen solkraft og batterier kan sette enda mer fart på utviklingen. Dagens modeller må forbedres for å representere distribuerte løsninger like godt som det sentraliserte kraftsystemet som modellene var bygget for.

- **Forbrukerfleksibilitet**
  Den potensielt viktige rollen for forbrukerfleksibilitet er et produkt av det tekniske potensialet, insentivene gjennom markedsdesign, og forbrukeratferd i respons til insentivene. Ingen av disse er godt nok representert i dagens modeller.

- **Adferd**
  Forbrukerens adferd i denne sammenheng inkluderer energiforbruk (innetemperaturen i bolig eller valg av fremkomstmiddel til arbeidsplass) og investeringer (energieffektiv rehabilitering av bolig eller valg av biltype). Atferd har stor påvirkning på energisystemet, men er ikke tatt hensyn til i de aller fleste teknologirike energimodeller. Økonomimodeller representerer atferd gjennom å inkludere økonomisk rasjonell atferd i respons til prissignaler, som er basert på antakelser om elastisiteter mellom valg av ulike tjenester. Samtidig er det ikke utelukkende prissignaler som styrer forbrukeratferd i virkeligheten. Modellene kan utvikles til å bedre fange opp den komplekse og viktige rollen til atferd. Eksempelvis har valg av fremkomstmiddel blitt inkorporert i energimodeller gjennom "travel time budgets", hvor empiriske data om akseptabel tidsbruk på transport nyanserer kostnadsoptimeringen i modellen. Valg av fremkomstmiddel i økonomimodeller kan nyanseres gjennom "discreet choice" metoder, som regner fram til *hvilket* alternativ (buss eller bil), i stedet "continuous choice", som regner *hvor mye*. Energi- og økonomimodeller kan også kobles sammen for å bedre representere atferd.

- **Økonomisk irrasjonalitet**
  De fleste modeller antar perfekt fremsyn og økonomisk rasjonell adferd hos alle aktører, til tross for at beslutninger hos forbrukeren ikke nødvendigvis er styrt av økonomisk rasjonalitet i samme grad som i næringslivet. En forbruker kan velge å installere solpaneler fremfor isolering av huset av mange ulike grunner, mens en modell kan velge det motsatte basert på økonomisk lønnsomhet. Noen modeller bruker ulike diskonteringsrater for å representere dette, men det er stort forbedringspotensial i måten økonomisk irrasjonalitet håndteres i modellene og i den underliggende kunnskapen om forbrukeratferd som må informere måten det modelleres.

3.1.3 Usikkerhet

Modellering av investeringer i det fremtidige energisystemet er sterkt påvirket av usikkerhet. Usikre faktorer inkluderer blant annet fysiske (som vindstyrke, tilsig og klima), teknologiske (kostnadsreduksjoner og gjennombrudd) og politiske, i tillegg til utviklinger i markeder og ulike drivkrefter som digitalisering, delingsøkonomi eller kunstig intelligens. Dette håndteres både i måten usikkerhet modelleres og hvordan forutsetningene utformes.

- **Stokastikk**
  Vannkraftmodeller for drift har lenge vært stokastiske, men nå etterspørres stokastisk håndtering av andre variabler enn tilsig til vannkraftverkene, sertifikatpriser og elpriser. De fleste energisystemmodeller er deterministiske, hvor potensielt usikre variabler bestemmes av modellkjøreren som eksogene forutsetningene og dermed er usikkerheten ikke modellert. Usikkerheten belyses i stedet gjennom scenario- og sensitivitetsanalyser, hvor modellkjøringer med ulike forutsetninger viser ulike resultater. Dette kan vise enda større utfallsrom enn stokastisk programmering, men et mindre nyansert bilde over usikkerheten. Med stokastisk programmering kan en eller flere usikre variabler tilordnes sannsynlighet og dermed integreres i langsiktige modeller for å gi en bedre representasjon av investeringsbeslutninger. Store forbedringer i regnekapasitet og en voksende

oppmerksomhet rundt usikkerhet har bidratt til at stokastiske teknikker begynner å bli vanligere i modellutvikling, men stokastikk kunne med fordel integreres ytterligere i flere modelleringsanalyser.

- **Forutsetninger om usikre faktorer som teknologiutvikling, politikk og drivkrefter**
  Forutsetninger underbygger all modellering, stokastiske eller ikke, og er avgjørende for hvilke resultater som kommer ut av modellen. Teknologiutvikling og endringshastighet har vært et omstridt tema i energisystemmodellering hvor forutsetninger har vært sentralt. Selv hvis læringskurven stemmer (hvordan kostnadsreduksjoner følger produksjonsøkninger), tar den ikke hensyn til teknologiske gjennombrudd eller politikk. Eksempelvis har utviklingen i solkraft vært vanskelig å beskrive i de fleste modellene fra et modellteknisk perspektiv, blant annet på grunn av aggressiv industripolitikk og resulterende overkapasitet i produksjon – faktorer som modellene ikke tar hensyn til. De få analysene som har "truffet" i beskrivelser av solkraftutviklingen har vært modellteknisk forenklet og i større grad styrt av forutsetningene. Det kan argumenteres at siden bare et fåtall modellanalyser forsøker å predikere utviklingen er dette mindre relevant for de fleste modeller, men dette forutser at brukerne av modellresultater alltid setter seg godt inn i modellen som står bak, noe som ikke er tilfellet. Derfor er det er viktig at også modellanalyser som ikke forsøker å predikere blir mer robuste mot slike usikre variabler. Dette kan gjøre resultatene mer relevant for brukerne og hindre at troverdigheten svekkes. I de kommende år blir det viktig at modellene tar hensyn til usikkerhet rundt EUs politikk, samt drivkrefter og trender med svært usikre utfall som digitalisering, delingsøkonomi og kunstig intelligens. Eksempelvis er det vanskelig å forutsi om selvkjørende biler fremmer mer effektivitet (gjennom økt bildeling) eller mindre (kjøring uten passasjerer i stedet for parkering).

3.1.4 Omfang

Energisystemmodellene burde utvides eller kobles til spesialiserte modeller for å kunne bedre analysere viktige aspekter av energisystemet som har hittil vært forenklet i de fleste analyser. Det trekkes fram Europa, koblingen mellom energi og økonomi, transport, bioenergi, samt klima, miljø og helse som eksempler.

- **Europa**
  Det norske energisystemet blir mer integrert med det europeiske i årene som kommer og "importerte" energipriser og politikk blir enda mer premissgivende for Norge. Modeller som representerer dynamikken i en integrert europeisk/nordisk energisystem vil øke i relevans i forhold til nasjonale/lokale modeller i takt med utbygging av kabler til Europa. Norske modeller må bli bedre til å analysere europeiske og nordiske energisystem, markedsdesign og politikk.

- **Koblingen mellom energisektoren og makroøkonomien**
  Brukerne ønsker at modellering av energisystemet og relaterte effekter på økonomien henger bedre sammen. Dette innebærer enten mer strukturerte og detaljerte koblinger mellom modeller for energisystemet og makroøkonomien (se andre punkt i seksjon B. "Koblinger mellom modellene"), eller utvikling av hybridmodeller som har tilstrekkelig detaljeringsnivå på både energiteknologi og verdiskapning.

- **Transport**
  Transportsektoren er avgjørende for at Norge skal nå klimamålene, men er for lite detaljert i energisystemmodellene. Dette gjelder både for brede modeller som dekker flere sektor og for spesialiserte modeller med transportrelatert energibruk i fokus. Modellene er ofte for

aggregerte og må bli mer heterogene på både teknologi og infrastruktur. Begrunnelsen for ulike teknologivalg og atferd i transport må integreres bedre i modellering for å analysere "modal shifts" mellom transportmidler og potensialet for reduksjoner i transportbehov. Sammenhengen mellom kraftsystemet, bioenergi og transportsektoren, samt ringvirkninger i forhold til fleksibilitet (eksempelvis lagring i elbilbatterier eller fleksibel produksjon av hydrogen og biodrivstoff) bør også modelleres bedre.

- **Bioenergi**
  Modellering av bioenergimarkedet er i dag begrenset til en mindre krets av forskere i Norge og hverken SSB, NVE eller Statnett har tilstrekkelig modelleringskompetanse på området. Biodrivstoff kan potensielt få stor betydning for omstillingen i transportsektoren og dermed ha økt relevans i klimadebatten fremover. Samarbeid med nordiske naboland kan bidra til en styrking av modellering på dette området og en tettere integrering av bioenergi i energysystemmodellene brukt i Norge. Bærekraftperspektiver (som for eksempel biodiversitet og andre miljøutfordringer) og livsløpsutslipp fra bioenergi må også tas bedre hensyn til.

- **Klima, miljø og helse**
  Miljø- og helsepolitikk er en viktig drivkraft for klimatiltak og sammenhengen mellom energi, klima, miljø og helse er prioritert politisk gjennom blant annet FNs bærekraftsmål. Til tross for det er miljøkonsekvenser utover CO_2-utslipp lite analysert i de aller fleste energisystemmodeller. I tillegg til å inkludere flere typer klimagassutslipp (som allerede gjøres i noen modeller), ønsker brukere at modellene inkludere også andre viktige aspekter som lokal luftforurensing og relaterte helsekostnader, utslipp til vann, arealbruk og skogbruk.

3.2 Organisering av modellene/miljøene

I tillegg til utvikling av modellverktøy som beskrevet over kan forbedret infrastruktur og organisering av modellene og miljøene bidra til å bedre imøtekomme brukernes behov. Svært forenklet har aktørene de beste dataene, modelleringsmiljøene sitter på de beste energisystemmodeller og konsulentene er mest opptatt av å gi svar på myndighetenes spørsmål med egne, enklere modeller. Forbedret organisering kan bidra til å sikre en tydeligere verdikjede fra modellforskning til politiske beslutninger.

3.2.1 Samarbeid mellom miljøene

Samarbeid mellom forskningsmiljøene og med brukerne er avgjørende for at energisystemmodellering skal lykkes med å bidra til en informert politikkutvikling. Samarbeid mellom forskningsmiljøene har allerede kommet langt gjennom en rekke enkeltprosjekter, og særlig innen FMEene CenSES og CREE, som henholdsvis har tatt utgangspunkt i teknologiske og økonomiske modelleringstradisjoner. FMEene har gitt miljøene fleksibilitet til å kunne svare på spørsmål fra brukere som ellers ikke hadde vært mulig under ordinær prosjektfinansiering, hvor ressurser er i større grad bundet til prosjektets opprinnelige målsetninger. Gjennom å bruke forskningsmiljøenes avanserte modeller også for enklere analyser og bestillinger, bidrar FMEene til å bygge verdikjeden nevnt over. Workshopdeltakere påpeker at til tross for FMEene mangler det fortsatt en felles arena/forum for modellforskning i Norge hvor alle modelltradisjonene er representert sammen med en bred krets av brukere. En slik arena/forum kan bidra til å heve brukerkompetanse, kvalitetssikre modellene mot brukernes behov, etablere en kritisk masse av modellbrukere, og danne tettere samarbeid med nordiske og europeiske modelleringsmiljøer.

3.2.2 Koblinger mellom modellene

Brukerne ønsker bedre integrasjon mellom sektorene og modelltradisjonene (energi, økonomi) for å tegne et mer helhetlig bilde av energisystemet. Eksempelvis ønskes det at modellering av energiforsyning og -bruk kobles tettere med klimatiltak, makroøkonomien og kraftmarkedet. Miljøene har mye erfaring med å koble sammen ulike modelltyper fra enkeltprosjekter og FMEene. Prosessen kan være tidskrevende, men åpner for mange muligheter, enten ved utvidelse av analysens omfang eller forsterkning av analysen på spesifikke områder som er dekket på en forenklet måte i den opprinnelige modellen. Energisystemmodeller kan kobles til modeller for kraftsystemet, energimarkeder, klima, skogbruk, landbruk, transport og økonomi, i tillegg til å koble sammen modeller med forskjellige geografisk- og tidsoppløsninger. Ved å koble teknologirike energimodeller med likevekts økonomimodeller kan det muligvis oppnås mer omfattende resultater om for eksempel disponering av kraftressurser (krafteksport eller grønn industri) og andre helhetlige problemstillinger enn hvis modellene var brukt hver for seg. For mange av de mulige koblinger påpekt over mangles det godt nok kunnskap om sammenhengene til å kunne modellere disse. Det er derfor også et behov for utviklet fagkunnskap for å informere det eventuelle modelleringsarbeidet.

Miljøene peker på at det mangler et felles rammeverk for kobling mellom modeller. Et slikt rammeverk kunne inneholde (i tillegg til felles databaser, se neste punkt) ulike felles delproblemløsninger for modellering av konkrete utfordringer som gjøres tilgjengelig for ulike modeller. Eksempler på dette er nye typer fleksibilitet, usikkerhet eller flere vannverdier i ulike magasin. Her er den generelle algoritmen og ikke kodingen viktigst, da implementeringen ville være ulike innen ulike modeller. Samarbeid på denne måten kunne føre til mer konsistente scenarier og forutsetninger, muliggjøre tverrfaglige tilnærminger og gjennom felles dokumentasjon av koblingsmetoder og felles løsninger effektivisere formidling av resultater. Det påpekes også at det praktiske vedlikeholdet til et slikt rammeverk ville vært krevende, at forskjellene mellom modellene kan være for store, og at teknologiutvikling for kobling av programvarer kan gjøre modellkobling lettere i fremtiden.

3.2.3 Datatilgang og -kvalitet

Brukerne etterlyser mer oppdaterte data, at forskningsmiljøene samarbeider med aktørene for å få etablert og adgang til bedre data, og en samordning av data som benyttes i ulike modeller. Samarbeid mellom miljøene om datatilgang og felles databaser og datastandarder (både historiske og virtuelle data om fremtiden som tilsig eller klima) vil kunne gjøre data mer konsistent mellom analysene. Oppdatering av modeller med nye data er tidskrevende og gjøres sjeldent for komplekse modeller. Samtidig er modellers datakrav økende. Utrulling av Elhub i 2019 med data fra AMS-målere vil åpne muligheter for samordning, men vil kreve videre arbeid for å tilrettelegger for direkte bruk i modellene. Samarbeid om datatilgang og -kvalitet kan bidra til etablering av nye brukerkretser for modellene, gjøre forskningen mer effektiv og føre til mer presise og sammenlignbare resultater.

3.2.4 Andre utfordringer knyttet til organisering av modeller/miljøene

- **Begrenset brukerkrets**
  Flere av modellene som er i bruk i Norge har begrenset brukerkrets. Med usikre prosjektbaserte finansieringskilder blir modellene sårbare for manglende vedlikehold, utvikling og kvalitetssikring. Dette kan forebygges gjennom deling av modellene med åpen kildekode og økt nasjonalt og internasjonalt samarbeid. Deling av modellene alene sikrer ikke bredere brukerkrets, men kan hjelpe i arbeidet med å bygge en kritisk masse av brukere.

