Electronic Supplementary Material

**Title:** Climate change, future Arctic Sea ice, and the competitiveness of European Arctic offshore oil and gas production on world markets

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Fig. S1 Mean seasonal cycle of sea ice area in million km\(^2\) for regions (1) EBB2 in the southern Barents Sea, (2), WGEC2 off the west coast of Greenland and (3) WSB2 in the Kara Sea: (a) Mean over the years 1979-2005 of satellite derived data OSI SAF (mean: solid line, standard deviation:grey shading) and single ensemble members of CMIP5 models; historical simulation. (b) Mean over the years 1979-2005 of satellite derived data OSI SAF (mean: solid line, standard deviation:grey shading) and four selected CMIP5 models; historical simulation. (c) Mean over the time period 2025-2040 from for CMIP5 models with emission scenarios RCP 4.5 (solid lines) and RCP 8.5 (dashed lines).
Fig. S2 March (a) and September (b) mean sea ice thickness in m for the regions (1) EBB2 in the southern Barents Sea, (2) WGEC2 off the west coast of Greenland and (3) WSB2 in the Kara Sea from four CMIP5 models with the emission scenarios RCP 4.5 (solid lines) and RCP 8.5 (dashed lines). If more than one ensemble member is available per model, the mean is shown by the line and the range over all ensemble members per model is indicated by the shading.
**Table S1** List of CMIP5 models analysed including modeling groups and their terms of use:

| Modeling Center (or Group)                                                                 | Institute ID          | Model Name                                                                 |
|------------------------------------------------------------------------------------------|-----------------------|----------------------------------------------------------------------------|
| CSIRO-BOM                                                                                 |                       | ACCESS1.0                                                                  |
| Beijing Climate Center, China Meteorological Administration                              | BCC                   | BCC-CSM1.1                                                                 |
| Canadian Centre for Climate Modelling and Analysis                                         | CCCMA                 | CanESM2                                                                   |
|                                                                                          |                       | CanCM4                                                                    |
| National Center for Atmospheric Research                                                 | NCAR                  | CCRM4                                                                     |
| Community Earth System Model Contributors                                                | NSF-DOE-NCAR          | CSM1(CAM5.1,FV2)                                                          |
| Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique | CNRM-CERFACS          | CNRM-CM5                                                                  |
| Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence | CSIRO-QCCCE           | CSIRO-Mk3.6.0                                                             |
| EC-EARTH consortium                                                                       | EC-EARTH              | EC-EARTH                                                                  |
| LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University | LASG-CESS             | FGOALS-g2                                                                 |
| LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences                      | LASG-IAP              | FGOALS-s2                                                                 |
| NOAA Geophysical Fluid Dynamics Laboratory                                                | NOAA GFDL             | GFDL-CM3                                                                  |
|                                                                                          |                       | GFDL-ESM2G                                                                |
|                                                                                          |                       | GFDL-ESM2M                                                                |
| NASA Goddard Institute for Space Studies                                                 | NASA GISS             | GISS-E2-H                                                                 |
|                                                                                          |                       | GISS-E2-R                                                                 |
| National Institute of Meteorological Research/Korea Meteorological Administration       | NIMR/KMA              | HadGEM2-AO                                                                |
| Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais) | MOHC                  | HadCM3                                                                    |
|                                                                                          |                       | HadGEM2-CC                                                                |
|                                                                                          |                       | HadGEM2-ES                                                                |
| Institute for Numerical Mathematics                                                       | INM                   | INM-CM4                                                                   |
| Institut Pierre-Simon Laplace                                                            | IPSL                  | IPSL-CM5A-LR                                                              |
|                                                                                          |                       | IPSL-CM5A-MR                                                              |
|                                                                                          |                       | IPSL-CM5B-LR                                                              |
| Institution                                                                 | Model  | Variants                                      |
|----------------------------------------------------------------------------|--------|----------------------------------------------|
| Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies | MIROC  | MIROC-ESM MIROC-ESM-CHEM                    |
| Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology | MIROC  | MIROC4h MIROC5                              |
| Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology) | MPI-M  | MPI-ESM-MR MPI-ESM-LR MPI-ESM-P             |
| Meteorological Research Institute                                          | MRI    | MRI-CGCM3                                    |
| Norwegian Climate Centre                                                   | NCC    | NorESM1-M NorESM1-ME                        |

