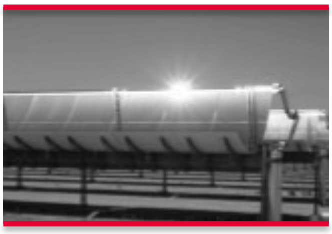
MENA FUELS

Sub-report 4 | October 2024

Description of the energy supply model WISEE-ESM-I

Report from the
Sub-project A.II: Synfuels Scenarios

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Status of the report:

November 2022

Please cite the report as follows:

Saurat, M., Doré, L., Janßen, T., Kiefer, S., Krüger, C., Nebel, A. (2022). Description of the energy supply model WISEE-ESM-I. MENA-Fuels: Sub-report 4 to the Federal Ministry of Economic Affairs and Climate Action (BMWK). Wuppertal Institut. Wuppertal, Stuttgart, Cologne, Saarbrücken.

Acknowledgments

This report was produced as part of the research project **MENA-Fuels - Roadmaps for the Generation of Sustainable Synthetic Fuels in the MENA Region for the Decarbonisation of Traffic in Germany.** It is supplemented by other published reports. The editors would like to thank all participating research institutes, the funding provider and its project management organization as well as the external experts from science and industry for their constructive cooperation and valuable contributions to this publication.

Disclaimer

The research project on which this report is based was funded by the Federal Ministry of Economic Affairs and Climate Action (BMWK) under grant number 3EIV181A-C. Responsibility for the content of this report lies with the authors.

Project duration: December 2018 - June 2022

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

Project partners:

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Publisher:

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Image sources:
Title page: GettyImages
Back page: own illustration

Contents

List of abbreviations, units and symbols

Abbreviations

RE	Renewable energies
ESM	Energy Supply Model
ESM-D	Energy Supply Model - Dispatch Module
ESM-I	Energy Supply Model - Invest Module
CP category	Cost potential category
MENA	Middle East and Northern Africa
OSeMOSYS	The Open Source Energy Modelling System
WI	Wuppertal Institute for Climate, Environment and Energy gGmbH
WISEE	Wuppertal Institute System Model Architecture for Energy and Emission Scenar-ios

List of tables

List of figures

1 Background

Sub-project A.II of the MENA-Fuels project involves the techno-economic modeling and evaluation of supply paths for Germany and Europe with electricity and synthetic fuels from the MENA region[1] . This requires a comprehensive mapping of the energy system consisting of generation and conversion plants, storage facilities and transport infrastructures. The Invest module of the WISEE-ESM is used to map this. WISEE stands for "Wuppertal Institute System Model Architecture for Energy and Emission Scenarios" and comprises a model network developed at the Wuppertal Institute for the model-based analysis and evaluation of future energy and industrial systems. The ESM - short for "Energy Supply Model" - is part of this model network and is used to analyse future energy systems. The ESM consists of two modules, which model the cost-optimal expansion (Invest Module ESM-I) and the cost-optimal operation (Dispatch Module ESM-D) of generation and conversion plants, storage facilities and transport infrastructures to meet an exogenously specified demand for energy sources. Only the ESM-I is used in the MENA-Fuels project; the ESM-D is therefore not described further below.

The ESM-I was developed based on the open source framework for energy system planning OSeMOSYS (Howells et al., 2011; Royal Institute of Technology (KTH) et al., 2022) by making the following extensions:

1 | Object-oriented translation of the framework in the Python programming language
2 | Embedding the framework in a working environment including a comprehensive database
3 | Adjustments to the mathematical formulation of the framework

As part of the MENA-Fuels project, the ESM-I was expanded and applied to the issues pursued here. This report first describes the mathematical formulation of the ESM-I (Section 2). To illustrate the further developments of the ESM-I compared to the OSeMOSYS framework, Section 3 provides an overview of the main differences in the mathematical formulation. In addition, Section 4 explains approaches for reducing the model complexity that were used here.

The application of the ESM-I, including the comprehensive database required for this, is described in other sub-reports of the MENA-Fuels project. As part of the modelling, a range of scenarios are analysed in order to derive robust implications. Initially, three scenarios - referred to as baseline scenarios - are examined, which model the energy system purely techno-economically without taking investment risks in the MENA region into account. The three scenarios differ only in terms of future demand development. → *Sub-report 6* presents the results of the base scenarios and also summarises the underlying database. The derivation of demand is explained in→ *Sub-report 5.*

Based on the baseline scenarios, further scenario variants are analysed that explicitly map investment risks in the MENA region by mapping country-specific investment costs for production facilities and storage facilities in the model. In addition,

1 MENA stands for "Middle East" (ME) and "North Africa" (NA)

individual issues are examined in greater depth in the context of sensitivities. The description of the scenario variants and sensitivities is presented in→ *Sub-report 7*.

2 Description of the WISEE-ESM-I model

WISEE-ESM-I, or ESM-I for short, is a model for the long-term planning and evaluation of energy systems. It models and evaluates cost optimal transformation paths of the energy system to cover exogenously specified requirements for energy sources and materials. In the following, the term "energy sources" is used for simplification purposes, although this term can also include substances such as ammonia for industry. The production of the required energy carriers from inputs (e.g. solar energy) in production plants via intermediate products is explicitly mapped in the model. Both the energy supply and the energy demand are considered geographically and temporally resolved. Different geographical regions are modelled so that an exchange of energy sources between regions is possible. The exchange takes place via transport infrastructures, which are explicitly taken into account in the model. Transmission capacities are modelled as connections between the regions. The transmission capacities are defined as transmission capacity at the regional borders. A transmission capacity thus represents all lines that connect these two regions. Assumptions regarding pipe diameters, voltage levels, etc. are used to determine the transmission capacity. However, the physical lines are not explicitly mapped in the model; for example, there is no load flow calculation.

At the temporal level, a distinction is made between years and *time* periods of less than a year, known as *time slices*. The mapping of years enables long-term modelling of the energy system over decades. *Time slices* represent periods of less than a year and make it possible to model short-term fluctuations in energy supply and demand. Storage facilities are explicitly taken into account in the model to compensate for these fluctuations. In addition to the storage facilities, injection and withdrawal units are mapped as further entities in the model. These are represented in the model as production technologies. Storage is limited to storage during the year, so storage between years is not possible. This model formulation significantly reduces the complexity of the planning problem.

