BioENergy OPTimisation model - BENOPT

A model for cost- and greenhouse gas optimal material and energy allocation

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Introduction

BENOPT was developed to integrate the most important aspects of the complex biomass usage and PtX within a systems perspective. A systems perspective does not merely consider each usage option or pathway independently, but their development in a system and is in the theory of industrial ecology manifested through the following areas[1,3]: (i) a life-cycle perspective, (ii) material and energy flow analyses, (iii) systems modelling and ideally (iv) interdisciplinary analyses. A further important aspect, (v) technological change, should also be mentioned in this context[2,3]. Aspects i-iii and v are included directly in the model[4], which enables a more holistic analysis than for instance LCAs of singular pathways. The results can be embedded within broader, interdisciplinary analyses.

BENOPT is a fully deterministic, bottom-up, perfect foresight, linear optimisation model for modelling cost-optimal and/or GHG abatement optimal allocation of renewable energy carriers across power, heat and transport sectors. The sectors are further divided into sub-sectors. The model has a yearly resolution, with an up to 15-min resolution in the power sector depending on the input data, which can be aggregated depending on the task.

The main goal functions used are minimising cost and maximising GHG abatement. The allocation of resources across transport, power and heat sectors (further divided into sub-sectors) is optimised simultaneously, enabling a systems perspective where the opportunity costs are minimised and thus sub-optimal solutions avoided, which would occur if only considering single sectors or pathways (as in standard life-cycle analyses)[4].

Greenhouse gas emissions

The GHG emissions $\varepsilon_{i,t}$ [kgCO_2eq GJ$^{-1}_{fuel}$] of option i at time-point t are calculated a sum of all emissions in the different stages of the process (Eqn. 1), with F, feedstock (biomass residues and crops, Excess electrical energy (ERE) and electricity mix); T_1, transport of the biomass to the conversion facility; P_1, first process step (with allocation factor α_1); P_2, second process step (α_2); transport of the energy carrier to the usage or fuelling station T_2. The emissions of all process steps preceding the end of P_1 are allocated to the fuel according to α_1, whereas those preceding the end of P_2 are additionally allocated according to α_2, divided by the feedstock specific energy content e_f multiplied with the feedstock-technology specific conversion efficiency.

For each input to any process, for all inputs k belonging to the respective process steps, the input amount $\dot{m}_{k,i,t}$ is multiplied by its emission factor $\varepsilon_{k,t}$. Byproducts which are not considered in the allocation, but through a credit, are denoted cr.

$$\begin{aligned}\varepsilon_{i,t} =& \frac{\alpha_1 \cdot \alpha_2}{e_f \cdot \eta_{i,f}} \left(\varepsilon_{f,t} + \sum_{k \in T_1} \dot{m}_{k,i,t} \cdot \varepsilon_{k,t} + \sum_{k \in P_1} \dot{m}_{k,i,t} \cdot \varepsilon_{k,t} - \dot{m}_{cr,i,t} \cdot \varepsilon_{cr,t} \right) \\ &+ \frac{\alpha_2}{e_f \cdot \eta_i} \left(\sum_{k \in P_2} \dot{m}_{k,i,t} \cdot \varepsilon_{k,t} - \dot{m}_{cr,i,t} \cdot \varepsilon_{cr,t} \right) + \sum_{k \in T_2} \dot{m}_{k,i,t} \cdot \varepsilon_{k,t}\end{aligned} \tag{1}$$

The inputs for the feedstock cultivation are on a hectare basis, thus a division by yield $Y_{f,t}$ [t$_{FM}$ ha^{-1}] is necessary for crops to calculate the emissions $\varepsilon^{crop}_{f,t}$ (Eqn. 2). The emissions of residues $\varepsilon^{res}_{f,t}$ and ERE $\varepsilon^{el,ere}_{f,t}$ are assumed to be zero in the standard version, while the electricity mix emissions $\varepsilon^{el,mix}_{f,t}$ are set in the scenarios.

$$\varepsilon^{crop}_{f,t} = \frac{1}{Y_{f,t}} \sum_{k \in F} \dot{m}_{k,i,t} \varepsilon_{k,t} \tag{2}$$

Please refer to Millinger et al.[6] for a more detailed description of the GHG calculations.