- **Vedlikehold av modeller og databaser**
  Forskningsmiljøene beskriver utfordringer med å sikre støtte til nødvendig vedlikehold av

modellene og databasene gjennom prosjektbaserte finansieringsordninger. Utvikling av ny funksjonalitet blir i større grad premiert.

- **Manglende "offisielle" modeller**
  På energiområdet finnes det i liten grad standardiserte modeller, modellmoduler, koblingsmetoder eller datasett på nasjonalt eller internasjonalt nivå. På klimaområdet er modelleringsarbeidet langt mer strukturert på internasjonalt nivå med standardiserte modellverktøy utviklet gjennom omfattende internasjonal samarbeid. Dette resulterer i nærmest "offisielle" modeller som effektiviserer analysearbeidet og forenkler formidling av resultatene da modelloppbyggingen ikke må beskrives i detalj i hver publikasjon. I tillegg har mange brukere større kjennskap og tillit til modellene, som bidrar til bedre kvalitet og etterprøvbarhet. En bevegelse i samme retning på energiområdet vil hjelpe både forskere og brukere, men det er uklart hvilke modellverktøy som er best egnet og hvilken type institusjon som er best plassert til å eie en slik prosess.

- **Kompleksitet og regnekapasitet**
  Komplekse modeller med høy oppløsning mht. tid, teknologi eller geografi krever IKT ressurser med stor regnekapasitet og per i dag opplever forskerne problematisk lange beregningstider. Samtidig åpner den raske utviklingen i regnekapasitet stadig nye muligheter for komplekse analyser. Samspillet mellom kompleksitet og regnekapasitet forventes å være en løpende trend i årene som kommer.

3.3 Bruk av modellene

Flere av brukerne har de samme overordnete politiske målsetninger om verdiskaping, miljø- og klimavennlighet og forsyningssikkerhet. Modellarbeid er sentralt for å vise hvordan disse kan oppnås, men per i dag utnyttes ikke modellenes fulle potensial. Dette kan løses ved forbedret brukerinvolvering og -kompetanse, og ved at modellene blir bedre tilpasset brukernes behov.

3.3.1 Brukerinvolvering og -kompetanse

Brukerne må bli mer involvert i modellutvikling, scenario-bygging og arbeid med forutsetninger enn det som har vært situasjonen i forskningsprosjektene hittil. Dette kan gi brukere mer relevante resultater og gjøre dem bedre utrustet til å ta forskningen i bruk i politikkutforming. Brukerkompetansen fremheves som særlig viktig og et område med forbedringspotensial. Med en grundig forståelse av styrker, svakheter og mangler ved en gitt modelleringsmetode får brukeren større tillit til resultatene. En bedre forståelse for hvordan resultatene kan brukes kan også være fordelaktig – for eksempel kan ikke en scenarioanalyse som optimaliserer oppnåelse av et politisk mål til lavest systemkostnad brukes som en prognose over hvordan energisystemet kommer til å utvikle seg. I forbindelse med dette, ønsker brukerne bedre oversikt om egenskaper til de ulike modellene som er i bruk i Norge i dag. En mulig løsning er en lett tilgjengelig oversikt over de ulike modellene og hvilke problemstillinger de er best egnet for å analysere. Takket være et initiativ fra miljøene i etterkant av workshopen kan *Vedlegg 1. Modelloversikt* legges ved som et utgangspunkt for en slik katalog.

3.3.2 Fleksibilitet i modellene

Brukerne beskriver en situasjon der de har bruk for både langsiktige scenarioanalyser (basert på komplekse modeller) og i tillegg en rekke andre mer kortsiktige behov som for eksempel forenklede kjøringer, tiltaksanalyser og sensitivitetsanalyser. Disse behovene har ofte kortere frister og kan i mange tilfeller oppfylles best av enklere modeller hos konsulenter. Problemet er at manglende fleksibilitet i forskningsmodellene og forskningsmiljøene fører til at de mest avanserte modellene blir lite brukt i politikkutforming da de ikke kan gi svar på brukernes spørsmål på kort varsel. Energisystemmodeller bør i langt større grad ha innebygd fleksibilitet for å kunne lett tilpasses de ulike problemstillinger de blir satt til å analysere. Modulær oppbygging av modeller og programmering i åpen kildekode er eksempler på dette.

3.3.3 Andre utfordringer knyttet til bruk av modeller

- **Brukervennlighet**
  Mer brukervennlige grensesnitt i modellene er ønsket av brukerne, noe som kan føre til økt brukerkompetanse og involvering. Det er antageligvis sub-optimalt at forskningsmiljøene selv skal påta seg utvikling og vedlikehold av brukergrensesnitt.

- **Selvstyring av modeller**
  Brukere ønsker modeller som åpner for en større grad av selvstyring. Eksempelvis kunne det tilrettelegges for automatisk innhenting av data fra Elhub og andre datakilder, i tilfeller hvor modellene krever veldig detaljerte og oppdaterte data. Igjen er det et spørsmål om forskningsmiljøene selv skal påta seg dette.

- **Dokumentasjon**
  Brukerne ønsker mer fullstendig dokumentasjon av modellene tilpasset brukernes behov. Dette inkluderer transparens i forutsetninger og at forutsetningene er presentert på en lett tilgjengelig måte for å hjelpe brukerne til å få oversikt over de viktige underliggende beslutninger som har påvirket resultatene. I tillegg ønskes det tydeligere forklaringer i analyser utgitt av modelleringsmiljøer rundt begrensningene ved modellen som er brukt.

- **Visualisering av resultatene**
  Bedre visualisering og formidling av resultater er ønsket av brukerne når scenarioer og tiltaksanalyser er presentert i rapporter og presentasjoner.

4 Oppsummering av forslagene

Listen under oppsummerer de ulike forslag til løsninger som fremkom under workshopen.

Modellene må utvikles for å bedre:

- fange behovet for fleksibilitet og effekt i et europeisk perspektiv, potensialet og begrensninger til fleksibilitetsløsninger, samt samspill mellom løsningene og på tvers av energibærer/sektorer
  Forslag: Høyere tidsoppløsninger; Økt fokus på markedsdesign; Mer detaljerte representasjon av fleksibilitetsløsninger

- håndtere distribuert produksjon og lagring, forbrukerfleksibilitet og forbrukeratferd i respons til insentiver
  Forslag: Kobling mellom energi- og økonomimodeller; Bruk av metoder for å representere atferd og økonomisk irrasjonalitet

- integrere robusthet mot politisk og andre typer usikkerhet, samt nye drivkrefter og trender
  Forslag: Stokastikk integreres i flere modelleringsanalyser; Forutsetningene og scenarioene har mer fokus på usikkerhet

- representere europeiske forhold, sammenhengen mellom energisektoren og økonomien, transportsektoren, bioenergi, samt klima, miljø og helse.
  Forslag: Modeller med bredere fokus; Modellkobling

Miljøene og modellene må organiseres slik at:

- miljøene samarbeider for å sikre en kritisk masse av brukere, heve kompetansenivået og sikre kvaliteten
  Forslag: En felles arena for modellforskning; Økt nordisk og europeisk samarbeid; Støtte for vedlikehold og utvikling av modeller og databaser

- modellene kan lettere kobles sammen
  Forslag: Et felles rammeverk for kobling mellom modeller på tvers av modelltradisjon og sektor

- datatilgang og -kvalitet forbedres
  Forslag: Tettere samarbeid mellom aktørene og modelleringsmiljøene; En felles database

Tilrettelegging for økt bruk av modellene som grunnlag for politikkutforming gjennom:

- økt brukerkompetanse hos myndighetene
  Forslag: Bedre involvering av brukere i modellutvikling; Etablering av en modellkatalog

- tilpasning av modellene for å gi raskere svar på myndighetenes spørsmål
  Forslag: Større grad av innebygd fleksibilitet i modellene, for eksempel modulær oppbygging

Vedlegg 1. Modelloversikt:

Overview of energy system models in use in Norway

Version 1. (1.9.2017)

I. Introduction and scope ... 2

II. Bottom-up technology-rich optimisation models ... 2

Multi-sector models ... 3

TIMES - Norway ... 3

TIMES – North Europe ... 5

ETSAP-TIAM ... 6

Balmorel ... 8

eTransport ... 10

Single-sector models ... 11

EMPIRE ... 11

Ramona ... 13

Stock-flow models for road transport ... 14

III. Top-down economic equilibrium models ... 14

General equilibrium models ... 15

SNOW ... 15

REMES ... 16

Partial equilibrium models ... 17

LIBEMOD ... 17

FRISBEE ... 19

PETRO ... 20

Nordic Forest & Bioenergy Sector Model ... 21

Partial equilibrium models including strategic behaviour ... 22

MultiMod ... 23

Global Gas Model ... 24

IV. Shorter-term technology-rich market optimisation models ... 26

EMPS – Samkjøringsmodell ... 26

SOVN ... 28

powerGAMA (formerly PSST) ... 29

ProdRisk ... 30

V. Important models outside the scope ... 31

I. Introduction and scope

This overview is a first step towards meeting to one of the needs pointed out at the modelling workshop held in April 2017 – a catalogue to help users of model-based analyses to better understand the diversity of modelling activity in Norway. The document categorises relevant models and provides a table with essential details about each model to facilitate comparison.

CenSES initiated the process by sending an overview of models used in that FME in the aftermath of the workshop. The Research Council has since developed that initial overview, expanding it to include model details submitted by a number of research institutions outside of CenSES.

The resulting overview provides a relatively thorough rundown of the key models in use in Norway in 2017, but is by no means exhaustive. Models for the transport sector, for example, will need significantly more detail in future versions. This document is assigned "version 1" and can be considered a starting point should an attempt be made in the future to create an exhaustive and continually updated catalogue.

The scope of the overview is limited primarily to research-based modelling activities that address the entire energy system and which can inform policy design, as was the scope of the workshop held in April 2017. The overview focuses on long-term models and only covers short-term operational models if they are commonly used in conjunction with long-term models. The same applies to sector-specific models, such as those for oil and gas. The overview does not provide details on models developed by other actors than research institutions, but mentions important models outside the scope of the overview in the final section.

The categorisation is of models into different sections of the document is not an exact science. The models could be grouped in a number of different ways and many models cut across categories depending on how they are operated. This overview groups the models into three main categories: Bottom-up technology-rich optimisation models, top-down economic equilibrium models, and finally, shorter-term technology-rich market optimisation models.

II. Bottom-up technology-rich optimisation models

This class of models use optimisation to represent how a system, either a single sector or multiple interlinked sectors, develops when assuming perfect competition. Commonly both system investments and operation are co-optimized by minimizing total costs in meeting an exogenously determined (and therefore inelastic) demand for energy services. The technological detail level in these models are usually reasonably rich, however, as short-term operational decisions are considered over long-term horizons, the problem size grows quickly unless some form of aggregation is used. Typical usages of investment optimisation models for long-term analysis are: Energy/climate policy analysis, analysis of energy system transition strategies, technology deployment analysis. Multi-sector models analyse the interaction between energy carriers and sectors, while single-sector models have been developed to better represent the dynamics of specific energy carriers (such as electricity under high shares of variable renewables).

Multi-sector models

TIMES - Norway

Model name:	TIMES-Norway
Main developer and partners:	TIMES-Norway is developed by Institute for Energy Technology (IFE) on commission of The Norwegian Water Resources and Energy Directorate (NVE).
Analysis objective:	Cost-optimal development of the Norwegian energy system Can include optimization wrt. policy measures and climate constraints
Short description	TIMES-Norway is a TIMES model with a detailed description of the Norwegian energy system. The model assumes perfect competition, uses a perfect foresight investment strategy and minimise the total energy system cost for the analysed model horizon to meet the final energy demand at a least cost. The wide sectoral coverage of the model captures the interaction, and the competition, between the energy supply, production, distribution and demand technologies. The TIMES-Norway model is a successor of the previous used MARKAL model of Norway. It is possible to extract the Oslo region from the model and analyse this region separately.
Specific strengths	• High temporal resolution • Detailed description of all end-use sectors (transport, buildings, industry) • The electricity demand is endogenous, since the use of energy carriers in the end-use sectors is a model decision • Continuously improved and updated through a collaboration between IFE and NVE • The TIMES (The Integrated MARKAL-EFOM System) model generator was developed as part of the IEA-ETSAP (Energy Technology Systems Analysis Program), and is continuously improved and updated through IEA-ETSAP • The TIMES model generator is used by national teams in nearly 70 countries • It is easy to revise the model in regards of model structure as well as the characterisation of technology and end-use
Inputs:	• Discount rate • Demand projections for future energy services • Demand profiles • Technology characteristics related to potential, efficiency and costs • Energy resource potentials • Energy generation profiles • Global fuel prices (fossil fuels and bio products) • Future development of the electricity market (outside the external model regions) • Energy policies, such as taxes and subsidies, emission restrictions etc.
Outputs:	• Cost-optimal investments and operation of the energy system covering energy supply, generation, transformation and end-use. • Energy generation, energy consumption, energy prices, technology adoption, and demands for energy carriers. • Cost-optimal adaption of policy instruments • System costs
Sector/Energy carriers:	Sector: Energy system Energy carriers: Fossil fuels (natural gas, diesel, heavy oil etc.), district heat, biomass (biodiesel, wood, bio coal etc.), waste and electricity.
Geography and granularity / data(sets):	The model is regionally divided into the electricity spot price areas of Norway, NO1 – NO5
Time resolution and horizon:	The model horizon is 2015 to 2050, with user-specified model periods within this horizon. Each model period is split in 260 time-slices; 52 weeks and 5 intraweek periods (day 1, day2, day3, night and weekend).
Level of detail (economy, energy system, technologies)	Bottom-up model with a detailed technology levels of the energy system. In total, there are about 75 to 78 end-use demand categories in each region. The end-use demand sector is further divided into sub sectors and demand types; electricity, heat, cooling and raw material.
Main future research challenges	• Improved modelling of energy efficiency • Include demand response (load shifting and load shaving) • Transition to a zero emission transport sector • CO_2 reduction in the industry