The system boundary of the model in terms of modelled energy sources and technologies as well as temporal and geographical resolution can be varied for each application by using appropriate input data.

The ESM-I is formulated as a linear optimisation model. For this purpose, parameters, variables, constraints and an objective function are defined. Parameters represent model-exogenous specifications and are therefore input data for the model. Variables are the result of the model and thus represent the cost-optimal decisions of the model with regard to the design of the future energy system. Constraints limit the characteristics of the variables and thus the solution space of the model. The objective function represents the decision criterion with regard to which the design of the energy system is optimised.

The various components of the model are described in detail below. Figure 2-1 graphically summarises the structure of the ESM-I for use in the MENA-Fuels project.

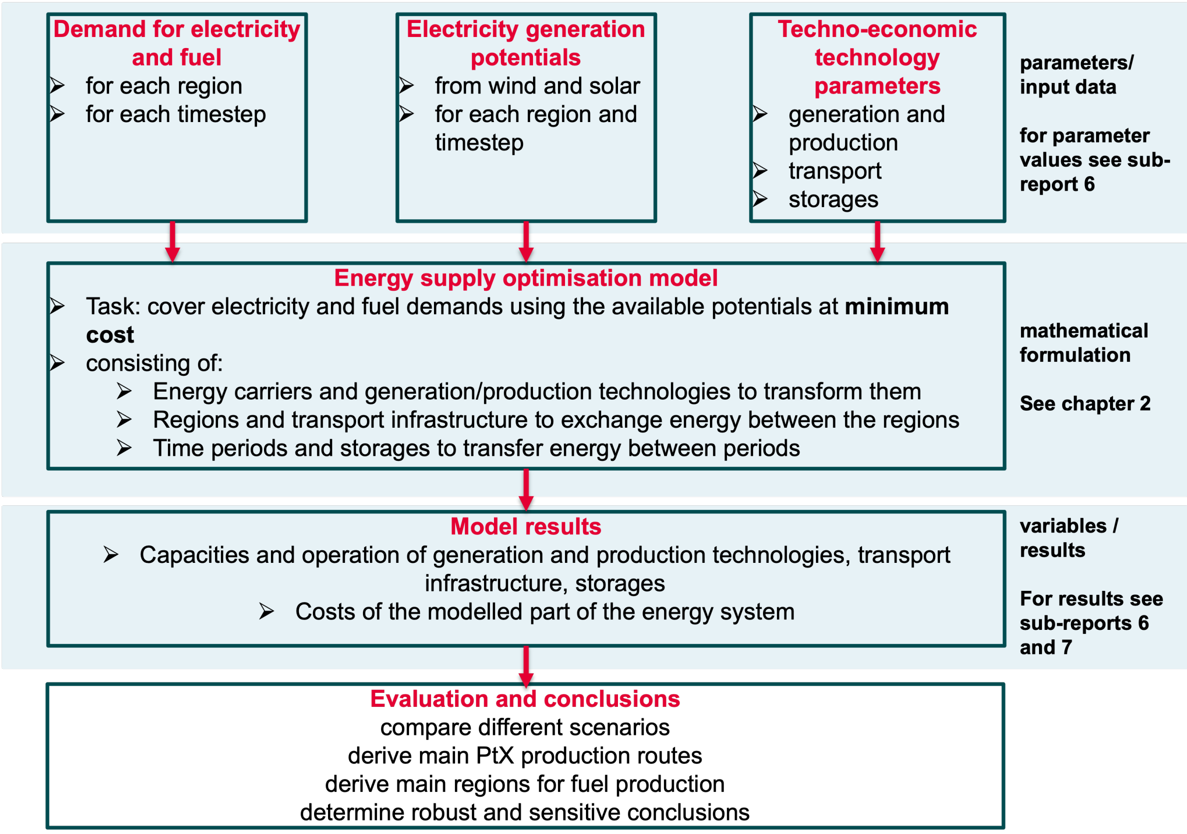

Figure 2-1: Structure of the WISEE-ESM-I

Parameters

A complete overview of the parameters mapped in the ESM-I can be found in Table 2-1. The parameters relate to the demand for energy sources, production technologies, storage and transport infrastructures as well as the accounting of emissions[2] . In addition, global parameters and auxiliary parameters are defined, although the latter are not shown in in Table 2-1. The most important parameters for understanding the model are explained below.

The demand parameters comprise the *SpecifiedAnnualDemand* and the *SpecifiedDemandProfile*. They represent the exogenously specified demand for energy sources, which must be met by the production of the corresponding energy sources in the model. *SpecifiedAnnualDemand* represents the annual demand for an energy source. As demand can fluctuate within a year, the *SpecifiedDemandProfile* maps the distribution of annual demand across the *time slices*, i.e. the time periods during the year.

Parameters are defined for production facilities, storage facilities and transport infrastructures, which describe the costs, technical parameters and the restrictions on the construction and operation of the facilities. Costs include both investment costs (*CapitalCost*, *CapitalCostStorage*, *ExchangeFixedCapitalCost*, *ExchangeVariableCapitalCost*) and fixed and variable operating costs (*VariableCost*, *FixedCost*,

2 Emissions accounting is not used in the MENA-Fuels project, as only the emission-free portion of the energy system is modelled (see→ *sub-report 6*).

ExchangeFixedCost, *ExchangeVariableCost*). Both distance-dependent ("*Variable*") and distance-independent ("*Fixed*") costs are shown for the transport infrastructures. It is possible to differentiate costs by year and also by region for the costs of production facilities and storage facilities.

The technical parameters include information on service life, plant availability and efficiency. For production plants, the efficiency is mapped using input and output coefficients (*InputActivityRatio* and *OutputActivityRatio*), which are used to take into account the relationship between the inputs and outputs of a plant. By modelling age cohorts, the input and output coefficients of a plant can be defined as a function of the time of construction of the plant and thus efficiency improvements in the plant fleet can be explicitly taken into account over time. For storage facilities, losses during injection and withdrawal are modelled using the *TechnologyToStorage* and *TechnologyFromStorage* parameters. Efficiency losses during the transportation of energy sources are taken into account using the *ExchangeEfficiency* parameter, which is formulated as a function of the transportation distance. The import of an energy source into a region is reduced accordingly by the efficiency losses.