Output from yellow highlighted models is available for unrestricted use. Output from the others may only be used for non-commercial research and educational purposes. [See complete “Terms of Use”: http://cmip-pcmdi.llnl.gov/cmip5/terms.html].
Table S2 Cost components considered in the cost estimation.

| Production / processing technology | Production supporting technology | Product transmission and export technology |
|-----------------------------------|----------------------------------|--------------------------------------------|
| - Floating production facilities (FPSO / FLNG) | - Drilling vessels (for appraisal wells and workover) | - Riser (oil, gas) |
| - Subsea production facilities | - Offshore supply vessels (with ice breaking ability) | - Pipelines (oil, gas) |
| - Fixed (concrete) production platforms | - Helicopters | - Flexible pipes and hard arms (for oil, gas or liquefied gas) for loading |
| - Fixed shallow water production facilities | - Sea going emergency, evacuation and rescue (EER) systems | - Turrets, mooring systems and shuttle tankers (for gas or liquefied gas or oil) |
| - Onshore production facilities | - | - |
| - Onshore plants for raw product receiving | - | - |
| - treatment (acid gas removal and drying) | - | - |
| - liquefaction or compression or GTL processing | - | - |
| - storage of products | - | - |
| - service station for offshore facilities | - | - |

**Floating Production Facility**

Floating production facilities can be both, platforms with a single main functionality (production and send-out of hydrocarbons) and platforms with combined functionality, production, treatment, processing and send-out.

All vessels operating in the Arctic have to provide ice breaking abilities and suitable rescue and evacuation schemes. Floating production facilities are permanently moored at location by means of internal turret mooring systems with gas production abilities.

In general, a cost share of 20-30 % of the overall costs has to be considered for oil / gas production.

**Subsea Production Facility**

Production from totally submerged facilities has the main advantage that during normal production no surface piercing structure has to withstand harsh environments and loads from drifting ice or icebergs. Nevertheless, the wells have to be maintained from time to time or in an emergency by means of work over drilling. Drilling vessels with significant ice breaking abilities have to be employed. These vessels are rare and expensive so that they are not purchased but long term contracted for the complete production campaign of >20 years.
The produced multiphase flow of gas, oil, water, and sand is processed and exported via pipeline to the shore receiving plant, where also the local operators of the subsea system are accommodated.

In general, a cost share of 20-30% of the overall costs has to be considered for oil/gas production with transport from the reservoir to the treatment plant, including control umbilical and export pipelines.

**Fixed Production Facility**
The fixed concrete platform option provides production, pre-treatment and storage capabilities. These platforms are restricted in (deck) space and are normally not suited to allow liquefaction of gas. Thus, the produced gas is sent to a shore liquefaction plant via pipeline. Produced oil and condensate can be either exported via scheduled shuttle tankers or pumped to shore via pipeline.

As the platform cannot be moved from location, it has to withstand all occurring environmental conditions like severe sea states, heavy winds and icing of deck structures as well as drifting ice or icebergs. Consequently, ice management by means of ice breaking Offshore Supply Vessels (OSVs) has been considered to reduce these loads to the fixed structure.

In general, a cost share of 20-30% of the overall costs has to be considered for oil/gas production with transport from the reservoir to the treatment plant, including gas processing and associated pipelines.

**Shallow Water Production Facility**
As stated above production facilities can be installed in shallow or even very shallow water. Examples are available for facilities which are constructed in benign areas like in middle or south of Europe and towed to an Arctic location by means of tugs.

Installation takes place at a prepared berm e.g. made of gravel. Due to a relatively short distance to shore and possibly restricted water depth send-out of the products is carried out by pipelines to separate onshore treatment and export facilities. The shallow water facilities have to be protected against drifting ice by means of passive ice barriers, optionally aided by an active ice management with Offshore Supply Vessels (OSVs).