	• Climate impacts
Necessary environment / operating system:	Windows
Commercial and other licences / solvers?	User interface Answer/ VEDA Language GAMS Solver XPRESS or CPLEX
Interface:	User interface Answer/ VEDA
Used in which previous analysis projects?	Energy demand projections towards 2050 (CenSES) Analysis of CO_2 reduction measures (Miljødirektoratet) Regional Effects of Energy Policy (KPN) Nordic Energy Technology Perspectives (NER/IEA) Climate- and Energy strategy (city of Oslo) Energy Scenario Analysis (Enova) Ongoing projects: Norwegian Energy Road Map, Security of supply, WINLAND, ASSETS
Clients, other users?	NVE, ENOVA, EU, Research Council of Norway, Nordic Energy Research
Existing / possible coupling to other models?	TIMES-Norway ⇔ EMPS TIMES-Norway ⇔ REMES TIMES-Norway ⇔ ETSAP-TIAM TIMES-Norway ⇔ EMPIRE
Reports and papers	Bye, B., K. Espegren, T. Fæhn, E. Rosenberg, O. Rosnes, 2016. Energiteknologi og energiøkonomi: Analyser av energipolitikk i to ulike modelltradisjoner (English: Energy technology and energy economy: Analysis of energy policy in two different model systems), Samfunnsøkonomen 6, 43–53 García-Gusano, D., Espegren, K., Lind, A., Kirkengen, M., 2016a. The role of the discount rates in energy systems optimisation models. Renewable and Sustainable Energy Reviews 59, 56-72. García-Gusano, D., Iribarren, D., Martín-Gamboa, M., Dufour, J., Espegren, K., Lind, A., 2016b. Integration of life-cycle indicators into energy optimisation models: the case study of power generation in Norway. Journal of Cleaner Production 112, Part 4, 2693-2696. Lind, A., Espegren, K., 2017. The use of energy system models for analysing the transition to low-carbon cities – The case of Oslo. Energy Strategy Reviews 15, 44-56. Lind, A., Rosenberg, E., 2013. TIMES-Norway model documentation. Institute for Energy Technology, http://www.ife.no/en/publications/2013/ensys/times-norway-model-documentation. Lind, A., Rosenberg, E., 2014. How do Various Risk Factors Influence the Green Certificate Market of Norway and Sweden? Energy Procedia 58, 9-15. Lind, A., Rosenberg, E., Seljom, P., Espegren, K., Fidje, A., Lindberg, K., 2013. Analysis of the EU renewable energy directive by a techno-economic optimisation model. Energy Policy 60, 364-377. Ramírez, A., Hoefnagels, R., van den Broek, M., Strachan, N., Fidje, A., Espegren, K., Seljom, P., Blesl, M., Kober, T., Grohnheit, P.E., Lüthje, M., 2011. A Comparison of national CCS strategies for Northwest Europe, with a focus on the potential of common CO2 storage at the Utsira formation. Energy Procedia 4, 2401-2408. Rosenberg, E., Espegren, K.A. (Eds.), 2014. CenSES-energiframskrivinger mot 2050, https://www.ntnu.no/documents/7414984/0/CenSES-Energiframskriving+Rapport_final.pdf/13bfdaff-d1ea-4c0f-9553-7bd48ac6fc2f. Rosenberg, E., Fidje, A., Espegren, K.A., Stiller, C., Svensson, A.M., Møller-Holst, S., 2010. Market penetration analysis of hydrogen vehicles in Norwegian passenger transport towards 2050.

	International Journal of Hydrogen Energy 35, 7267-7279. Rosenberg, E., Lind, A., Espegren, K.A., 2013. The impact of future energy demand on renewable energy production – Case of Norway. Energy 61, 419-431. Seljom, P., Rosenberg, E., Fidje, A., Haugen, J.E., Meir, M., Rekstad, J., Jarlset, T., 2011. Modelling the effects of climate change on the energy system—A case study of Norway. Energy Policy 39, 7310-7321. Strachan, N., Hoefnagels, R., Ramírez, A., van den Broek, M., Fidje, A., Espegren, K., Seljom, P., Blesl, M., Kober, T., Grohnheit, P.E., 2011. CCS in the North Sea region: A comparison on the cost-effectiveness of storing CO2 in the Utsira formation at regional and national scales. International Journal of Greenhouse Gas Control 5, 1517-1532.

TIMES – North Europe

Model name:	TIMES – North Europe
Main developer and partners:	IFE/ NTNU
Analysis objective:	Cost-optimal development of the energy system in Northern Europe.
Short description:	TIMES-North Europe is a stochastic TIMES model that covers the Northern European Countries. The model covers the energy system in the Scandinavian countries; Denmark, Norway and Sweden, and the electricity sector of Finland, Germany, the Netherlands and the UK. The model assumes perfect competition, uses a perfect foresight investment strategy and minimise the expected energy system cost for the analysed model horison to meet the final energy demand at a least cost. The model uses stochastic programming to consider the short-term uncertainty related to the variability of renewable electricity generation, heat demand and fuel prices.
Specific strengths	• Explicitly value flexibility through a stochastic modelling of short-term uncertainty • Covers several end-use sectors and the interaction between these • A high detail level on the Scandinavian energy system • The TIMES (The Integrated MARKAL-EFOM System) model generator was developed as part of the IEA-ETSAP (Energy Technology Systems Analysis Program), and is continuously improved and updated through IEA-ETSAP • The TIMES model generator is used by national teams in nearly 70 countries • It is easy to revise the model in regards of model structure as well as the characterisation of technology and end-use
Inputs:	• Discount rate • Demand projections for future energy services • Demand profiles • Technology characteristics related to potential, efficiency and costs • Energy resource potentials • Energy generation profiles • Global fuel prices • Future development of the electricity market outside the external model regions
Outputs:	• Cost-optimal investments and operation of the energy system covering energy supply, generation, transformation and end-use. • Energy generation, energy consumption, energy prices, technology adoption, and demands for energy carriers. • Cost-optimal adaption of policy instruments • System costs
Sector/Energy carriers:	Sector: Energy system Energy carriers: Fossil fuels (natural gas, diesel, heavy oil etc.), district heat, biomass (biodiesel, wood, bio coal etc.), waste and electricity.
Geography and granularity / data(sets):	The model is regionally divided into the Nord Pool price areas for Scandinavia , with two regions in Denmark, five regions in Norway and four regions in Sweden. The remaining countries are modelled as one region.
Time resolution	The model periods are every fifth year within the time horizon from 2010 to 2050. Further, each

and horizon:	model period is divided into 48 time-slices, with a representative day with 12 two-hour steps in four seasons. The time-slice structure is chosen to capture the seasonal and diurnal characteristics of energy supply and demand. Winter is defined as December, January and February, spring is defined as March, April, May, summer is June, July and August and autumn is September, October and November.
Level of detail (economy, energy system, technologies)	Bottom-up model with a detailed technology levels of the energy system.
Main future research challenges	• Load shifting and shaving • Flexibility of the transport system • Optimal time-slice structure • Optimal scenario generation method • End-use flexibility inthe building sector
Necessary environment / operating system:	Windows
Commercial and other licences / solvers?	User interface Answer/ VEDA Language GAMS Solver XPRESS or CPLEX
Interface:	User interface Answer/ VEDA
Used in which previous analysis projects?	The future Norwegian energy system in a North-European context, Research Council of Norway (207067) Ongoing projects: ASSETS
Clients, other users?	Research Council of Norway
Existing / possible coupling to other models?	TIMES - North Europe⇔ TIMES-Norway TIMES - North Europe⇔ ETSAP-TIAM TIMES - North Europe⇔ EMPS TIMES - North Europe⇔ EMPIRE
Reports and papers	Seljom, P., Lindberg, K.B., Tomasgard, A., Doorman, G., Sartori, I., 2017. The impact of Zero Energy Buildings on the Scandinavian energy system. Energy 118, 284-296. Seljom, P., Tomasgard, A., 2015. Short-term uncertainty in long-term energy system models — A case study of wind power in Denmark. Energy Economics 49, 157-167. Seljom, P., Tomasgard, A., 2017. The impact of policy actions and future energy prices on the cost-optimal development of the energy system in Norway and Sweden. Energy Policy 106, 85-102.

ETSAP-TIAM

Model name:	ETSAP-TIAM
Main developer and partners:	The starting version of the ETSAP-TIAM model was developed by Richard Loulou, Maryse Labriet, Amit Kanudia while working at GERAD (1999-2000). The seed of model was embodied in the initial version of the global models developed by US-EIA (SAGE), IEA (ETP) and EFDA. Furthermore, the ETSAP-TIAM model was developed further through the IEA implementing agreement, ETSAP. The ETSAP-TIAM model is available for all ETSAP members, and is continuously updated and improved through a joint effort of these members. Some research teams have further developed the ETSAP-TIAM model to meet specific needs. These models are denoted TIAM-ECN, TIAM-UCL, TIAM-FR etc.
Analysis objective:	Cost-optimal development of the global energy system
Short description:	ETSAP-TIAM is a global TIMES model that comprises several thousand technologies in all sectors of the energy system. It is characterized by several technical and economic parameters and by emission coefficients for the three main GHG's: CO_2, CH_4, and N_2O. The model assumes perfect

	competition and has perfect foresight, and the total energy system cost for the whole model horison is minimised to meet the final energy demand at a least cost
Specific strengths	• Endogenous fuel prices, covering oil, natural gas, biomass & electricity • Covers the entire energy system with all end-use sectors • Climate module • Models global climate targets • Endogenous trade of energy carriers between model regions • Technology rich • Includes an option for endogenous technology learning • Can model long-term uncertainty by stochastic programming • Can include endogenous technology learning • The TIMES (The Integrated MARKAL-EFOM System) model generator is continuously improved and updated through IEA-ETSAP • The TIMES model generator is used by national teams in nearly 70 countries • It is straight forward to revise the model in regards of model structure as well as the characterisation of technology and end-use
Inputs:	• Discount rate • Initial demand, drivers and demand elasticity for the future energy demand • Demand profiles • Technology characteristics related to potential, efficiency and costs • Energy resource potentials • Energy generation profiles • Climate change target
Outputs:	• Optimal investments and operation of the energy system covering energy supply, generation, transformation and end-use. • Energy production, energy consumption, energy prices, technology adoption, abandonment, emissions, emission prices, climate variables and demands for energy services • System costs
Sector/Energy carriers:	• Covers the energy system, including energy supply, energy production, energy transformation and the end-use sectors (agriculture, commercial, industry, residential and transportation). Each segment of the energy system is divided into sub-groups; Agriculture (1), Transport (15), Industry (7), Residential (11), Commercial (8) • All energy carriers are covered.
Geography and granularity / data(sets):	Global coverage; 16 regions: Africa, Australia-New Zealand, Canada, Central and South America, China, European Union+, Central Asia Caucasus, Other Eastern Europe, Russian Federation, India, Japan, Mexico, Middle-East, Other Developing Asia, South Korea, United States.
Time resolution and horizon:	The model horizon is 2005 to 2100, with user-specified model periods within this horizon. Each model period is split in 6 time-slices; 3 seasons (summer, intermediate and winter) and 2 intraday (day, night).
Level of detail (economy, energy system, technologies)	Bottom-up model with a detailed technology levels of the energy system.
Main future research challenges	• Update and improve input data • Improve the method used to consider the variability of energy generation and use
Necessary environment / operating system:	Windows
Commercial and other licences / solvers?	User interface VEDA Language GAMS Solver XPRESS or CPLEX
Interface:	User interface VEDA
Used in which previous analysis projects?	• ETSAP • CenSES • Smart path, Research Council of Norway (268200) • The future Norwegian energy system in a North-European context, Research Council of Norway (207067)
Clients, other	EU, Research Council of Norway, CenSES

users?	
Existing / possible coupling to other models?	ETSAP-TIAM ⇔ TIMES-Norway ETSAP-TIAM ⇔ TIMES-North Europe ETSAP-TIAM ⇔ GCAM
Reports and papers	Karlsson, K.B., Wouter, N., Lodewijks, P., Føyn, T.H.Y., Seljom, P.M.S., Balyk, O., Lüthje, M., Gregg, J.S., 2001. A global or a partial climate agreement – what difference does it make?, Abstract from ETSAP Workshop, Palto Alto, CA, United States, https://iea-etsap.org/workshop/stanforduniversity_california_2011/bioccs_china_climatedeal_keka2.pdf. Loulou, R., 2008. ETSAP-TIAM: the TIMES integrated assessment model. part II: mathematical formulation. Computational Management Science 5, 41-66. Loulou, R., Labriet, M., 2008. ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure. Computational Management Science 5, 7-40. Seljom, P., 2013. Modelling an ambitious climate constraint with ETSAP–TIAM, IFE/KR/F-2013/123, http://www.ntnu.no/documents/7414984/202064323/IFEKRF-2013_123+Modelling+an+ambitious+cilmate+constraint+with+ETSAP-TIAM.pdf/a552cb49-a81d-4612-8787-06cc3a9626bd.

Balmorel

Model name:	Balmorel
Main developer and partners:	RAM-løse, Technical University of Denmark (DTU), Ea Energy Analyses & NMBU
Analysis objective:	Welfare optimal operation and investment in the power and heat systems
Short description:	Balmorel is a partial equilibrium model for simultaneous optimisation of generation, transmission and consumption of electricity and heat under the assumption of perfectly competitive markets. The model finds the optimal way to satisfy the energy demand maximising social welfare (consumers' utility minus producers' cost of electricity)
Specific strengths	• Open source – which enables a collaborative development, a broad user community and a diversity of applications and users • Large flexibility in temporal and spatial resolution • Combined long term investment horizon and short term operational optimization model • Includes a detailed representation of the technical characteristics of a wide range of power, heat and storage technologies. • Allows for modelling of elastic electricity and heat demand, which is not commonly covered in energy system models • A number of enhancements (addons) for specific analysis, e.g., transport, hydrogen, unit commitment • Coded in a modelling system that facilitates code extension to the needs of specific analyses
Inputs:	• Installed base-year generation and transmission capacities • Generation O&M costs and fuel efficiencies • Investment costs of generation and storage units and transmission lines • Costs and capacities of storage technologies • Fuel and carbon prices • Annual power and heat Consumption • Consumption profiles • Taxes, subsidies and regulations affecting optimal dispatch or investments
Outputs:	• System costs • Energy generation • Energy consumption • Energy prices • Transmission • Storage levels • Emissions