Other parameters restrict the construction and operation of production plants, storage facilities and transport infrastructure. For production facilities, these are exogenous specifications for the minimum or maximum expansion of capacities or the operation of the facilities. Both the annual capacity expansion (*TotalAnnualMaxCapacityInvest*, *TotalAnnualMinCapacityInvest*) and the total installed capacity (*TotalAnnualMaxCapacity*, TotalAnnualMinCapacity) can be limited. The latter can be used, for example, to take into account the potential limits of resources. The operation of production facilities can be restricted by minimum or maximum activity specifications, whereby specifications can be made at an annual level (*TotalTechnologyAnnualActivityUpperLimit* & *TotalTechnologyAnnualActivityLowerLimit*) as well as in relation to the entire planning period (*TotalTechnologyModelPeriodActivityUpperLimit* & *TotalTechnologyModelPeriodActivityLowerLimit*).

For storage facilities, the minimum fill level can be specified exogenously depending on the storage size (*MinStorageCharge*). The transportation of energy sources between different regions can be restricted by net import or export specifications (*NetExportFrac* & *NetImportFrac*). The import and export restrictions are formulated as a percentage of the demand for an energy source.

The ESM-I enables the modelling of emissions (e.g. CO_2) that arise during the operation of production facilities. Parameters for modelling emissions relate to the emissions output of plants (*EmissionActivityRatio*), penalties for emissions (*EmissionsPenalty*) and specifications for maximum emissions output - both on an annual basis (*AnnualEmissionLimit*) and in relation to the entire planning horizon (*ModelPeriodEmissionLimit*). Other emissions that arise in addition to those from the production facilities explicitly mapped in the model can also be taken into account (*AnnualExogenousEmission*, *ModelPeriodExogenousEmission*).

Table 2-1: Parameters of the WISEE-ESM-I model

Parameter name	**Description of the parameter**
Global parameters	
Timestep	Distance between the explicitly mapped years (in the context of timestep modelling)
YearSplit	Duration of a time slice (defined as a proportion of the total year)
DiscountRate	Discount rate
DepreciationMethod	Amortization method
Demand parameters	
SpecifiedAnnualDemand	Annual demand for an energy source, per energy source, year, region
SpecifiedDemandProfile	Share of demand for an energy source in a time slice, per energy source, time slice, year, region
Parameters for the production facilities	
CapacityToActivityUnit	Conversion factor between capacity and production volume of a plant, per technology, region
CapacityFactor	Capacity factor of a system, per technology, time slice, year, region
AvailabilityFactor	Annual availability of a system, per technology, year, region
OperationalLife	Service life of a system, per technology, region
InputActivityRatio	Input coefficient of an energy source, per energy source, technology, operating mode[3] , year, region

[3] Some technologies may have different operating modes. If a technology has different input or output energy carriers and can choose the mix (i.e. any linear combination) of these input or output energy carriers, each mix can be accounted for as a separate operating mode. For example, a CHP plant can generate heat in one operating mode and electricity in another.

Parameter name	Description of the parameter
OutputActivityRatio	Output coefficient of an energy source, per energy source, technology, operating mode, year, region
CapitalCost	Investment costs of a system, per technology, year, region
VariableCost	Variable operating costs of a system, per technology, operating mode, year, region
FixedCost	Fixed operating costs of a system, per technology, year, region
TotalAnnualMaxCapacity	Maximum installable capacity of a production technology per year (refers to the total capacity available in a year, i.e. newly installed capacity in a year plus capacity installed in previous years), per technology, year, region
TotalAnnualMinCapacity	Minimum capacity of a production technology to be installed per year (refers to total capacity, i.e. newly installed capacity in a year plus capacity installed in previous years), per technology, year, region
TotalAnnualMaxCapacityInvestment	Maximum installable capacity of a production technology per year (refers to the newly installed capacity in a year), per technology, year, region
TotalAnnualMinCapacityInvestment	Minimum capacity of a production technology to be installed per year (refers to the newly installed capacity in a year), per technology, year, region
TotalTechnologyAnnualActivityUpperLimit	Maximum activity level of a technology (in one year), per technology, year, region
TotalTechnologyAnnualActivityLowerLimit	Minimum activity level of a technology (in one year), per technology, year, region
TotalTechnologyModelPeriodActivityUpperLimit	Maximum activity level of a technology (in the entire planning period), per technology, region
TotalTechnologyModelPeriodActivityLowerLimit	Minimum activity level of a technology (in the entire planning period), per technology, region
Parameters for storages	
TechnologyToStorage	Storage efficiency, per technology[4] , storage technology, operating mode, region

4 Storage and retrieval units are modelled in ESM-I as production facilities, analogous to OSeMOSYS.

Parameter name	Description of the parameter
TechnologyFromStorage	Withdrawal efficiency, per technology, storage technology, operating mode, region
MinStorageCharge	Minimum storage level, per storage technology, year, region
OperationalLifeStorage	Service life of a storage system, per storage technology, region
CapitalCostStorage	Investment costs of a storage facility, per storage technology, region, year
e2p	Coefficient for coupling the amount of energy that can be stored and the charging capacity of a storage system[5] , per storage technology, region, year
Parameters for the transport infrastructure (extension of OSeMOSYS)	
ExchangeRoute	Binary parameter indicating whether the construction of a defined transport infrastructure between 2 regions is possible, per energy source, transport technology, year, region 1, region 2
ExchangeCapacityToActivity	Conversion factor between capacity and transport volume of a transport infrastructure, per transport technology
ExchangeEfficiency	Transport efficiency of an energy source, per energy source, transport technology, year
ExchangeDistance	Transport distance, per transport technology, region 1, region 2
ExchangeFixedCost	Volume-dependent, distance-independent transportation costs, per energy source, transportation technology, year
ExchangeVariableCost	Volume- and distance-dependent transportation costs, per energy source, transportation technology, year
ExchangeOperationalLife	Service life of transportation infrastructure, per transportation technology, region
ExchangeFixedCapitalCost	Distance-independent investment costs of transport infrastructures, per transport technology, year, region
ExchangeVariableCapitalCost	Distance-dependent investment costs of transport infrastructures, per transport technology, year, region

[5] The e2p coefficient thus describes the time in hours that a storage tank requires for a complete discharge process at its nominal capacity (E is energy; P is power; E2P is therefore E/P).