In general, a cost share of 15-25% of the overall costs has to be considered for oil/gas production with transport from the reservoir to the treatment plant, including gas processing and associated pipelines.

**Onshore Production Facility**
Production facilities located onshore in the Arctic have to consider related harsh environmental constraints. Although no wave, ice or iceberg loads can occur it is possible that future climatic changes might result in melting surface soils or even the development of swamp areas.

Due to the demanding environments in the Arctic construction at location often suffers from significant time delays caused by insufficient infrastructure, complicate or unsteady material supply, or problems with personnel provision. Nevertheless, realized examples can be found for Alaska and Siberia.
In general, a cost share of 15-20 % of the overall costs has to be considered for oil / gas production with transport from the reservoir to the treatment plant, including gas processing and associated pipelines.

**Treatment, Storage, Loading, Shipping and receiving for gas production**

Treatment of the raw products gas and oil is required to allow either send-out to the connected gas network or to export tankers. Case dependent treatment can comprise de-hydration, de-sanding, recovery of flow assuring inhibitors (e.g. Methyl Ethylene Glycol, MEG) and removal of CO₂, mercury or N₂ and the liquefaction of the gas for efficient storage and transportation. Liquids like LNG, CNG or GTL products are stored until they are loaded to dedicated shuttle tankers. These tankers provide the worldwide market with the required energy deliveries, which can be comparably handled in terms of quantities of British Thermal Units (BTU).

For the assessment a mean transportation distance between the treatment plant and the European receiving plant of 5000 km has been considered.

**Treatment, Storage, Loading, Shipping and receiving for oil production**

Treatment of the raw oil is required to allow either send-out to the connected pipeline network or to export tankers. Case dependent treatment can comprise de-hydration, de-sanding, recovery of flow assuring inhibitors (e.g. MEG) and removal of CO₂, mercury or N₂ for efficient storage and transportation. Especially transportation by tankers allows providing the worldwide market with the required energy deliveries, which can be comparably handled in terms of quantities of British Thermal Units (BTU). Again a mean transportation distance between the treatment plant and the European receiving plant of 5000 km has been considered.
### Table S3 Data and information sources for cost estimates.

| Source | Information contained |
|--------|-----------------------|
| www.offshore-technology.com; www.upstreamonline.com | Online databases providing general information about license holders, operators, technology, investments of international oil and gas projects. |
| Norwegian Petroleum Directorate: http://factpages.npd.no/factpages/ | Database providing general information about license holders, operators, technology, investments of Norwegian oil and gas projects. |
| The Economy 2010, www.economics.gov.nl.ca | Provides information about oil and gas production economic performance in Newfoundland and Labrador and medium term outlook. |
| Energy Information Agency (EIA), Russia, Country Analysis Briefs, www.eia.doe.gov, Nov. 2010 | General information about energy production, consumption, stakeholder, (Oil and Gas) investments, outlook. |
| EIA, Norway, Country Analysis Briefs, www.eia.doe.gov, Aug. 2010 | Compare EIA (Russia). |
| EIA, Canada, Country Analysis Briefs, www.eia.doe.gov, July 2009 | Compare EIA (Russia). |
| EIA: The Global Liquefied Natural Gas Market: Status and Outlook, www.eia.gov/oiaf/analysispaper/global/lngindustry.html, December 2003; | Information about costs for gas production, liquefaction, shipping, storage, regasification. |
| Bambulyak, A., and B. Frantzen. 2005. Oil transport from the Russian part of the Barents Region; Status per January 2005. Kirkenes: Norwegian Barents Secretariat. | Information about oil and gas production, infrastructure, transport volumes, logistics along Northern Sea Route. |
| Chan, L., G. Eynon, and D. McColl. 2005. The Economics of High Arctic Gas Development: Expanded Sensitivity Analysis. Calgary: Canadian Energy Research Institute. | Comparison of most relevant gas production and export scenarios including relevant cost contributors. |
| OPEC. 2010. World Oil Outlook, OPEC Secretariat, Vienna, Austria | Status quo of oil and gas production, demand, world economic development, outlook to 2030, consideration of all relevant fields of the energy supply chain. |