	• Marginal costs, interpreted as prices of i.a. electricity and heat
Sector/Energy carriers:	Sector: Energy sector Energy carriers: Fossil fuels (Lignite, black coal, natural gas, diesel, heavy oil etc.), district heat, biomass (biodiesel, wood, wood waste, pellets etc.), hydrogen, renewable gases, waste and electricity.
Geography and granularity / data(sets):	Space is in Balmorel defined by using three layers of geographical entities: Country, Region and Area. The Country layer allows for general economic input to be defined, such as policy measures, renewable energy targets, resource restrictions and fuel prices. Between Regions, power transmission limitations can be defined such that congestion can be modelled between Regions. Another distinguished feature of the Regional layer is that here the electric power demand is defined and electricity balance is maintained. The model may be set up for the Regions to depict market bidding entities, nodes or used for congestion analysis. No power grid is considered inside a Region i.e. a copper plate system is assumed. Areas are used to represent individual geographical characteristics within a Region. Wind, hydro, solar and other climate conditions are defined on the Area level, as well the type and capacity of all power and heat generating and storage units. Because a Region can include multiple Areas, more than one set of climate conditions can be defined within a Region. Heat demand can also be defined in Areas, such that one Area can either depict a single district heating network or an aggregated heat supply and demand from multiple networks. The current NMBU version of Balmorel includes 11 countries, 18 regions and 42 areas the Nordic countries, the Baltics and western Europe.
Time resolution and horizon:	In Balmorel, time might be defined chronologically using three hierarchic layers: Year, Season and Term. The model setup can include one or more Years, each of which is divided into an equal number of Seasons and Seasons are further divided into an equal number of Terms. The combination of the chosen number of Seasons and Terms dictates the total number of modelled time segments in a Year. If for instance, the chosen number of Seasons and Terms are 52 and 168, respectively, there would be a total of 8736 basic time units available in a Year, which could in that case be interpreted as hours. Furthermore, final individual time segments can have different weights (duration) allowing for great flexibility when choosing the level of detail in temporal representation. In recent application of Balmorel, NMBU has run the model with annual time slices and for the time horizon to 2030 or 2050.
Level of detail (economy, energy system, technologies)	Bottom-up energy system model with a detailed representation of the covered energy sector.
Main future research challenges	• Better representation of the transportation and gas sectors (ongoing) • Develop a structured framework for the analysis of uncertainty due to stochastic variations such as weather, generation units availability etc • Reduce computational time through optimal aggregation of time and of space, solver tuning and decomposition for parallel computing • Improved modeling of biomass supply and competition for biomass from other industries • Coordination of input data collection, documentation and storage among Universities and research institutions using Balmorel
Necessary environment / operating system:	Windows, Linux or possibly others
Commercial and other licences / solvers?	Language GAMS Solver CPLEX or similar commercial, or open source solvers
Interface:	Typically using the GAMS interface
Used in which previous analysis projects?	Flexelterm, Energy Norway, Research Council of Norway (226260) Nordic Energy Technology Perspectives (at DTU) (NER/IEA) Flex4RES, Nordic Flagship Project (NER) BioNEXT, Research Council of Norway FME Bio4Fuels, Research Council of Norway FutureGas, Danish xxx A large number of projects by Ea Energy Analyses around the world
Clients, other users?	Other users: RAM-løse, DTU, KTH, Aalto University, VTT, Talling University, Ea Energy Analyses, Danish Energy Association, Elering, Estonian Transmission System Operator, Mexican Ministry

	of Energy, and others. Clients: Norwegian Research Council, EU, Nordic Energy Research, IEA, Energinet DK, Dansk Energi, Energi Norge, and others
Existing / possible coupling to other models?	Optiflow, NFSM (Nordic Bioenergy Sector Model), CorWind
Reports and papers	Selected recent papers: H. Ravn, The Balmorel Model Structure version 3.03 (2016), http://balmorel.com/images/downloads/model/BMS303-20160907.pdf, (assessed: 11 July 2017). K. Hedegaard, M. Munster, Influence of individual heat pumps on wind power integration – Energy system investments and operation, Energy Conversion and Management 75 (2013) 673{684. doi:10.1016/j.enconman.2013.08.015. A. G. Tveten, J. G. Kirkerud, T. F. Bolkesjø, Integrating variable renewables: the benefits of interconnecting thermal and hydropower regions, International Journal of Energy Sector Management 10 (3) (2016) 474{506. doi:10.1108/IJESM-08-2014-0006. A. G. Tveten, T. F. Bolkesjø, I. Ilieva, Increased demand-side flexibility: market effects and impacts on variable renewable energy integration, International Journal of Sustainable Energy Planning and Management 11 (2016) 33{50. doi:10.5278/ijsepm.2016.11.4. N. Juul, P. Meibom, Optimal configuration of an integrated power and transport system, Energy 36 (5) (2011) 3523{3530. doi:10.1016/j.energy.2011.03.058. K. Hedegaard, H. Ravn, N. Juul, P. Meibom, Effects of electric vehicles on power systems in Northern Europe, Energy 48 (1) (2012) 356{368. doi:10.1016/j.energy.2012.06.012. A. G. Tveten, T. F. Bolkesjø, Energy system impacts of the Norwegian-Swedish TGC market, International Journal of Energy Sector Management 10 (1) (2016) 69{86. doi:10.1108/IJESM-07-2014-0003. M. Munster, P. E. Morthorst, H. V. Larsen, L. Bregnbak, J. Werling, H. H. Lindboe, H. Ravn, The role of district heating in the future Danish energy system, Energy 48 (1) (2012) 47{55. doi: 10.1016/j.energy.2012.06.011. J. G. Kirkerud, E. Trømborg, T. F. Bolkesjø, A. G. Tveten, Modeling the Power Market Impacts of different Scenarios for the Long Term Development of the Heat Sector, Energy Procedia 58 (2014). doi:10.1016/j.egypro.2014.10.421. J. G. Kirkerud, T. F. Bolkesjø, E. Trømborg, Power-to-heat as a flexibility measure for integration of renewable energy, Energy 128 (2017). doi:10.1016/j.energy.2017.03.153.

eTransport

Model name:	eTransport
Main developer and partners:	SINTEF Energy
Analysis objective:	Planning of local energy systems where multiple energy carriers and technologies are considered simultaneously.
Short description:	The eTransport model gives the user a graphical overview of a given energy system (e.g municipality, city, suburb) with respect to costs, environmental consequences and use of local energy resources. The current version can optimize the construction of infrastructure for most relevant energy carriers; electricity, district heating, cooling, gas, waste and biomass, including conversions between these. It is not limited to continuous transport like lines, cables and pipes, but can also include discrete transport by ship, road or rail. The main task of the model is to optimize investments in infrastructure over a planning horizon of several decades to bring available energy to the end user in such quantities and in such form that the end users demands are covered in the economically and environmentally best way

	possible. As part of the investment analysis, however, the model also optimizes diurnal operation for different periods of the year for each alternative system design.
Specific strengths	Multi-energy carrier optimisation over several decades
Inputs:	Bottom up system description, energy carrier prices, demand, input output vector
Outputs:	Dispatch, energy prices (power, heat)
Sector/Energy carriers:	electricity, district heating, cooling, gas, waste and biomass
Geography and granularity / data(sets):	Norway / Nordic / EU (local system)
Time resolution and horizon:	2010/2020/2030/2050
Level of detail (economy, energy system, technologies)	
Main future research challenges	Stochastic optimisation, Life-Cycle-Analysis
Necessary environment / operating system:	Windows, will be implemented new in Python
Commercial and other licences / solvers?	AMPL and an optimisation solver (COIN Clp, CPLEX, Gurobi, Xpress...)
Interface:	Graphical, Window, …
Used in which previous analysis projects?	eTransport Susplan https://www.sintef.no/en/projects/etransport/
Clients, other users?	
Existing / possible coupling to other models?	
Reports and papers	Bakken, B. H., Skjelbred, H. I., & Wolfgang, O. (2007). eTransport: Investment planning in energy supply systems with multiple energy carriers. *Energy*, 32(9), 1676–1689. doi:10.1016/j.energy.2007.01.003 Bakken, B. H., & von Streng Velken, I. (2008). Linear models for optimization of infrastructure for CO2 capture and storage. *IEEE Transactions on Energy Conversion*, 23(3), 824–833. doi:10.1109/TEC.2008.921474

Single-sector models

EMPIRE

Model name:	EMPIRE – European Model for Power system Investments with (high shares of) Renewable Energy
Main developer and partners:	NTNU/CenSES
Analysis objective:	Optimal capacity expansion analysis for the European power sector Power system decarbonization Analysis of climate and energy policies for the European power sector
Short description:	EMPIRE is a capacity expansion model for the European power system, formulated as a multi-horizon stochastic program. The objective is to minimize system cost of the European power system including investment cost and expected operational costs. The model represents load and RES generation under short-term uncertainty, so that hourly variations and their correlations are considered when designing the system. This is particularly important when considering the technologies included in the energy mix and their actual role in the operations in terms of utilization factors. EMPIRE can therefore model the interplay between low carbon technologies with different characteristics such as solar PV, wind energy, carbon-capture and storage and

	nuclear power. Flexibility options such as demand response, energy storage and grid expansion are also included.
Specific strengths	Captures both long and short-term dynamics. A high number of operational hours modelled. Possibility to optimize investments using multi-annual data due to the stochastic programming formulation.
Inputs:	• Long-term electricity demand projections country level • Long-term fuel price projections • Carbon mitigation policy (price/cap) • National policies affecting the power system (technology support, phase out, etc.) • Hourly load profiles (country level) • Hourly wind/solar production profiles (country/regional level) • Hydropower production data (as detailed as possible) • Hydropower reservoir sizes (country level) • Generation/storage/grid technology characteristics (costs and other technical data) • Generation/storage/grid investment potentials • Base year system characteristics (installed generation/storage/grid capacities)
Outputs:	• Optimal investments in generation/storage/grid capacities at a national level • Optimal operation of the power system for a high number of operational time steps • Emission trajectories • System costs
Sector/Energy carriers:	Electricity sector (links to gas/heat sectors under development)
Geography and granularity / data(sets):	European coverage with regional to national granularity depending on the dataset. Transmission system represented as a transport model. Europe 2010-2050 datasets exist
Time resolution and horizon:	EMPIRE optimize power system investments and operation over a time horizon of about 40 years (typically), with steps of 5 years (2015, 2020, … , 2050). Each operational year is modelled using representative seasons with an hourly resolution.
Level of detail (economy, energy system, technologies)	**Generation technologies**: nuclear, fossil generation (hard coal, lignite, gas), CCS (hard coal, lignite, gas), biomass (regular, co-firing, co-firing CCS), hydropower (reservoir, pump, run-of-the-river), wind (onshore, offshore), solar PV **Storage and demand response:** Pumped hydropower, utility scale batteries, load shedding and load shifting
Main future research challenges	• Establish link to the RAMONA model (making it a gas-electric infrastructure model) • Model electricity system's interaction with heat • Represent decentralized generation • Further develop flexible demand side modelling • Develop functionality to represent long-term (strategic) uncertainty • Improve modelling of thermal power generation (represent inflexibility) • (Improve temporal/geographical detail level)
Necessary environment / operating system:	Windows (Linux can also be used) Fico Xpress Optimization Suite useful for editing files
Commercial and other licences / solvers?	Fico Xpress Optimization Suite
Interface:	Command line/Xpress Optimization Suite GUI
Used in which previous analysis projects?	ZEP Market Economics Group (European Technology Platform for Zero Emissions Fossil Fuel Power Plants) LinkS - Linking Global and Regional Energy Strategies (Research Council of Norway) SET-Nav (H2020)
Clients, other users?	A number of Norwegian an international partners has signalled ineptest to use it. A version will be released for free use under academic licence.
Existing / possible coupling to other models?	Possible: EMPIRE ⇔ EMPS EMPIRE ⇔ powerGAMA EMPIRE ⇔ TIMES-Norway (TIMES-North Europe) EMPIRE ⇔ Ramona
Reports and papers	Skar, C., Doorman, G. L., Pérez-Valdés, G. A., & Tomasgard, A. (2016). A multi-horizon stochastic programming model for the European power system (CenSES working paper No. 2/2016). Trondheim.

Ramona

Model name:	RAMONA
Main developer and partners:	NTNU/SINTEF
Analysis objective:	RAMONA main objective is to analyse the design of the Natural Gas Infrastructure. It can address research questions such as: -How should new areas be developed (sequencing of field - development, infrastructure and connection to existing infrastructures and markets) to maximize their value? - How do investment in gas networks components affects the system operation in regards to gas quality, volume and pressure flows?
Short description:	RAMONA is a mixed-integer linear optimization model that includes both investment decisions and operational decisions in the gas network. Pressure-flow relationships, compressors, operation of processing facilities as well as multi-commodity flows are optional features in the model. RAMONA can handle different types of objective functions depending on the problem at hand, such as (expected discounted) cost minimization, and maximization of (expected) profit or social welfare. The model can handle several (strategic) infrastructure decisions such as development of new fields, construction and redesign of infrastructure (pipelines, compressors, processing plants). On the operational level, the model can handle the relationship between pressure and flow, gas quality, processing and security-of-supply restrictions. RAMONA uses a multi-horizon stochastic framework to represent both long-term strategic uncertainty and short-term operational uncertainty.
Specific strengths	-High technical detail in short-term operations and strong representation of system effects -Well documented modelling experiences and implementation on the Norwegian continental shelf -Provides an investment plan (long-term infrastructure gas network design) under production assurance constraints
Inputs:	Technologies (transport and field concepts), resources, production profiles, capacities, time windows, costs, prices, rate of return
Outputs:	Investment plan and operational decisions
Sector/Energy carriers:	Gas sector: production fields, pipelines pressure flows, processing plants, compressors, and market nodes.
Geography and granularity / data(sets):	• Dataset1: A detailed dataset of the Norwegian offshore natural gas infrastructure considers pipelines and major components of the natural gas system (compressors and processing plants). • Dataset2: An aggregate representation of the European natural gas system. That is, a single node in the network represents each country along with simple cross-border interconnectors.
Time resolution and horizon:	• Investments are modelled yearly or in 5 years time steps. • Operational features have daily time resolution.
Level of detail (economy, energy system, technologies)	• High technical and operational decisions • Maximize expected social welfare
Main future research challenges	• Implement a more detailed operation of the EU system. A full multi-horizon implementation for EU. Update datasets. • Linking to other models: EMPIRE, REMES • RAMONA high technical features significantly increases the model computational efforts.
Necessary environment / operating system:	Model developed in Xspress mosel language. Database built in MS Access along with an interface in Excel.
Commercial and other licences / solvers?	Fico Xpress Optimization Suite
Interface:	Excel GUI to setup the main parameters of the model
Used in which previous analysis	Ramona (2006-2011): Managing uncertainty in the Norwegian natural gas network. Reliability analysis and risk management in a portfolio perspective. Cooperation with StatoilHydro and

projects?	Gassco. OptOp(2005-2008): Integrated design and operation of processing oriented natural gas value chains . EMF28 (2012-2013): Gas infrastructure development in Europe
Clients, other users?	
Existing / possible coupling to other models?	Possible: RAMONA integration with EMPIRE
Reports and papers	Frode Rømo, et. al., Optimizing the Norwegian Natural Gas Production and Transport, Interfaces, January-February 2009; 39: 46 - 56.' Tomasgard, Asgeir, et al. "Optimization models for the natural gas value chain." *Geometric modelling, numerical simulation, and optimization*. Springer Berlin Heidelberg, 2007. 521-558. Werner, A, Ramona. Multi-stage stochastic programming in natural gas networks: Model specification and documentation for prototype implementation. SINTEF report, 2012. Hellemo, Lars, et al. "Multi-stage stochastic programming for natural gas infrastructure design with a production perspective." *World Scientific Book Chapters* (2013): 259-288.