Parameter name	Description of the parameter
NetExportFrac	Share of demand to which the net export of an energy source is limited, per energy source, year, region
NetImportFrac	Share of demand to which the net import of an energy source is limited, per energy source, year, region
Parameters for modelling emissions	
EmissionActivityRatio	Emission factor of a technology (per unit of activity), per technology, operating mode, emission, year, region
EmissionsPenalty	Penalty payment for emissions, per emission, year, region
AnnualExogenousEmission	emissions to be taken into account in addition to the model endogenous emissions (defined per year), per emission, year, region
AnnualEmissionLimit	Annual emission limit, per emission, year, region
ModelPeriodExogenousEmission	emissions to be taken into account in addition to the model-endogenous emissions (defined for the entire planning horizon), per emission, region
ModelPeriodEmissionLimit	Issue limit for the entire planning horizon, per issue, region

Variables

The variables are the result of the optimisation and therefore represent the output of the model. Similar to the parameters, variables are modelled to represent the demand, production facilities, storage and transport infrastructures as well as emissions.

A complete overview of the variables can be found in Table 2-2. However, many of the variables are only auxiliary variables or result directly from other variables, for example by summing up all *time slices*, operating modes, technologies, regions, years, etc. (see also the explanations below in the section "Secondary conditions"). For this reason, only the variables that represent the key decisions of the model are explained in detail below.

Variables for production plants, storage facilities and transport infrastructures model the installed capacities, the operation of the plants, storage facilities and transport infrastructures as well as the costs arising from the construction and operation of the installed capacities. The model depicts the new capacities built each year for production facilities, storage and transport infrastructures, differentiated by region (*NewCapacity*, *NewStorageCapacity*, *NewExchangeCapacity*). Taking into account the lifespan of the facilities, storage facilities and infrastructures, the total capacity installed in a year (*AccumulatedNewCapacity*, *AccumulatedNewStorageCapacity*, *AccumulatedNewExchangeCapacity*) can be determined on the basis of the newly installed capacities. The newly installed capacity in a year is relevant for the investment costs incurred by the construction. The total capacity installed in a year is relevant, for example, for the limitation of production, storage or transportation and thus for the operating costs in the year in question. With a large number of technologies, regions and years mapped, this results in a large number of variables that model the construction of production plants, storage facilities and transport infrastructures. For this reason, the timestep modelling in ESM-I only explicitly models the construction of new plants, storage facilities and transport infrastructure in every x^{th} year. This modelling can significantly reduce the complexity of the planning problem (see explanations in Section 3).

Variables for the operation of production facilities and transport infrastructures relate to the activity of these (*TotalTechnologyAnnualActivity* or *ExchangeActivity*) and other resulting variables. Further variables of the production facilities are the quantity of energy sources used and produced (*Use* and *Production*), which result from the activity of a production facility and the input and output coefficients. Variables that result directly from the activity of transport infrastructures are *import* and *export* - i.e. the quantity of an energy source imported into or exported from a region.

Variables for the operation of the storage contain the injection or withdrawal into or from a storage (*StorageCharge*, *StorageDischarge*). The storage *level* (*StorageLevel*) results directly from the difference between *StorageCharge* and *StorageDischarge* and the storage level from the previous time slice.

Variables that represent the operation of production plants, storage facilities and transport infrastructures are defined both per time period during the year (in a given year) and per year. This will be explained using the variables that represent the production of energy sources as an example. The following variables are modelled for production:[6]

- *Production*
- *ProductionAnnual*
- *RateOfProduction*

Production represents the production of an energy source per *period of less than years*. *ProductionAnnual* is the *annual* production of an energy source; this variable thus represents the sum of *Production* over all periods of less than a year. *RateOfProduction* is an auxiliary variable and represents the quantity of an energy carrier that would be produced in a time period during the year if the latter lasted the entire year. *RateOf variables*, which are defined to represent both production and storage, are used in the formulation of the capacity constraints.[7]

[6] There are other production variables (for example, to differentiate production per production technology). These are not necessary to understand the definition of variables per time period or year during the year, so they are not included in the explanation.

[7] As the modelling of the transport is an extension of ESM-I compared to OSeMOSYS, the logic of the *RateOf variables* was not adopted for the modelling of the transport. This logic is also used to model demand, although it is not exclusively variables, but also parameters in some cases (see *SpecifiedAnnualDemand*).

Investment and operating costs are incurred for the construction and operation of production facilities, storage and transportation in structures. These costs are stored in other variables, whereby the value of these variables is derived directly from the installed capacities and the cost parameters. The residual value of plants, storage facilities and transport infrastructures that have not yet reached the end of their service life at the end of the planning period is stored in other variables and taken into account accordingly in the target function.

Discounting the costs or residual values results in discounted costs or residual values as additional variables. The sum of all discounted costs less the discounted residual values (*total discounted cost*) is minimised as part of the ESM-I target function (see explanations in the "Target function" section).

Variables in the context of emissions accounting are the amounts of emissions emitted, which result directly from the operation of the production facilities, as well as penalties due to emissions.

Table 2-2: Variables of the WISEEE-ESM-I model

Name of the variable	Description of the variables
Variables for mapping demand	
RateOfDemand	Auxiliary variable; demand for one energy source per time slice, if the latter would last the entire year, per energy source, time slice, year, region
Demand	Demand for an energy source per time slice, per energy source, time slice, year, region

Name of the variable	Description of the variables
Variables for mapping production	
NewCapacity	newly installed capacity of a production plant in one year, per technology, year, region
AccumulatedNewCapacity	Total installed capacity of a production plant in a year (calculated as the sum of the newly installed capacity in the year in question plus the capacity installed in previous years, provided that the end of the plant's service life has not been reached), by technology, year, region
RateOfActivityVintage	Auxiliary variable; represents the activity of a technology of a certain age cohort per time slice, if the latter would last an entire year, per technology, operating mode, time slice, year of construction, year, region
RateOfTotalActivity	Auxiliary variable; represents the activity of a technology per time slice, if the latter would last an entire year (summed for all age cohorts and operating modes), per technology, time slice, year, region
TotalTechnologyAnnualActivity	Annual activity of a technology, per technology, year, region
TotalAnnualTechnologyActivityByMode	Annual activity of a technology (differentiated by operating mode), per technology, operating mode, year, region
RateOfProductionByTechnologyByMode	Auxiliary variable; production volume of an energy source per time slice, if the latter would last the entire year, per energy source, technology, operating mode, time slice, year, region
RateOfProductionByTechnology	Auxiliary variable; production volume of an energy source per time slice, if the latter would last the entire year (totalled across all operating modes), per energy source, technology, time slice, year, region
RateOfProduction	Auxiliary variable; production volume of an energy source per time slice, if the latter would last the entire year (totalled across all production technologies and operating modes), per energy source, time slice, year, region
ProductionByTechnology	Production of an energy source per time slice, per energy source, technology, time slice, year, region
ProductionByTechnologyAnnual	Production of an energy source per year (corresponds to the sum of *ProductionByTechnology* across all *time slices*), per energy source, technology, year, region

Name of the variable	Description of the variables
Production	Production of an energy source per time slice (totalled across all technologies), per energy source, time slice, year, region
ProductionAnnual	Production of an energy source per year (total across all technologies), per energy source, year, region
RateOfUseByTechnologyByMode	Auxiliary variable; quantity of an energy carrier used in a production technology in a time slice, if the latter would last the entire year, per energy carrier, technology, operating mode, time slice, year, region
RateOfUseByTechnology	Auxiliary variable; quantity of an energy carrier used in a production technology in a time slice, if the latter would last the entire year (totalled across all operating modes), per energy carrier, technology, time slice, year, region
RateOfUse	Auxiliary variable; quantity of an energy source used in a production technology in a time slice, if the latter would last the entire year (totalled across all production technologies and operating modes), per energy source, time slice, year, region
UseByTechnology	Use of an energy source in a production plant per time slice, per energy source, technology, time slice, year, region
UseByTechnologyAnnual	Use of an energy source in a production plant per year (corresponds to the sum of *UseByTechnology* across all *time slices*), per energy source, technology, year, region
Use	Use of an energy source in a production plant per time slice (totalled across all technologies), per energy source, time slice, year, region
UseAnnual	Use of an energy source in a production plant per year (total across all technologies), per energy source, year, region
CapitalInvestment	Investment costs for established production capacities, per technology, year, region
DiscountedCapitalInvestment	Discounted investment costs for the installed production capacities, per technology, year, region
SalvageValue	Residual value of installed production capacities at the end of the planning period, per technology, year, region
DiscountedSalvageValue	Discounted residual value of installed production capacities at the end of the planning period, per technology, year, region
Name of the variable	**Description of the variables**

OperatingCost	Operating costs per year for production facilities; calculated as the sum of *AnnualVariableOperatingCost* and *AnnualFixedOperatingCost*, per technology, year, region
DiscountedOperatingCost	Discounted operating costs per year for production facilities, per technology, year, region
AnnualVariableOperatingCost	Variable operating costs per year for production facilities, per technology, year, region
AnnualFixedOperatingCost	Fixed operating costs per year for production facilities, per technology, year, region
TotalDiscountedCostByTechnology	Total discounted costs of a production plant per year; calculated as the sum of investment costs, operating costs and penalty payments for emissions, less residual value, per technology, year, region
Variables for storages	
RateOfStorageCharge	Auxiliary variable; quantity of an energy carrier that would be stored in a storage facility per time slice if the latter lasted the entire year, per storage technology, time slice, year, region
RateOfStorageDischarge	Auxiliary variable; quantity of an energy source that would be withdrawn from a storage facility per time slice if the latter lasted the entire year, per storage technology, time slice, year, region
StorageCharge	Quantity of an energy source stored in a storage facility per time slice, per storage technology, time slice, year, region
StorageDischarge	Quantity of an energy carrier withdrawn from a storage facility per time slice, per storage technology, time slice, year, region
StorageLevel	Fill level of a storage per time slice, per storage technology, time slice, year, region
StorageLowerLimit	Minimum capacity of a storage facility, per storage technology, year, region
NewStorageCapacity	New storage capacity installed in one year, per storage technology, year, region
AccumulatedNewStorageCapacity	Total installed capacity of a storage facility in a year (corresponds to the sum of the newly installed capacity of a storage facility in a year plus installed capacities from previous years, unless the end of the storage facility's service life has been reached), per storage technology, year, region
CapitalInvestmentStorage	Investment costs of installed storage facilities, per storage technology, year, region
Name of the variable	**Description of the variables**
DiscountedCapitalInvestmentStorage	Discounted investment costs of the installed storage facilities, per storage technology, year, region

SalvageValueStorage	Residual value of installed storage facilities at the end of the planning period, per storage technology, year, region
DiscountedSalvageValueStorage	Discounted residual value of the installed storage facilities at the end of the planning period, per storage technology, year, region
TotalDiscountedStorageCost	Discounted investment costs less the residual value at the end of the planning period of the installed storage facilities, per storage technology, year, region
Variables for mapping the transport (extension of OSeMOSYS)	
NewExchangeCapacity	New transportation infrastructure capacity built in one year, per energy source, transportation technology, year, region 1, region 2
AccumulatedNewExchangeCapacity	total transport infrastructure capacity in a year (results from the newly constructed capacity in the year in question plus constructed capacity from previous years whose end of life has not yet been reached), per energy source, transport technology, year, region 1, region 2
ExchangeActivity	Activity of a transportation infrastructure between 2 regions per time slice, per energy source, transportation technology, time slice, year, region 1, region 2
ExchangeActivityAnnualByTech	Activity of a transport infrastructure between 2 regions per year, per energy source, transport technology, year, region 1, region 2
ExchangeActivityAnnual	Activity of a transportation infrastructure between 2 regions per year (summed across all transportation technologies), per energy source, year, region 1, region 2
Import	Quantity of an energy source imported into a region per time slice, per energy source, time slice, year, region
ImportAnnual	Quantity of an energy source imported into a region per year, per energy source, year, region
Export	Quantity of an energy source exported from a region per time slice, per energy source, time slice, year, region
ExportAnnual	Quantity of an energy source imported from a region per year, per energy source, year, region