Stock-flow models for road transport

Specialised models for vehicle fleets and energy use in transport are used to inform transport-related energy and climate policy. Further details on these models are expected to be integrated in a later version of this document. Tentatively, two models developed by the Norwegian Institute of Transport Economics are briefly outlined below:

BIG – A stock-flow vehicle fleet model. It simulates future scenarios for vehicle sales, stock and usage, as well as fuel consumption and environmental impacts. It provides information on the time lag between technological improvements affecting new vehicles and their penetration into the car fleet. Outputs include fuel consumption, greenhouse gas and pollutant emissions. The model includes 6 vehicle types, 11 sources of energy, 31 age groups and 9 weight classes for each vehicle type. Future research challenges include developing additional granularity in vehicle types (currently limited to 6).

SERAPIS – A dynamic car fleet and propulsion technology model. It handles qualitative incentives, such as access to bus lanes, reserved parking spaces within a detailed geographic specification.

III. Top-down economic equilibrium models

General and partial equilibrium models are based on economic theory and are used to analyse the interaction of agents in a market assuming either perfect competition (typically) or strategic interaction. These models account for substitution possibilities, both in production (between different inputs) and in consumption (between different goods and services). In addition to substitution, the economic agents can adjust the level of production/consumption in response to policies. This is a key difference to bottom-up optimisation models where demand is typically determined through exogenous assumptions and is therefore inelastic.

General equilibrium models

Computable General Equilibrium (CGE) models model all markets and market agents' behaviour in interaction. Hence, they are well-suited to capture both direct and indirect effects of a policy. CGE models are top-down models, with less detailed modelling of technologies (although hybrid models include detailed descriptions of certain technologies), and the temporal detail is usually low.

SNOW

Model name:	SNOW (Statistics Norway's World model)
Main developer and partners:	SSB
Analysis objective:	• Policy analyses: Economic effects of a policy for the whole Norwegian economy • Projections: How would the Norwegian economy develop under given assumptions
Short description:	SNOW is a recursive dynamic multi-sector Computable General Equilibrium (CGE) model for Norway (SNOW-NO) or the global (SNOW-W) economy. It supersedes the MSG model.
Specific strengths	• Models interactions between optimising economic agents (individuals and firms) in all national and international markets. The model is therefore well-suited to study interactions of different policies and feedback effects. • Flexible sectoral aggregation, fast to solve, easy to change. • Same sectoral aggregation as GTAP (https://www.gtap.agecon.purdue.edu/), hence, we can use data for other countries and link it to other models.
Inputs:	• National Accounts (input-output tables) describing economic flows between different sectors, input use, subsidies and taxes in the base year • Emissions in the base year • Substitution elasticities • Projections for exogenous growth parameters
Outputs:	• Equilibrium levels for supply, demand, imports, exports and relative prices in all 46 sectors • Use of production factors (labour, capital, resource) and investments in all 46 sectors • Consumption of different goods • Welfare cost • Emissions for 12 pollutants (6 GHGs and 6 other)
Sector/Energy carriers:	46 industrial sectors plus households and government sector. - 5 energy producing sectors: oil & gas extraction, refineries, district heating & gas production & distribution, coal, electricity production & distribution. - 6 energy products (incl. renewables) in household consumption
Geography and granularity / data(sets):	SNOW-NO: Norwegian economy, with trade with the rest of the world SNOW- W: Norwegian economy and all other countries solved simultaneously (with different aggregations possible)
Time resolution and horizon:	1 year, any number of years in the recursive dynamic version
Level of detail (economy, energy system, technologies)	46 production sectors of the economy produce one good each. In addition, households can consume 22 different final consumption goods. Government sector.
Main future research challenges	Abatement technologies for GHG emissions Energy efficiency in commercial buildings and industries Inertia in investments Fully dynamic model (intertemporal optimization) Unbundling of electricity sector (into renewable and conventional; production and distribution)
Necessary environment / operating system:	Windows
Commercial and other licences / solvers?	Language: GAMS Solver: PATH, MPSGE
Interface:	GAMS-IDE, Excel
Used in which previous analysis projects?	ENTRACTE (EU 7th Framework Programme) WILL (NFR) Perspektivmeldingen 2017

Clients, other users?	Ministry of Finance, Norwegian Environment Agency, other government agencies
Existing / possible coupling to other models?	Uses GTAP sector definitions, and can therefore use and import data from other models (e.g. global data) and link to similar models of other countries
Reports and papers	**SNOW-NO:** Bye, B., K. Espegren, T. Fæhn, E. Rosenberg, O. Rosnes (2016): Energiteknologi og energiøkonomi: Analyser av energipolitikk i to ulike modelltradisjoner, Samfunnsøkonomen 6, 43–53 Bye, B., T. Fæhn, O. Rosnes (2015): Residential energy efficiency and European carbon policies: A CGE-analysis with bottom-up information on energy efficiency technologies, Discussion Papers No. 817, Statistics Norway Greaker, M., O. Rosnes (2015): Robuste norske klimamålsetninger, Samfunnsøkonomen 1, 67–77 **SNOW-Global:** Böhringer, C., B. Bye, T. Fæhn and O. Rosnes (2017): Carbon policies and competitiveness: The case of Norway, manuscript Böhringer, C., B. Bye, T. Fæhn, and K.E. Rosendahl (2016): Output-based rebating of carbon taxes in the neighbor's backyard: Competitiveness, leakage and welfare, forthcoming, in the Canadian Journal of Economics. Böhringer, C., B. Bye, T. Fæhn, and K.E. Rosendahl (2015): Targeted carbon tariffs: Carbon leakage and welfare effects, Discussion Papers No. 805, Statistics Norway Böhringer, C., B. Bye, T. Fæhn, and K.E. Rosendahl (2012): Alternative designs for tariffs on embodied carbon: A global cost-effectiveness analysis, Energy Economics 34, 143-153.

REMES

Model name:	REMES
Main developer and partners:	SINTEF Teknologi og Samfunn
Analysis objective:	Macroeconomic equilibrium of the Norwegian/European economy
Short description:	REMES is a Computable General Equilibrium model with regional divisions. It uses Social Accounting Matrices to construct an equilibrium state of an open economy (e.g. Norway's), and then introduces shocks in the form of increased availability of production factors, taxes, subsidies, and technological changes. REMES tries to find a new state of equilibrium for the economy according to macroeconomic assumptions.
Specific strengths	Flexible resolution and sectoral aggregation, fast to solve, easy to change
Inputs:	Social Accounting Matrix in regions, Elasticities of substitution for each sector
Outputs:	Relative prices, activity levels, demands and consumption budgets for each actor of the economy in question
Sector/Energy carriers:	Varies with the aggregation level
Geography and granularity / data(sets):	Norway / EU
Time resolution and horizon:	One year for the static run, any number of years for the recursive version
Level of detail (economy, energy system, technologies)	Up to 163 sectors and 200 products, depending on the type of analysis and processing power
Main future research challenges	Full dynamicity and financial systems, Demographic modelling, land use and emissions consideration
Necessary environment / operating system:	GAMS, Windows, UNIX,
Commercial and other licences / solvers?	GAMS, PATH, MPSGE
Interface:	GAMS IDE/Command line

Used in which previous analysis projects?	Regpoll (NFR, 216513/E20) SET-Nav (EU 691843) KMD consultancy
Clients, other users?	EU commission, Norwegian KMD department, Norwegian county governments
Existing / possible coupling to other models?	TIMES
Reports and papers	Regpoll – Regional Effects of Energy Policy - http://www.sintef.no/en/projects/regpol-regional-effects-of-energy-policy-/

Partial equilibrium models

Partial equilibrium models apply the same economic principles as CGE models but to a specific part of the economy, often to achieve greater technological or temporal detail.

LIBEMOD

Model name:	LIBEMOD
Main developer and partners:	Frisch Centre and SSB
Analysis objective:	Effects of energy and environmental policies, new technologies, and exogenous market developments on the European energy markets.
Short description:	Partial equilibrium model of energy markets, with a focus on the power and gas markets in Europe. LIBEMOD determines simultaneously investment, extraction, production, trade, transport and consumption of all energy goods (prices and quantities) in 31 European countries. In addition, the model determines prices and quantities of the globally traded energy goods biofuel, coking coal, steam coal and oil, as well as emissions of CO2 by sectors and countries. The model can be run under alternative assumptions about market structure and whether there is uncertainty.
Specific strengths	• Simultaneous determination of the entire energy value chain in the European energy markets, including investment, demand and prices • Detailed modelling of the electricity market • Endogenous investment in renewable electricity when these technologies are treated similar to other technologies (costs, efficiency) • Investment in international transportation networks • Allows for stochastic analysis
Inputs:	• Calibration requires a full set of quantities and prices in a specific year • Target demand and income elasticities • Expected future GDP by country • Comprehensive cost data for supply of energy • Characteristics of future electricity technologies
Outputs:	• All quantities and prices for the modelled energy markets, including transport of energy and emissions of CO2 by country and sector
Sector/Energy carriers:	• Four end-user sectors and the power generation sector • Three types of coal, natural gas (piped and LNG), oil, two types of bio energy and electricity
Geography and granularity / data(sets):	Energy markets in each of 31 European countries as well as global energy markets
Time resolution and horizon:	Electricity: decided by the model runner Fossil fuels: Annual Horizon: Decided by the model runner, but subject to data availability.
Level of detail (economy, energy system, technologies)	Energy system
Main future research challenges	• Modelling of alternative design of capacity mechanisms and their implied impact on the energy markets • Modelling and analyses of batteries/storage technologies

	• Feasible refinement of time resolution • Improved modelling of transport technologies
Necessary environment / operating system:	GAMS
Commercial and other licences / solvers?	PATH
Interface:	WINDOWS
Used in which previous analysis projects?	Analyses effect of interventions in energy, climate and environmental policy. New technology impacts incl. CCS
Clients, other users?	Norwegian Research Council
Existing / possible coupling to other models?	Possible to couple to GCE or IAM models
Reports and papers	International publications: Aune, F., Golombek, R. and Kittelsen, S. A. C.: "Does Increased Extraction of Natural Gas Reduce Carbon Emissions?" *Environmental and Resource Economics, 29 (4): 379-400, 2004.* Aune, F., Golombek, R., Kittelsen, S. A. C. og K.E. Rosendahl: "Liberalising the Energy Markets of Western Europe – A Computable Equilibrium Model Approach". *Applied Economics*, 36, 2137-2149, 2004. Aune, F., Golombek, R., Kittelsen, S. A. C. and K. E. Rosendahl: *Liberalizing European Energy Markets - An Economic Analysis*. Edward Elgar Publishing, 2008. Golombek, R., M. Greaker, S.A.C. Kittelsen, O. Røgeberg and F.R. Aune (2011): Carbon capture and storage in the European power market. *The Energy Journal*, Vol. 32 (3), 209-237. Golombek, R., S.A.C. Kittelsen and I. Haddeland (2012): Climate change: impacts on electricity markets in Western Europe, *Climatic Change*, 113, 357-370. Golombek, R., S.A.C. Kittelsen and K.E. Rosendahl (2013): Price and welfare effects of emission quota allocation, *Energy Economics* 36, 568–580. Golombek, R., K. A. Brekke and S.A.C. Kittelsen (2013): "Is electricity more important than natural gas? Partial liberalizations of the Western European energy markets". *Economic Modelling*, 35, 99-111. Aune, F.R., R. Golombek, A. Moe, K.E. Rosendahl and H. Hallre Le Tissier (2015): Liberalizing Russian gas markets – an economic analysis. *Energy Journal*, Vol. 36, Adelman special issue, 63-97. Brekke, K.A., R. Golombek, M. Kaut, S.A.C. Kittelsen and S.W. Wallace (2017): Stochastic energy market equilibrium modeling with multiple agents. *Energy*, 134, 984-990. Aune, F. R., R. Golombek, A. Moe, K. E. Rosendahl and H. H. Le Tissier (2017): The future of Russian gas Export. *Economics of Energy & Environmental Policy*, forthcoming. National publications: Aune, F.R., R. Golombek, S. Jaehnert, H. Hallre Le Tissier, S. Völler and Ove Wolfgang (2015): «Mot et grønnere Europa: Virkninger av EUs klimapolitikk for 2030.» *Samfunnsøkonomen*, nr. 3, p. 34-46. Aune, F. R., R. Golombek, A. Moe, K. E. Rosendahl and H. H. Le Tissier (2016): Eksport av russisk gass til Europa. *Samfunnsøkonomen*, nr. 2, p. 10-19.

	Golombek, R. and S. Kverndokk (2016): Paris-avtalen: Konsekvenser for EU og Norge. (The Paris-agreement: Implications for the EU and Norway). *Samfunnsøkonomen*, 2, 27-36.

FRISBEE

Model name:	FRISBEE (Framework of international Strategic Behaviour in Energy and Environment)
Main developer and partners:	SSB
Analysis objective:	Simulations of future demand and supply of fossil fuels, electricity and renewables in 15 regions worldwide (incl. Norway). Can study the effects of e.g. climate policies, changes in energy efficiency, increased introduction of renewables, variations in regional producer taxes on oil and gas.
Short description:	A recursive dynamic partial equilibrium model for fossil fuels, electricity and renewable energy sources.
Specific strengths	Explicit description of discoveries, reserves, field development and production of oil and gas. The supply side of each region is divided into four field categories, e.g., the Norwegian continental shelf is divided into the North Sea, the Norwegian Sea, Lofoten-Vesterålen-Senja and the Barents Sea. Differ between the investment and production phase for oil and gas. Optimization of present value of investments. The Norwegian petroleum tax system is modelled in-depth.
Inputs:	Oil price is exogenous (but can be calculated ad hoc as endogenous defined as OPECs optimal oil price), GDP per capita growth, population growth, energy efficiency, short and long-term elasticities for price and income, investment and operating costs, cost convexity and technological growth, petroleum tax systems, reserves of oil and gas: producing, undeveloped and undiscovered.
Outputs:	Regional production and regional/sectorial consumption of oil, gas, coal, electricity and renewables. Regional gas, coal and electricity prices. Distribution of gas as LNG or through pipelines, CO_2 emissions.
Sector/Energy carriers:	Sectors: Industry, households (including services) and power generation. Energy carriers: oil, gas, coal, electricity, biofuel and six other renewable energy sources.
Geography and granularity / data(sets):	15 demand and supply regions: Africa, Canada, Caspian Region, China, Eastern Europe, Latin America, OECD Pacific, OPEC Core, OPEC Rest, Rest of Asia, Russia, USA, Norway, United Kingdom, Rest of Western Europe. Greenland modelled as an oil and gas supplier.
Time resolution and horizon:	One year, 50-100 years.
Level of detail (economy, energy system, technologies)	15 regions, 3 sectors, 11 energy carriers, 8 consumable energy goods: two oil types (transport, stationary), gas, three coal types, electricity, biofuel.
Main future research challenges	Implement the model version with CCS and endogenous supply of renewables with the updated model version (without CCS and with exogenous supply of renewables). Endogenous oil price.
Necessary environment / operating system:	Windows
Commercial and other licences / solvers?	Language: GAMS Solver: CONOPT
Interface:	GAMS IDE
Used in which previous analysis projects?	Renergi (NFR), Petrosam (NFR), Petrosam II (NFR), ECONOR (Arctic Council)
Clients, other users?	Ministry of Foreign Affairs, Nordic Council of Ministers, AMAP-Arctic Monitoring and Assessment Programme.
Existing / possible coupling to other models?	
Reports and papers	**Ongoing work:** Aune, F. R. and L. Lindholt (2017): «Can a more stringent petroleum tax system increase

government income in Norway?"