Name of the variable	**Description of the variables**
ExchangeCapitalInvestment	Investment costs for the construction of transport infrastructure capacities, per energy source, transport technology, year, region 1, region 2
ExchangeCapitalInvestmentByRegion	Investment costs for the construction of transport infrastructure capacities (the investment costs for the transport infrastructure capacities are allocated to the region to which the transport infrastructure leads), per transport technology, year, region
DiscountedExchangeCapitalInvestment	Discounted investment costs for the construction of transport infrastructure capacities, per transport technology, year, region
ExchangeSalvageValue	Residual value of transport infrastructure capacities at the end of the planning period, per energy source, transport technology, year, region 1, region 2
ExchangeSalvageValueByRegion	Residual value of transport infrastructure capacities at the end of the planning period (the residual value for the transport infrastructure capacities is allocated to the region to which the transport infrastructure leads), per transport technology, year, region
DiscountedExchangeSalvageValue	Discounted residual value of transport infrastructure capacities at the end of the planning period, per transport technology, year, region
ExchangeCost	Total volume-dependent transportation costs per year (costs are allocated to the region to which transportation takes place), per energy source, year, region
DiscountedExchangeCostByFuel	Sum of discounted, volume-dependent transportation costs per year, per energy source, year, region
DiscountedExchangeCost	Sum of discounted, volume-dependent transportation costs per year (summed across all energy sources), per year, region
Other variables for mapping costs	
TotalDiscountedCost	total discounted payments per year; calculated as the sum of investment and operating costs of the production facilities, storage facilities and transportation infrastructure and the penalty payments for emissions, less the residual value of production facilities, storage facilities and transportation infrastructure at the end of the planning period, per year, region
ModelPeriodCostByRegion	Total discounted payments (corresponds to the sum of *total discounted costs* over all years), per region

Name of the variable	Description of the variables
Variables for mapping emissions	
AnnualTechnologyEmissionByMode	annual emissions of a production plant, per emission, technology, operating mode, year, region,
AnnualTechnologyEmission	annual emissions of a production plant, per emission, technology, year Region
AnnualTechnologyEmissionPenaltyByEmission	Penalties for emissions, per emission, technology year
AnnualTechnologyEmissionsPenalty	Penalties for emissions (totalled across all emissions), per technology, year
DiscountedTechnologyEmissionsPenalty	Discounted penalties for emissions (totalled across all emissions), per technology, year
AnnualEmissions	annual emissions of a production plant (totalled across all technologies and operating modes), per emission, year, region
ModelPeriodEmissions	Total sum of emissions per planning period; results from the sum of model-endogenously determined emissions *AnnualEmissions* and model-exogenously specified *AnnualExogenousEmission*, per emission, region

Target function

The objective function of the ESM-I minimises the discounted total costs of the energy system (*ModelPeriodCostByRegion*). The total costs include the investment and operating costs of the production plants, storage facilities and transport infrastructure less their residual value plus penalties for emissions for all modelled regions and years.

Secondary conditions

The constraints of the ESM-I describe and restrict the solution space of the optimization model. The constraints can be divided into the following four categories:

- Variable definition
- Capacity restrictions
- Mass and energy balances
- Emissions accounting

Individual variables are related to each other as part of the **variable definition**. For example, the total installed capacity of a production technology in a year corresponds to the newly installed capacity in that year plus the newly installed capacity in previous years, provided that the end of the plant's service life has not yet been reached. There are many other such constraints. The relationship between these variables has already been explained above in the description of the variables (cf. **Fehler! Verweisquelle konnte nicht gefunden werden.**), so the following will focus on the descriptions of capacity restrictions, mass/energy balances and emissions balancing.

Capacity restrictions limit the expansion and operation of production tion plants, storage facilities and transportation infrastructure. Their operation is limited by their installed capacities in the corresponding region, whereby the installed capacities are variables in the model (see explanations in the "Variables" section). For production facilities, the unavailability of production facilities, e.g. due to maintenance work, is also taken into account in the capacity restrictions.

The operation of production facilities continues to be limited by minimum and maximum activity levels - both in relation to one year and the entire planning period. The operation of injection and withdrawal units continues to be limited by exogenous specifications for maximum injection and withdrawal rates. The operation of transport infrastructures and thus the transported quantity of energy sources is restricted by exogenous specifications on maximum import and export quantities for individual regions (see also explanations in the "Parameters" section).

In addition, the expansion of production facilities is limited by exogenous minimum and maximum expansion targets. Both the annual new investment in production facilities and the total installed capacity of a production technology can be restricted. For example, annual investment targets can be used to set minimum or maximum expansion rates for technologies. Restrictions on total installed capacity can reflect potential limits, for example for wind and solar energy.

Mass and energy balances ensure that the physical laws governing the transformation, storage and transportation of energy carriers are observed. The basic mass and energy balance ensures that the sum of the production and import of an energy source in a region, in a time slice and in a year at least covers the sum of its use in further process steps, its export to other regions and the coverage of demand for this energy source.

For the transformation of energy carriers in the production plants, secondary conditions are used to ensure that the use or production of energy carriers in a production plant corresponds to the activity of the plant in question multiplied by an input or output coefficient. Similarly, for transportation, the activity of a transportation infrastructure is linked to the import or export of an energy carrier within the framework of further constraints. Efficiency losses during transportation are taken into account accordingly in the imported quantity of an energy source.

As part of the ancillary conditions for mapping the storage of energy carriers, it is guaranteed that the amount of energy stored in a storage facility, in a region, in a time slice and in a year corresponds to the energy stored in this time period minus the energy withdrawn plus the storage level of the previous *time slice*. The storage conditions are formulated cyclically, i.e. the storage level at the beginning of a year corresponds to the storage level at the end of a year. However, the model is free to determine how high the storage level is at the beginning or end of a year (although it must not be negative). In addition, storage is limited to storage during the year in order to reduce the complexity of the model (see Section 3).

Compliance with the model-specific emission reduction targets is ensured as part of the **emissions accounting** process.