Under review in International Journals:

Glomsrød, S. and L. Lindholt (2017): "Phasing out coal and phasing in renewables – good or bad news for arctic gas producers?". Under review in *Energy Economics*.

Published in International Journals:

Lindholt, L. and S. Glomsrød (2013): The Arctic: No big bonanza for the global petroleum industry, *Energy Economics* 34, 1465-1474.

Peters, G.P., Nilssen, T.B., Lindholt, L., Eide, M.S., Glomsrød, S. Eide, L.I. and J.S. Fuglestvedt (2011): Future Emissions from Shipping and Petroleum Activities in the Arctic, *Atmospheric Chemistry and Physics* 11, 5305-5320.

Aune, F.R., G. Liu, K. E. Rosendahl and E. L. Sagen (2010): Subsidising carbon capture: Effects on energy prices and market shares in the power market, *Environmental Economics* 1 (1), 76-91.

Aune, F.R., K.E. Rosendahl and E.L. Sagen (2009): Globalisation of natural gas markets – effects on prices and trade patterns, *The Energy Journal* 30 (Special Issue "World Natural Gas Markets and Trade: A Multi-Modeling Perspective"), 39-54.

Rosendahl, K.E. and E.L. Sagen (2009): The Global Natural Gas Market. Will transport cost reductions lead to lower prices? *The Energy Journal* 30 (2), 17-40.

Other publications:

Bourmistrov, A. and L. Lindholt (2017): Adaptation Actions for a Changing Arctic - Perspectives from the Barents Area. Arctic Monitoring and Assessment Programme (AMAP). In press. Chapter: "Oil and gas industry".

Glomsrød, S. and L. Lindholt (2017): ECONOR – The Economy of the North (2015): "Arctic petroleum extraction under climate policies". Statistical Analyses 112, Statistics Norway.

Glomsrød, S. and L. Lindholt (2008): ECONOR – The Economy of the North (2008): "Future production of petroleum in the Arctic under alternative oil prices", Statistical Analyses 151, Statistics Norway

PETRO

Model name:	PETRO 2
Main developer and partners:	SSB
Analysis objective:	Policy analyses of the long-term global oil market.
Short description:	The Petro 2 model is a long-term, dynamic oil market model. In the model, oil is modelled as a non-renewable resource and decision makers can make intertemporal trade-offs. The model assumes perfect foresight.
Specific strengths	OPEC has market power, and the fringe producers are forward-looking agents that take the oil price as given. The model solves for global, regional and sectoral oil prices and consumption, and the regional and sectoral consumption of the remaining energy carriers in the model. The model can reveal market effects such as carbon leakages, demand rebound and the green paradox.
Inputs:	Growth rates of GDP, population growth, prices of other energy goods than oil, energy efficiency improvements, short- and long-term demand and supply elasticities, technological growth, cost convexity, marginal extraction costs, reserves of oil by region.
Outputs:	Global, regional and sectorial production and consumption of oil, regional consumption of gas, electricity, coal, biomass and biofuels for transport.
Sector/Energy carriers:	There are six sectors in each geographical region: Industry, households, other sectors (private and public services, defense, agriculture, fishing, other), electricity, road and rail transport, domestic and international aviation and domestic shipping. There is one global sector: international shipping. Energy carriers: oil (aggregate of different oil products), gas, electricity, coal, biomass and biofuels for transport.
Geography and granularity / data(sets):	The model has seven regions, where both demand and production take place: OPEC, Western Europe (EU/EFTA), U.S., Rest-OECD, Russia, China and Rest of the World (on the supply side one may divide OPEC into OPEC-Core and Non-Core OPEC if needed).
Time resolution and horizon:	One year, 50-100 years

Level of detail (economy, energy system, technologies)	7 regions, 6 regional sectors and 1 global sector,
Main future research challenges	Recalibrate the model; currently, the base year for the model is 2007. Include a renewable energy sector.
Necessary environment / operating system:	Windows
Commercial and other licences / solvers?	Language: GAMS Solver: CONOPT
Interface:	GAMS IDE
Used in which previous analysis projects?	ENTRACTE (Research project by the European Union), Petrosam II (NFR)
Clients, other users?	
Existing / possible coupling to other models?	
Reports and papers	Aune, F.R., Bøeng, A.C., Kverndokk, S., Lindholt, L. and K. E. Rosendahl (2017): Fuel efficiency improvements –Feedback mechanisms and distributional effects in the oil market, *Environmental and Resource Economics*, doi:10.1007/s10640-017-0134-7 Aune, F. A., Grimsrud, K., Lindholt, L. Rosendahl, K.E. and H. B. Storrøsten (2016): Oil consumption subsidy removal in OPEC and other Non-OECD countries: oil market impacts and welfare effects, Discussion papers 846, Statistics Norway (resubmitted to *Energy Economics*)

Nordic Forest & Bioenergy Sector Model

Model name:	**Nordic Forest Sector Model (NFSM)**
Main developer and partners:	NMBU
Analysis objective:	Localization of, and competition between forest-based energy generation technologies, taking into account resource availability and synergies/competition with the existing forest-based industry.
Short description:	NFSM is a partial equilibrium model, which covers the forest-based value chain, from biomass growth to final consumption of forest-based products and bioenergy. Market equilibrium is calculated for each region at an annual rate based on market product demand, timber/biomass supply, production costs and revenue, capacity maintenance and transportation costs. In addition, an investment module for forest-based energy generation technology is made available in the objective function. The model is solved as a MILP model, where non-linear terms have been linearized by piecewise linear approximation.
Specific strengths	Detailed representation of forest biomass prices, the forest industries and novel forest-based energy technologies.
Inputs:	Reference timber/biomass prices and forest/biomass stock, detailed representation of forest-based industry at unit level, reference capacities, reference product demand and techno-economic data of novel forest-based technologies.
Outputs:	• Category-specific forest-based feedstock prices and production levels in the forest and bioenergy sector • Investments in new bioenergy, pulp and paper industries • Regional and international trade with forest-based feedstock, pulp, paper, boards and biofuels • Forest stock
Sector/Energy carriers:	Heat and biofuel sectors.
Geography and granularity / data(sets):	Nordic model covered by 31 regions and an additional region covering the rest of the world.
Time resolution and horizon:	Annual time resolution and is most appropriate for mid-term horizons (10-15 years).

Level of detail (economy, energy system, technologies)	Technologies
Main future research challenges	Stochasticity, model integration with Balmorel.
Necessary environment / operating system:	Windows
Commercial and other licences / solvers?	Language: GAMS Solver: CPLEX
Interface:	GAMS IDE/Python API/Command line
Used in which previous analysis projects?	"BioNEXT – The role of bioenergy in the future energy system" [NFR-255265]. FME- Bio4Fuels
Clients, other users?	Clients: Research Council of Norway, Statkraft, Avinor and others
Existing / possible coupling to other models?	Existing: NFSM <=> Balmorel (via Python)
Reports and papers	Mustapha, W. F. (2016). The Nordic Forest Sector Model (NFSM): Data and Model Structure. Retrieved from Ås, Norway: http://www.umb.no/statisk/ina/publikasjoner/fagrapport/if38.pdf Mustapha, W. F., Bolkesjø, T. F., Martinsen, T., & Trømborg, E. (2017). Techno-economic comparison of promising biofuel conversion pathways in a Nordic context - effects of feedstock costs and technology learning. Energy Conversion and Management, 149C 368-380. doi:https://doi.org/10.1016/j.enconman.2017.07.004 Mustapha, W. F., Trømborg, E., & Bolkesjø, T. F. (In press). Forest-Based Biofuel Production in the Nordic Countries: Modelling of Optimal Allocation. Forest Policy and Economics. doi:https://doi.org/10.1016/j.forpol.2017.07.004

Partial equilibrium models including strategic behaviour

These models are based on game theory, as opposed to the majority of equilibrium models that assume perfect competition. The scope of the models is usually a single sector or several inter-linked sectors, often investment and operation are simultaneously considered, and the technological detail level is usually high. However, unlike the perfect competition models, where a single objective is optimized, the game theoretical models consider the objectives of several market actors while seeking an equilibrium solution (most commonly a Nash type). This formulation opens the possibility to analyse strategic behaviour of various forms (Cornot, Betrand, Stackelberg). As both the electricity and natural gas markets (and the energy system as a whole) typically have large participants with significant market shares, the game theoretical models can often better reflect realistic market outcomes than the perfect competition models. The computational tools for solving these models are not as mature as those developed for optimization, which tend to limit the detail level (spatial and temporal) of game theoretical models relative to perfect competition models. The purpose of these models is commonly analysis of the following topics: energy/climate policy, energy system transition strategies, market design, trade flows, or strategic behaviour.

MultiMod

Model name:	MultiMod
Main developer and partners:	NTNU with DIW Berlin – The German Institute for Economic Research
Analysis objective:	Long-term developments in global energy markets, infrastructure and trade considering upstream market power.
Short description:	Multi-fuel multi-period energy market equilibrium model representing (country-level) supply, trade, seasonal and intra-day demand variation (summer/winter – day/night, three sectors) with (country-level) transmission (over land and over sea), storage, electricity generation and refinery infrastructure. Upstream supplier-specific market power assumptions (hybrid market or pure oligopoly à la Cournot; can implement cartelization). Calibrated to recent projections by International Energy Agency and others. Data set contains ~25 regions with focus on EU detail. Planning horizon until 2050 in 10 year steps. Model very much suited for what-if analysis; There is a stochastic version which is not yet implemented for a global data set.
Specific strengths	• In-depth analysis of global energy markets and infrastructure development. • Fuel substitution in power generation, refineries and demand sectors • Demand for "services" rather than energy carriers. • GHG emissions • National, regional and global policies, incl. carbon tax & trading, efficiency standards, biofuel mandates • Cross-fuel market power exertion • Model is fully parameterized. Can easily be adjusted to higher or lower level of detail in regions, seasonality, demand sectors, etc. • Upstream market power exertion • Model calibrated to projections by recognized agencies; with added detail and market power considerations • Model very well-suited for what-if analysis • Stochastic version can analyze impact of uncertainty on decisions • Relatively small number of smart, flexible model equations which allow many ways to customize and expand the model based on data only.
Inputs:	• Production capacities and costs for all periods • Consumption levels, sector shares and seasonality for all periods • Capacities, operational and investment costs, and efficiencies / loss rates for pipelines, power generation, refineries, storages and shipping import and export terminals. • Shipping distances, costs and efficiencies.
Outputs:	• International trade • Infrastructure development. • Fuel mix by sector • (In what-if analysis): production, consumption and price developments (the reference scenario is these are calibrated to closely match outlooks.) • When CO2 ceiling is imposed: a CO2 emission price • When a CO2 price is imposed: CO2 output.
Sector/Energy carriers:	Energy system
Geography and granularity / data(sets):	Global. Currently six energy carriers and four demand sectors
Time resolution and horizon:	2050 – ten-year steps + seasonality & daily variation
Level of detail (economy, energy system, technologies)	Energy system
Main future research challenges	• We have recently developed a method that allows much shorter solution times. This means the data set can be disaggregated, for the deterministic as well as the stochastic version. • Improve representation of short-term variability and flexibility to better analyze role and management of renewables.

	• Allow flexible aggregation / disaggregation of regions, sectors and seasons and intra-day periods • Investigate the potential to use CGE-based demand (c.f.. Libemod, REMES) rather than inverse demand curves. • Investigate and implement automatic (re-)calibration routines in the literature to reduce manual labor after updating the reference data set • Transfer to open / free / publicly available platform – at least for academics.
Necessary environment / operating system:	GAMS (currently).
Commercial and other licences / solvers?	PATH (currently); MS Access (input data, currently)
Interface:	Windows; (Command line is possible)
Used in which previous analysis projects?	• H2020 LCE21 SETNav 2016 – 2019 Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation www.set-nav.eu/ • NAMAs Central Asia - Green Growth in Kazakhstan • Stanford Energy Modeling Forum 28: Effects Technology Choices EU Climate Policy • Stanford Energy Modeling Forum 31: North American Natural Gas Markets in Transition
Clients, other users?	DIW Berlin
Existing / possible coupling to other models?	MultiMod – REMES – EXIOBASE: Three-way linkage to assess the energy system in the context of the broader economy as well as assessing more detailed climate and environmental impact of the energy system. Feedback loops at wider economy level and more detailed emissions and footprints MultiMod – EMPIRE / Ramona – European or global boundary conditions on availability and prices of (other) fuels and energy carriers.
Reports and papers	• Su, Z., Egging, R., Huppmann, D. & Tomasgard, A. 2015. A Multi-stage Multi-Horizon Stochastic Equilibrium Model of Multi-Fuel Energy Markets. CenSES Working paper 2/2015. • H Huntington, 2015, EMF 31: North American Natural Gas Markets in Transition • D. Huppmann, R. Egging, 2014. Market power, fuel substitution and infrastructure – A large-scale equilibrium model of global energy markets, Energy V75 pp. 483-500, http://dx.doi.org/10.1016/j.energy.2014.08.004 • R. Egging, D. Huppmann, 2012. Investigating a CO_2 tax and a nuclear phase out with a multi-fuel market equilibrium model, IEEE Conference Proceedings, Ninth International Conference on the European Energy Market (EEM), pp.1-8. doi: 10.1109/EEM.2012.6254690

Global Gas Model

Model name:	Global Gas Model
Main developer and partners:	NTNU with DIW Berlin – The German Institute for Economic Research
Analysis objective:	Long-term developments in global gas markets, infrastructure and trade considering upstream market power.
Short description:	Natural gas market equilibrium model representing (country-level) supply, trade, seasonal demand (summer/winter, three sectors) with (country-level) pipeline, LNG and storage infrastructure. Upstream supplier-specific market power assumptions (hybrid market or pure oligopoly à la Cournot; can implement cartelization). Calibrated to recent projections by International Energy Agency and others. Data set contains ~85 countries and regions. Planning horizon until 2050 in 5 year steps. Model very much suited for what-if analysis; There is a stochastic version without seasonality
Specific strengths	• In-depth analysis of global gas markets and infrastructure developments. • Model is fully parameterized. Can easily be adjusted to higher or lower level of detail in regions, seasonality, demand sectors, etc. • Regional / country-level detail & large countries split up e.g., USA, Russia, China, India…) About 100 geo nodes