3 Customisation of the open source framework OSeMOSYS

OSeMOSYS is a comprehensive framework for energy system planning (Royal Institute of Technology (KTH) et al., 2022). However, some adjustments to the mathematical formulation of the framework are necessary in order to meet the requirements for the model calculations within the MENA-Fuels project. The following key adjustments were made:

- **Differentiated mapping of transportation:** In OSeMOSYS, the exchange of energy sources between different regions is mapped in a simplified way; capacities and technologies (e.g. pipelines, tankers) of transport infra structures are not explicitly modelled. Costs associated with the construction and operation of transport infrastructure are also not modelled. Only the quantity of energy carriers exchanged is taken into account in the mass and energy balance. For the ESM-I, this simplified illustration is extended: the investment and operation of transport infrastructure tu with the associated investment and operating costs are explicitly mapped. The transportation of energy carriers is only possible if the infrastructure suitable for the transportation of the corresponding energy carrier is built or operated between the corresponding regions. In addition, imports and exports can be limited by model-exogenous specifications, although this model property is not used in the MENA-Fuels project. Transport infrastructures are thus mapped in ESM-I as exchange capacities between two regions, which have length-specific, performance- and export dependent costs.
- **Consideration of age cohorts for production facilities:** OSeMOSYS does not explicitly consider age cohorts for production facilities. However, since important techno-economic parameters, such as the efficiency of production facilities, can change over time, the time of investment should be explicitly taken into account in the model. This is possible by modelling age cohorts, as taken into account in ESM-I. This in turn involves additional complexity for the mapping of residual (existing) capacities of storage facilities and production plants, which was dispensed with in the context of this project.
- **No differentiation between Season, DayType and DailyTimeBracket**: OSeMOSYS differentiates between *Season*, *DayType and DailyTimeBracket* in order to be able to map temporal fluctuations in energy supply and demand at different time levels. In ESM-I, the modeling of time periods is simplified and no differentiation is made between *Season*, *DayType* and *DailyTimeBracket* . This means that only years and *time slices* are modeled in ESM-I with regard to temporal differentiation. The mapping of years enables the consideration of long-term developments over decades. *Time slices* represent time periods of less than a year and thus allow fluctuations in energy supply and demand during the year to be mapped. The simplification of the temporal mapping in ESM-I reduces the complexity of the planning problem. At the same time, it is detailed enough to enable the strategic modeling and evaluation of energy systems, taking into account fluctuations in energy supply and demand during the year. The dispatch module ESM-D can be used for more in-depth questions in the context of operational planning, which require a differentiated temporal resolution (described in Nebel

et al., 2020). However, this is not used in the MENA-Fuels project due to the strategic nature of the issues involved.

- **Adjustments to the mapping of the storage of energy sources:** The lack of differentiation between Season, DayType and DailyTimeBracket makes it possible to adapt and simplify the mapping of storage in ESM-I compared to OSeMOSYS. In ESM-I, storage between *time slices* and thus storage of energy sources during the year is mapped. As described in Section 2 the storage equations are formulated cyclically. This modelling ensures that renewable energy (RE) plants that cannot generate energy or can only generate a small amount of energy in the first modelled time slice are not disadvantaged by the model. In addition, storage is limited to storage during the year; storage between years is not possible. This significantly reduces the complexity of the model and at the same time corresponds to a realistic representation, as in practice renewable energy sources are primarily stored at a short-term to seasonal level.
- **Consideration of losses during injection and withdrawal**: OseMOSYS does not consider losses during storage. In ESM-I, however, losses during the injection or withdrawal of substances or energy sources are taken into account. For this purpose, the binary OSeMOSYS parameters *TechnologyToStorage* and *TechnologyFromStorage* are defined in ESM-I as a non-negative, real number that can be used to map the losses.
- **Timestep modelling:** OSeMOSYS explicitly models all years within a planning period. This modelling means a high number of variables and therefore a high level of model complexity. Timestep modelling is being introduced as part of ESM-I. In timestep modelling, only every xth year is explicitly mapped in the model, whereby the number of years modelled can be adjusted on a case study-specific basis. This means that investments in production facilities, storage facilities and transport infra structures are only possible in the explicitly modelled years. For their operation in the non-modelled years, it is implicitly assumed that it corresponds to the operation of the explicitly modelled years. The variable and fixed operating costs in the modelled years are taken into account x times accordingly in order to take into account the operation in the non-modelled years on the cost side. In addition, the discounting and the calculation of the residual value in the model are adjusted so that they are consistent with the timestep modelling. Timestep modelling significantly reduces the number of variables and thus the complexity of the model due to the lower number of modelled years.
- **No mapping of reserve capacities and targets for RE generation:** OSeMOSYS enables the mapping of reserve capacities and targets on RE generation volumes. However, these model features are not (yet) used in the MENA-Fuels project or other work with the ESM-I, so they are not described in this report.

4 Approaches to reducing model complexity

In order to model and evaluate the long-term supply paths of Germany and Europe with renewable electricity and synthetic fuels, a large number of technologies, time periods and regions must be represented. The resulting optimization problem is correspondingly complex. Various measures were therefore implemented to reduce the complexity. Firstly, the mathematical formulation of the ESM-I was adapted. These adjustments are described in detail in Section 3 described in detail. They are therefore mentioned here for the sake of completeness without explaining them in detail. Specifically, the following adjustments were made to the mathematical formulation:

1 | No differentiation between *Season*, *DayType* and *DailyTimeBracket*; modelling only of years and time periods during the year (*time slices*)
2 | Formulation of cyclical storage equations that limit storage to less than one year

Secondly, the number of time periods (reduction of temporal complexity) and regions (reduction of spatial complexity) to be modelled is reduced in order to further reduce complexity. These measures to reduce complexity are explained in more detail below.

As described in Section 2 a distinction is made at the temporal level between *years* and *time slices* in order to take into account both long-term developments and short-term fluctuations in energy supply and demand. The reduction of temporal complexity is based on both temporal levels: On the one hand, only support years, i.e. every xth year, and not all years within half of a planning period are explicitly modelled (see also the explanations on timestep modelling in Section 3). Secondly, the number of time steps during the year is reduced by aggregating the hours. Temporal aggregation is carried out for demand and solar radiation data by selecting data points from the entire year at regular intervals. For a temporal resolution of 25 hours, for example, every 350th hour is taken into account (corresponds to a two-week rhythm). The intervals in the selection of data points result in a synthetic daily time series (as hours are used at intervals of x*24+1). This represents the typical intraday fluctuations and also the seasonality of the feed-in or load, even if only in a very stylised form with a low temporal resolution.