	• Upstream market power exertion • Model calibrated to projections by recognized agencies; with added detail and market power considerations • Model very well-suited for what-if analysis • Stochastic version can analyze impact of uncertainty on decisions
Inputs:	• Production capacities and costs for all periods • Consumption levels, sector shares and seasonality for all periods • Capacities, operational and investment costs, and loss rates for pipelines, storages and LNG import and export terminals. • LNG shipping distances, costs and efficiencies.
Outputs:	• International trade • Infrastructure development. • (In what-if analysis): production, consumption and price developments (the reference scenario is these are calibrated to closely match outlooks.)
Sector/Energy carriers:	Natural gas
Geography and granularity / data(sets):	Global - mostly at country level.
Time resolution and horizon:	2050 – five-year steps + seasonality
Level of detail (economy, energy system, technologies)	Natural gas system mostly at country level.
Main future research challenges	• Endogenize reserve expansions + adequate cost and potentials + calibration. • Allow flexible aggregation / disaggregation of regions, sectors and seasons • Investigate and implement automatic (re-)calibration routines in the literature to reduce manual labor • Transfer to open / free / publicly available platform – at least for academics.
Necessary environment / operating system:	GAMS (currently).
Commercial and other licences / solvers?	PATH (currently)
Interface:	Windows; (Command line is possible)

Used in which previous analysis projects?	• H2020 LCE21 SETNav 2016 – 2019 Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation www.set-nav.eu/
	• Stanford Energy Modeling Forum 28: Effects Technology Choices EU Climate Policy
	• Predecessor World Gas Model (WGM, developed by R. Egging during his dissertation at UNiv. Maryland, US) used in studies for:
	  ○ GDFSuez
	  ○ United States Energy Information Administration DOE
	  ○ Resources for the Future in Washington DC
	  ○ Stanford EMF 23: World Natural Gas Markets and Trade
	  ○ SSB Statistics Norway

Clients, other users?	DIW Berlin
Existing / possible coupling to other models?	Possible: MultiMod – development of gas reserves expansion under different scenarios. Possible: Ramona – European or global boundary conditions on gas availability and prices.
Reports and papers	• F. Holz, P.M. Richter, R. Egging, 2016. The Role of Natural Gas in a Low-Carbon Europe: Infrastructure and Supply Security, Energy Journal 37 • R. Egging, F. Holz, 2016. Risks in global natural gas markets: investment, hedging and trade. Energy Policy Vol.94, p.468 • F. Holz, P. Richter, R. Egging (2015). A Global Perspective on the Future of Natural Gas: Resources, Trade, and Climate Constraints. Review of Environmental Economics and Policy 2015 9: 85-106 • R. Egging (2013). Benders decomposition for multi-stage stochastic mixed

	complementarity problems – Applied to a global natural gas market model. European Journal of Operational Research 226 • R. Egging (2010) – DISSERTATION. *Multi-Period Natural Gas Market Modeling - Applications, Stochastic Extensions and Solution Approaches* **Additionally – EGM & WGM publications** • S.A. Gabriel, K.E. Rosendahl, R. Egging, H. Avetisyan, S. Siddiqui (2012) Cartelization in Gas Markets: Studying the Potential for a 'Gas OPEC', Energy Economics, 34 pp. 137–152. • D. Huppmann, R. Egging, F. Holz, C. Von Hirschhausen, S. Rüster (2011) The world gas market in 2030 – development scenarios using the World Gas Model, Int. Journ. of Glob Energy Issues, 35(1). • R. Egging, F. Holz, S. Gabriel, 2010. The World Gas Model - A Multi-Period Mixed Complementarity Model for the Global Natural Gas Market, Energy 35(10). • R. Egging, S. Gabriel, F. Holz, C. Von Hirschhausen, 2009. Representing GASPEC with the World Gas Model, Energy Journal 30(Special Issue I). • S. A. Gabriel, J. Zhuang, R. Egging, 2009. Solving Stochastic Complementarity Problems in Energy Market Modeling Using Scenario Reduction, European Journal of Operational Research, 197(3). • R. Egging, S. A. Gabriel, F. Holz, J. Zhuang, 2008. A Complementarity Model for the European Natural Gas Market, Energy Policy 36(7).

IV. Shorter-term technology-rich market optimisation models

The market models for the short and intermediate term differ from the long-term models by usually not representing endogenous investments, and naturally by their much shorter time horizon. Whereas the long-term models tend to look decades into the future, the short-term models are often used to study a single year of operation or even shorter periods. These models usually have richer technical details (such as disaggregated representation of hydropower reservoirs) and use hourly or sub-hourly temporal resolution.

Compared long term models designed to inform policy and investment, short and intermediate term models are typically used for control and decision support in the operation of the power system, where frequent use necessitates a high degree of accuracy. However, these models also have an important role in long-term analyses through linkages to long-term models. Short and medium term models can be used to analyse a given year in a long-term scenario that spans decades, using their greater level of technological and temporal detail to assess system constraints and market characteristics that would be inadequately represented in long-term models.

EMPS – Samkjøringsmodell

Model name:	**EMPS Market simulator** **EOPS – Price taker model**
Main developer and partners:	SINTEF Energy
Analysis objective:	Optimal long-term dispatch of hydropower in hydrothermal power systems taking into account stochastic climate variables EMPS is a market simulator (Samkjøringsmodellen) EOPS is price-taker model for planning and operating hydropower (Vansimtap)

Short description:	The long-term operation optimization model developed by SINTEF since 1970 is called EMPS. It is a fundamental model for the power market, specifically suited for hydro-thermal power systems or systems with energy storage. The model is generic and data driven and can be used on small or large systems. Detail level and geographical area covered by the model is only limited by calculation time. The total system is divided into a set of areas that are connected by transport corridors. The market equilibrium is calculated for each area and time-step on the basis of demand-, supply and transmission options. All power generation technologies can be represented. A module suggesting generation, transmission investments and decommissioning is also available. The problem is solved as a minimum cost system optimization including SDP, LP and heuristics. The stochastic variables include all climate variables such as inflow to reservoirs, temperatures, and intermittent generation (wind-power, and solar-power).
Specific strengths	Detailed bottom-up model for hydrothermal power systems, taking into account uncertainty of renewable power production as well as storage possibility in hydro reservoirs.
Inputs:	Long-term and short-term weather stochasticity hourly, daily, weekly resolution for all reservoirs, wind turbines and solar panels. Generation portfolio (thermal power plants and hydro power plants with water courses), demand of electricity, climatic scenarios (wind, sun, temperature, hydro inflow), transmission system (NTCs)
Outputs:	Optimal strategy for operating individual hydro power reservoirs (storage option), operation of thermal units including CHP together with the area wise and total power system dispatch. On area level the model calculates: water values (incremental cost of storage), power prices in the area, certificate prices, emissions, realized power demand, use of transmission in and out of the area, flow on each line either by application of the transport model - or a load flow model option.
Sector/Energy carriers:	Power sector, heat power coupling, power transmission
Geography and granularity / data(sets):	The model is generic and data driven. Different users have different datasets that typically comprise: Price region / Norway / Nordic / EU
Time resolution and horizon:	The model can be set up for different stages ex. 2010/2020/2030/2050, forecast for system parameters must be known for each stage, hourly resolution possible, it is possible to optimize with rough time resolution and simulate with hourly time resolution. Horizon in the optimization on a given state is 1 – 25 years.
Level of detail (economy, energy system, technologies)	Description for thermal power plant level with time - and temperature dependent efficiency, fuel type, start-up cost, ramping limitations, heat demand for CHP units, maintenance availability etc. Fuel cost for all technologies must be supplied. Hydropower (storage) is described by time and head dependent efficiency curves, inflow scenarios for regulated and non-regulated inflow, hydrohalic connections between plants, and hydro plants can be connected to represent water courses, reservoir-volume curves, all non-state dependent constraints are represented but not all state dependent constraints are represented. Demand is price dependent, demand can be optimization, etc. switch to oil boilers when electricity prices increases. Demand can be adjusted according to climate data/change and are given per area. Typically, demand is aggregated in categories such as: household, industry, flexible demand etc. The EMPS model has functionality for detailed transmission grid analyses, e.g. monitoring and flow control on critical interconnections and computation of active power losses.
Main future research challenges	Demand-side modelling, better description of short-term flexibility of the hydro system and state-dependent constraints, pumping (charging) cycles can be improved and extended to new storage technologies, batteries, compressed air, heat-storage. Improving thermal system description regarding representing short-term flexibility ex. Technical CCS limitations, CCS water use. Consistent market modelling off all energy and capacity reservation markets as well as system service markets.
Necessary environment / operating system:	Windows
Commercial and other licences / solvers?	CPLEX, Gurobi, Coin Clp (free), the model is also using free license tools such as HDF5, Python, Windows MPI
Interface:	Command line interface, API for time series with calendar
Used in which previous analysis	Market4RES (EU IEE) NorStrat (Nordic Energy Research)

projects?	Twenties (EU FP7) Susplan (EU FP7) (Consultant analyses)
Clients, other users?	All large Nordic power producers, except one, Scandinavian TSOs, consultants, regulators. Approximately 15 active users that use the model for control and decision support.
Existing / possible coupling to other models?	Existing: EMPS => SHOP EMPIRE => EMPS EMPS => PSST (powerGAMA) Times => EMPS
Reports and papers	Wolfgang, O., Haugstad, A., Mo, B., Gjelsvik, A., Wangensteen, I., & Doorman, G. L. (2009). Hydro reservoir handling in Norway before and after deregulation. *Energy*, *34*(10), 1642–1651. doi:10.1016/j.energy.2009.07.025 A. Helseth, G. Warland and B. Mo, "A hydrothermal market model for simulation of area prices including detailed network analyses". International Transactions on Electrical Energy Systems, vol. 23, no. 8, pp 1396–1408, 2013. DOI: 10.1002/etep.1667 Ove Wolfgang, Stefan Jaehnert, Birger Mo, Methodology for forecasting in the Swedish–Norwegian market for el-certificates, Energy, Volume 88, 2015, Pages 322-333, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2015.05.052. Stefan Jaehnert, Ove Wolfgang, Hossein Farahmand, Steve Völler, Daniel Huertas-Hernando, Transmission expansion planning in Northern Europe in 2030—Methodology and analyses, Energy Policy, Volume 61, 2013, Pages 125-139, ISSN 0301-4215, http://dx.doi.org/10.1016/j.enpol.2013.06.020. Ingeborg Graabak, Leif Warland, A carbon neutral power system in the Nordic region in 2050 D3.1 in the NORSTRAT project, Sintef Report, TR A7365, 2014 Steve Völler et al, D5.2 Report on the quantitative evaluation of policies for post 2020 RES-E targets, EU IEE project Market4RES, Report, 2016

SOVN

Model name:	**SOVN**
Main developer and partners:	SINTEF Energy
Analysis objective:	Hydro-thermal power system model for minimizing system operation cost. The model includes detailed representation of the hydropower system and detailed power flow analyses at transmission grid level. Stochasticity in weather (inflow, wind, temperature etc.) is represented by scenario fans. It can be used to forecast electricity prices and transmission line utilization, and to assess the socio-economic benefit of both local (e.g. new pumped-storage plant) and system-wide (e.g. new HVDC cable) expansion projects.
Short description:	A more complex and detailed version of EMPS. Simulates repeated solutions of two-stage stochastic LP problems with a rolling horizon. The model is a generic and data driven power system model for operation and planning of hydrothermal energy systems. It is still a prototype that is undergoing test in the power industry, but currently not in operative use.
Specific strengths	Detailed representation of the hydropower, dependent water values (cuts) are computed for each reservoir without system aggregation. Allows detailed representation of the transmission grid, and flexible definition of price zones (from system price to nodal prices).
Inputs:	Similar to the EMPS model
Outputs:	Similar to the EMPS model
Sector/Energy carriers:	Similar to the EMPS model
Geography and granularity / data(sets):	So far use in a Scandinavian setting.
Time resolution and horizon:	User defined model size, up to hourly time resolution. Long calculation times can be balanced with aggregation in time resolution and geographical coverage.

Level of detail (economy, energy system, technologies)	Same as the EMPS model
Main future research challenges	Make the model work for real life application on larger energy systems. Extending the number of stochastic variables are easy in this concept, but calculation time explodes.
Necessary environment / operating system:	Windows cluster
Commercial and other licences / solvers?	For other than the smallest examples where Coin can be applied a commercial solver such as Gurobi/Cplex is needed.
Interface:	Command line
Used in which previous analysis projects?	None
Clients, other users?	It has not been used outside the tests performed by the project partners.
Existing / possible coupling to other models?	Similar to the EMPS model
Reports and papers	A. Helseth, B. Mo and G. Warland, ”Long-term scheduling of hydro-thermal power systems using scenario fans”, Energy Systems, vol. 1, no. 4, pp 377-391, 2010. DOI: 10.1007/s12667-010-0020-7 A. Helseth, B. Mo and K. S. Gjerden, "On Designing a Stochastic Optimization Model for Detailed and Long-Term Hydro-Thermal Scheduling in the Nordic Power Market", XIII Symposium of Specialists in Electric Operational and Expansion Planning (SEPOPE), Foz do Iguacu, Brazil, 2014. A. Helseth, B. Mo, A. L. Henden and G. Warland, "SOVN Model Implementation", Technical Report TR A7618, SINTEF Energi, 2017.

powerGAMA (formerly PSST)