A different aggregation method is used for the feed-in of wind energy: In each case, the contiguous time interval from the annual time series with the highest spread between maximum and minimum availability of the potentials is used to ensure that fluctuations are adequately represented. Scaling the aggregated time series ensures that the full load hours of the aggregated time series correspond to those of the non-aggregated original time series. The two approaches for reducing time complexity significantly reduce the number of variables and boundary conditions and therefore the complexity of the model.

The spatial complexity is reduced by clustering individual countries into larger regions. For region clustering, the country-specific input data of the model is aggregated. The countries to be grouped into clusters and the logic (mean values, sums, weighted means, etc.) to be used for clustering the parameters can be adapted to the specific case study. The assignment of countries to clusters, which was carried out in the MENA-Fuels project, is documented in Section 2 in→ *Sub-report 6*. The parameters are clustered as follows: Data on demand and on the maximum and minimum installable capacities are totalled for all countries within a cluster. The possible ExchangeRoutes are also totalled as part of the clustering. The demand profile (*SpecifiedDemandProfile*) is clustered using the weighted average - with demand as the weighting factor. All other parameters, which are formulated on a country-specific basis (this applies in particular to the techno-economic parameters of the production facilities, storage facilities and transport infrastructures as well as the transport distances), are clustered using the arithmetic mean.

By clustering individual countries into regions, the number of variables and thus the complexity of the model can be significantly reduced. In order to obtain country-specific results, the model results are again distributed to individual countries as part of post-processing; disaggregation is carried out using the following methodology: The electricity generation volumes and capacities of RE installations shown in the model results are fully allocated to the country within a cluster with the best capacity factor in the relevant CP category (in the relevant year) for each cost potential category (CP category, see Section 3 in→ *Sub-report 6)*. If, according to the model results, the capacity of a CP category is greater than the maximum installable capacity of the country with the best capacity factor, the remaining electricity generation or RE capacity is allocated to the country with the second-best capacity factor. This procedure is repeated until the total electricity generation or RE plant capacity is allocated to the countries within a cluster according to the model results. Based on this allocation, the share of total electricity generation (i.e. summed across all CP categories) in the total electricity generation of the entire cluster in the relevant year is determined for each country and each year. This share is then used as a distribution key for calculating country-specific production volumes and plant capacities of gaseous and liquid fuels as well as transport volumes and capacities of transport infrastructures.[8]

[8] When calculating country-specific transport volumes and transport infrastructure capacities, it is also checked which energy volumes are only transmitted through a cluster but not produced in it (i.e. the cluster acts as a transit region). These transit volumes are assumed to be allocated to one country per cluster.

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Overview of the MENA-Fuels sub-reports

All sub-reports (written in German) can be downloaded from the following website: www.wupperinst.org/MENA-Fuels/

Teilprojekt A.I: Technologiebewertung für synthetische Kraftstoffe

1	Auswahl der zu bewertenden synthetischen Kraftstoffe und ihrer Bereitstellungstechnologien
2	Ökobilanzen für synthetisches Kerosin – Vergleich von Produktionsrouten in MENA und Deutschland
3	Multikriterielle Bewertung von Bereitstellungstechnologien synthetischer Kraftstoffe

Teilprojekt A.II: Potenzial- und Infrastrukturanalyse für EE-Strom, Wasserstoff und synthetische Folgeprodukte

4	Beschreibung des Energieversorgungsmodells WISEE-ESM-I
5	Nachfrageszenarien – Storylines und Herleitung der Entwicklung der Nachfrage nach Synfuels und Grundstoffen
6	Basisszenarien – Ergebnisse und Infrastrukturauswertung
7	Weitere Szenarioanalysen: Berücksichtigung von Investitionsrisiken und Sensitivitäten der Basisszenarien
8	Risikobewertung und Risikokostenanalyse der MENA-Region

Teilprojekt B.I: Analyse der Exportpotenziale in den MENA-Ländern

9	Szenarien zur Eigenbedarfsanalyse für die MENA-Länder
10	Technische und risikobewertete Kosten-Potenzial-Analyse der MENA-Region
11	Synthese der Kurzstudien für Jordanien, Marokko und Oman

Teilprojekt B.II: Künftige Märkte, Handelsprodukte und Wertschöpfungsketten

12	MENA-Fuels – Analyse eines globalen Marktes für Wasserstoff und synthetische Energieträger hinsichtlich künftiger Handelsbeziehungen
13	Gesamtwirtschaftliche Effekte von Investitionen zur Versorgung Deutschlands mit Wasserstoff und synthetischen Energieträgern aus der MENA-Region

Teilprojekt B.III: Synthese und Handlungsoptionen

14 (DE)	Synthese und Handlungsoptionen – Ergebnisbericht des Projekts MENA-Fuels
14 (EN)	Synthesis and courses of action – Report on results of the MENA-Fuels project
14 (FR)	Synthèse et pistes d’action – Rapport sur les résultats du projet MENA-Fuels

The future of mobility in Germany and the EU offers a wide range of technologies and solutions. In addition to electric mobility, the use of synthetic fuels represents one conceivable solution.

The production of large amounts of synthetic fuels (and feedstocks) requires substantial quantities of renewable energies at affordable prices. In particular, sunny and windy countries in the MENA region (North Africa and the Middle East) have the potential to serve as locations for producing synthetic fuels and their precursors due to the large potentials they offer in terms of renewable energies. In addition, trade relationships with and infrastructure already existing in many countries can be built up.

But what potentials are available in the individual countries? At what costs are corresponding resources available? What transport structures are required? What impacts do imports have on value creation both in Germany as well as in the MENA countries? What level of interest exists in the countries in the MENA region itself in terms of utilising their renewable energy potentials to supply their domestic demand but also for exports? What competitors need to be taken into consideration outside of the MENA region and the EU?

Taking these questions as its starting point, the MENA-Fuels project analysed the extent to which the MENA region can serve as a strategically relevant trade partner in supplying Germany (and the EU) with synthetic fuels or their precursors.

www.wupperinst.org/MENA-Fuels/