Model name:	**powerGAMA** (formerly PSST)
Main developer and partners:	SINTEF Energy
Analysis objective:	Determination of the DC-optimal power flow of a large-scale power system
Short description:	PowerGAMA is an open-source Python package for deterministic power system grid and market analyses. It is a lightweight simulation tool for high level analyses of renewable energy integration in large power systems. The simulation tool optimises the generation dispatch, i.e. the power output from all generators in the power system, based on marginal costs for each timestep over a given period, for example one year. It takes into account the variable power available for solar, hydro and wind power generators. It also takes into account the variability of demand. Moreover, it is flow-based meaning that the power flow in the AC grid is determined by physical power flow equations.
Specific strengths	Analysis of large-scale power systems with a detailed description and large amounts of RES
Inputs:	Bottom-up power system description on individual bus level and single power plants
Outputs:	Power system dispatch and power flow, nodal power prices
Sector/Energy carriers:	Power sector
Geography and granularity / data(sets):	EU Western EU + North Africa
Time resolution and	2014/2030, static system, hourly resolution

horizon:	
Level of detail (economy, energy system, technologies)	
Main future research challenges	Stochastic optimisation
Necessary environment / operating system:	Python
Commercial and other licences / solvers?	COIN
Interface:	Command line, API
Used in which previous analysis projects?	EuroSunMed PSST: Role-of-the-North-Sea Twenties TradeWind
Clients, other users?	
Existing / possible coupling to other models?	EMPS => PSST
Reports and papers	Svendsen, H. G., & Spro, O. C. (2016). PowerGAMA: A new simplified modelling approach for analyses of large interconnected power systems, applied to a 2030 Western Mediterranean case study. *Journal of Renewable and Sustainable Energy*, *8*(5). doi:10.1063/1.4962415 Lie, A. Ø., Rye, E. A., Svendsen, H. G., Farahmand, H., & Korpås, M. (2017). Validation study of an approximate 2014 European power-flow model using PowerGAMA. *IET Generation, Transmission & Distribution*, 11(2), 392–400. doi:10.1049/iet-gtd.2016.0856

ProdRisk

Model name:	**ProdRisk**
Main developer and partners:	SINTEF Energy
Analysis objective:	Calculate the optimal long-term price-taker strategy for hydropower plants in a cascaded water course.
Short description:	Primarily used for regional hydropower scheduling, but can also serve as a fundamental market model. Modelling principle based on a combination of Stochastic Dual Dynamic Programming (SDDP) and stochastic dynamic programming (SDP). This enables the model to calculate dependent water values (cuts). Dependent water value means the value of stored water in one reservoir depends on the distribution of water in all other reservoirs in the system. Inflows and exogeneous power prices are typically modelled stochastic. Research prototypes of the model has been used to include (stochastic) wind power, detailed power flow constraints and the possibility to sell both energy and reserve capacity. The operative model is used by most large hydropower producers in the Nordic market.
Specific strengths	Detailed representation of the hydropower, dependent water values (cuts) are computed for each reservoir without system aggregation. Proven, state-of-the-art hydropower scheduling methodology.
Inputs:	Similar to the EMPS model
Outputs:	Similar to the EMPS model
Sector/Energy carriers:	Primarily hydropower producers, but generally similar to the the EMPS model.
Geography and granularity / data(sets):	Typically, one watercourse, but can also be used as a market model. ProdRisk has recently been tested as a merket model on the Norwegian and Icelandic system.
Time resolution and horizon:	User defined model size with down to hourly time resolution. Typically the horizon is 2-5 years.

Level of detail (economy, energy system, technologies)	Detailed results are produced for hydropower and other units in the model, dependent water values that provides coupling/boundary condition to the short-term model SHOP.
Main future research challenges	Make the model work for real life application on larger energy systems. Extending the number of stochastic variables are easy in this concept, but calculation time explodes. Could be used to handle heat storage in district heating systems.
Necessary environment / operating system:	Windows. Allows use of large-scale parallel processing through Windows MPI.
Commercial and other licences / solvers?	Requires an optimization solver, interfaces exists for Coin Clp (free), CPLEX or Gurobi.
Interface:	Command line or API. ProdRisk as a service can be established with the API.
Used in which previous analysis projects?	This model has been applied on pump-storage development projects and to investigate consequences of revision of hydropower concessions.
Clients, other users?	There is ~10 companies using ProdRisk on a weekly/daily basis.
Existing / possible coupling to other models?	Boundary conditions can be provided from EOPS. Price forecast can be provided from EMPS.
Reports and papers	A. Helseth, M. Fodstad and B. Mo, "Optimal Medium-Term Hydropower Scheduling Considering Energy and Reserve Capacity Markets", IEEE Transactions on Sustainable Energy, vol. 7, no. 3, pp 934-942, 2016. DOI: 10.1109/TSTE.2015.2509447 A. Helseth, A. Gjelsvik, B. Mo and U. Linnet, "A model for optimal scheduling of hydro thermal systems including pumped-storage and wind power". IET Generation, Transmission and Distribution, vol. 7, no. 12, pp 1426-1434, 2013. DOI: 10.1049/iet-gtd.2012.0639 A. Helseth and H. Braaten, "Efficient Parallelization of the Stochastic Dual Dynamic Programming Algorithm Applied to Hydropower Scheduling", Energies, vol. 8, no. 12, pp 14287-14297, 2015. DOI: 10.3390/en81212431 K. S. Gjerden, A. Helseth, B. Mo and G. Warland, "Hydrothermal scheduling in Norway using stochastic dual dynamic programming; a large-scale case study", in Proc. Of PowerTech, Eindhoven, Netherlands, 2015. A. Helseth, A. Gjelsvik, B. Mo and G. Warland, "Prodnett – A Market Model Based on SDDP Including Power Flow Constraints", SINTEF Energi, Technical report TR A7165, 2012.

V. Important models outside the scope

A number of models outside the scope of this overview play an important role in energy system modelling. They have been determined to be outside the scope because they are not typically used in research activities intended to inform public policy development. These models are typically either commercial models developed by consultancies or very short-term models that are not suited to linking with longer-term models. The following list provides some examples of these models and is not intended to be exhaustive.

- **TheMA electricity market analyser** (developed by Thema Consulting) – a commercial power market optimisation model implemented in GAMS with a user interface in Excel. It has an hourly resolution and is used for a range of analyses, from short-term to long-term price prognoses and scenario analyses. It can been soft-coupled to TIMES and EMPS and is used by a TSOs, traders and regulators, such as NVE**.**

- **BID3** (developed by Pöyry) – A commercial power market optimisation model using either Linear or Mixed Integer Programming to minimise system costs in a year subject to given constraints. BID3 is used by TSOs, energy companies and regulators, as well as by Pöyry.
- **PUMA** (Power markets under Uncertainty Modelling Architecture) and **NEMM** (New Electricity certificate Market Model) (developed by Optimeering) – are two power market models with a focus on the agent behaviour in free markets.
- **POWEL AS** offers a suite of commercial optimisation models for production planning and investment.
- **ProdRisk** – when used for hydropower production planning (see section above for further details on ProdRisk).
- **SHOP** and **SHARM** – are very short-term models designed to inform bidding strategies for hydropower producers in the spot and balancing markets. Details are provided in the table below to exemplify this type of short-term model and facilitate comparison with the longer-term models within the scope of this document.

Model name:	SHOP/SHARM
Main developer and partners:	SINTEF Energi, NTNU, SINTEF Anvendt Matematikk
Analysis objective:	Daily dispatch of hydropower units and decision support towards the spot, intra-day, reserve markets. Simulation of generation to calculate back to actual inflow in the hydropower system.
Short description:	SHOP is a generic data driven model and is based on Successive Mixed Integer Linear Programing. SHOP optimizes the daily dispatch of the hydropower units in one or several cascaded water courses. The methods allow the model to handle non-linearity and state-dependency and includes all details relevant to scheduling of hydropower units taking into account all constraints inside and outside the power plants. The model can be used for hydrothermal dispatch, but focus is on best possible representation of the hydropower. SHARM is a stochastic extension of SHOP where prices and inflows can be stochastic.
Specific strengths	Representing all constraints, detailed efficiency and losses the model can find the optimal generation level on all units simultaneously respecting obligations in all markets.
Inputs:	Function and curve based input on all hydro and reservoir data. Efficiency and constraints for thermal units if needed.
Outputs:	Decisions on operation of each unit, pump, gate in the modelled system. Expected revenues and cost from use of water, start-up, weir and tier etc.
Sector/Energy carriers:	Power only
Geography and granularity / data(sets):	Typically, one water course, but larger producers will use the model to decide which part of their obligations that should be covered from each water course, and plant.
Time resolution and horizon:	Time resolution is flexible from minutes to year. Typically time resolution is 15 minutes in the beginning of the period and may aggregate to hours per increment closer to the horizon. The horizon is typically 3-21 days but also yearly calculations can be performed.
Level of detail (economy, energy system, technologies)	Detailed results are generation of units, losses in tunnels, flows in gates, spillage, pressure in tunnels etc.
Main future research challenges	State-dependent constraints not yet implemented ex dynamic time delay. Calculation time for practical use with minute resolution. Non-convex optimization, solving large integer problems. Optimal planning and splitting of maintenance tasks. Nodal prices. Other storage technologies.
Necessary environment / operating system:	Window, windows cluster / server in the stochastic version

Commercial and other licences / solvers?	More complex systems require a solver such as Gurobi/Cplex, but the model can be used with Coin as well.
Interface:	Command line or API. SHOP as a service can be established with the API.
Used in which previous analysis projects?	In an early version, the model was applied to investigate the possible ramping rate of the Norwegian hydropower system in response to Europe. NFR project.
Clients, other users?	There is 20+ companies that are using SHOP for scheduling purposes. SHARM is a prototype in industry testing. SHOP is also part of the simulation and investment calculation in chain with other models.
Existing / possible coupling to other models?	Boundary conditions from ProdRisk (EMPS or VANSIMTAP)
Reports and papers	O.B. Fosso and M.M. Belsnes, “Short-term Hydro Scheduling in a Liberalized Power System”, PowerCon 2004, Singapore, Nov. 2004 M. M. Belsnes, I. Honve, SINTEF Energy Research Prof. O. B. Fosso, Norwegian University of Science and Technology, “Bidding in the secondary reserve market from a hydropower perspective”, PSCC 2005, Liege, Aug.2005. T. Follestad, O. Wolfgang, M. M. Belsnes, "An approach for assessing the effect of scenario tree approximations in stochastic hydropower scheduling", PSCC 2011, Stockholm, Aug. 2011. M.M. Belsnes, Fosso, O.Wolfgang, T. Follestad, E.K. Aasgård, "Applying successive linear programming for stochastic short-term hydropower optimization", Electric Power Systems Research 130 (2016) 167-180

Workshop: Modellering av energisystemet

0930 – 1600, tirsdag 25. april 2017
Forskningsrådet (Abel 1), Drammensveien 288, Lysaker
Kontakt: Benjamin Smith (bds@rcn.no, 90406203) eller Hans Otto Haaland (hoh@rcn.no, 41282182)

Forskningsrådet arrangerer en workshop om energi- og kraftsystemmodeller for Norge/Europa. Vi ønsker et bedre samspill fremover mellom brukernes behov og hva forskningsmiljøene kan modellere. Målsettingen er derfor å skape en felles forståelse for energisystemmodellene og en synliggjøring av hva som må utvikles for å møte fremtidens behov. Vi understreker at seminaret handler om modeller og modellbaserte analyser som adresserer hele energisektoren, og at diskusjonen vil bli rettet inn mot fremtidige overordnede utviklingsbehov og i mindre grad mot spesifikke tekniske utfordringer.

0900 – 0930	**Kaffe**
0930 – 1045	**Brukernes behov** *Hvilken rolle har modellering i politikk- og strategiutforming i dag og i nær fremtid?* *Hva er de viktigste mangler i dagens modeller og modellbaserte analyser?* - Velkommen v/ Hans Otto Haaland, Forskningsrådet - Introduksjon v/ møteleder Jan Bråten, Statnett (medlem i programstyret, ENERGIX) - Presentasjoner fra sentrale brukere: OED, NVE og Statnett - Replikk fra Enova og Miljødirektoratet
1045 – 1100	**Pause**
1100 – 1200	**Modellforskningen i dag** *Hva kan modellene gjøre i dag og i nær fremtid? Hva kan de ikke gjøre?* - Presentasjoner fra FMEer: CenSES og CREE
1200 – 1300	**Lunsj**
1300 – 1345	**Kommentarer og diskusjon** *Har vi fått et helhetlig bilde over hva brukerne trenger og hva modellene kan levere?* - Korte innlegg fra andre deltakere (meldes til arrangøren under lunsjen)
1345 – 1500	**Gruppearbeid** *(se baksiden)* *Hva skal til for at modellene bedre kan imøtekomme brukernes behov?* - Gruppenes "topp 3" utfordringer, samt mulige tiltak
1500 – 1600	**Resultater fra gruppediskusjon og oppsummering** - Presentasjoner fra gruppene, diskusjon - Oppsummering v/møteleder

Gruppearbeid (1345 – 1500)

Bakgrunn: Vi ønsker med denne workshopen å legge til rette for et bedre samspill mellom brukernes behov og hva forskningsmiljøene kan modellere. Diskusjonen skal dreie seg om modeller og modellbaserte analyser som adresserer hele energisektoren, og ta for seg fremtidige overordnede utviklingsbehov.

Oppgave: Hva skal til for at modellene bedre kan imøtekomme brukernes behov? Gruppen skal identifisere sine "topp 3" utfordringer, samt mulige tiltak for å møte de identifiserte utfordringene.

Gruppelederne fordeler oppgavene seg imellom: 1. Styre diskusjonen og 2. Lage en presentasjon / presenterer gruppens "topp 3" utfordringer, samt mulige tiltak

Forslag til forløp:

- Alle deltakerne bruker 5-7 minutter til å skrive egne topp 3 utfordringer på gule lapper
- Gule lappene henges på veggen
- Kort runde hvor deltakere presenterer sine topp 3 utfordringer
- Diskusjon og systematisering av forslagene
- Gruppelederen utarbeider presentasjonen underveis
- Oppsummering og enighet om gruppens konklusjon
- Presentasjon i plenum

Deltakerliste

Anders Sivertsgård	Energi Norge	A
Ane Brunvoll	NFR	C
Anne Vera Skrivarhaug	NVE	B
Asbjørn Aaheim	Cicero	B
Asgeir Tomasgard	NTNU	C
Benjamin Smith	NFR	C
Brian Glover	NFR	B
Cathrine Hagem	SSB	C
Eli Jensen	OED	C
Ellen Skaansar	OED/NVE	A
Erik Figenbaum	TØI	B
Erland Eggen	NFR	A
Fredrik Weidemann	Miljødirektoratet	C
Gudmund Bartnes	NVE	A
Hans Otto Haaland	NFR	A
Heidi Bull-Berg	Sintef Teknologi og Samfunn	B
Ivar Døskeland	Statnett	C
Jan Bråten	Statnett	A
Kari Åmodt Espegren	IFE	B
Katrine Wyller	NFR	B
Ketil Flugsrud	Miljødirektoratet	B
Kjetil Trovik Midthun	Sintef Teknologi og Samfunn	A
Lasse Fridstrøm	TØI	C
Michael Belsnes	Sintef Energi	A
Monica Havskjold	Statkraft	C
Orvika Rosnes	SSB	B
Per Ivar Helgesen	Enova	C
Pernille Seljom	IFE	A
Rolf Golombek	UiO (Frisch Centre/CREE)	A
Ruud Egging	NTNU (Indøk)	B
Stefan Jaehnert	Sintef Energi	C
Torjus Bolkesjø	NMBU	A
Øyvind Leistad	Enova	B