Feedstock costs

The crop prices are derived by using wheat as a benchmark, with other crops set to achieve the same profit per hectare. The hectare profit for wheat is calculated as the market price $p_{w,t}$ [€ t_{FM}^{-1}] times yield $Y_{w,t}$ [t_{FM} ha^{-1}] minus production costs $c_{w,t}$ [€ ha^{-1}]. Other crops are to achieve this profit per ha, adding production costs $c_{f,t}$ [€ ha^{-1}]. The prices are then divided with the yield $Y_{f,t}$ [t_{FM} ha^{-1}] to come up with a market price $p_{f,t}$ [€ t_{DM}^{-1}] of feedstock f. Over time, this results in a market price development including opportunity costs for each feedstock (Eqn. 3).

$$p_{f,t} = \left(p_{w,t} \cdot Y_{w,t} - c_{w,t} + c_{f,t}\right) {Y_{f,t}}^{-1} \tag{3}$$

Please refer to Millinger and Thrän[5] for a more thorough description of the crop price function.

For the biomass residues, each type $\phi_{f,t}$ is divided into three equally large groups for each time-point, with the price for the categories set to the minimum value, the average of the minimum and maximum values and the maximum value, respectively. The span is given exogenously and in the standard setting follows the set price increase of wheat.

The price of ERE and electricity mix is likewise set exogenously, and may be set to vary over time.

Variable Renewable Energy developments

For the VRE generation, i.e. on- and offshore wind and solar photovoltaic (PV), hourly (or alternatively 15-min resolution) generation time series as well power load can be used from Open Power System Data[8], with data read from the data base based on the given weather year and country code.

The future development of electricity demand as well as on- and offshore wind and solar PV capacities, capacity factors (C_f, the ratio of actual output to the maximum possible output of a power plant, over a period of time) and electricity storage capacities are assumed for 5-year time steps from 2020 until 2050 according to defined scenario conditions. Electricity generation from river hydro power can be modelled as a fixed feed-in to the production time series, with an invariable electricity generation (MW) totalling the projected energy generation volume (TWh) in the respective year.

The generation time series data are normalized and scaled[9,10] according to the assumed capacity expansions and their capacity factor developments. The power load time series are likewise scaled to comply with the assumed development of total annual electricity demand.

The resulting time series for VRE and hydro power production are then subtracted from the power load time series on an hourly basis for each time step, resulting in hourly time series for the residual load that model the development of electricity generation and consumption from 2020 until 2050.

The residual load data are then sorted, resulting in residual load duration curves (RLDC) for every 5 years. These are then interpolated to obtain RLDCs for each year between 2020-2050.

Optimal material and energy allocation

An optimal resource allocation without requiring sub-sectoral renewable or GHG targets is enabled through a two-stage modelling. First, the total possible GHG abatement under the given restrictions is maximised (Eqn. 4), with ε_{tot} being the total GHG abatement, given by the avoided reference fossil emissions $\varepsilon_{sub,t,s}$ multiplied by the relative end conversion efficiency to the sub-sector specific service, compared to the sub-sector specific reference option (e.g. for road transport the Tank-To-Wheel (TTW) relative fuel economy compared to an Otto ICEV) ω_i of the energy carrier type i, minus the production emissions $\varepsilon_{i,t}$, multiplied by the production of the renewable fuel $\pi_{i,t}$, at time point t. The factor ω_i ensures that the fuel economy for a given transport service is being compared, and thus a source to energy service (in transport Well-to-Wheel, WTW) analysis is performed[7].

$$\varepsilon_{max} = \sum_{i,t} (\varepsilon_{sub,t,s} \cdot \omega_i - \varepsilon_{i,t}) \cdot \pi_{i,t} \tag{4}$$

Second, the resulting maximal total GHG abatement is set as a boundary condition (Eqn. 5), which can be step-wise reduced in runs where the costs are minimised (Eqn. 6), with the total cost C_{tot} being the sum of the product of the endogenously installed capacities $\kappa_{i,t}^{endo}$ and their investment costs $I_{i,t}^{+}$, and the production $\pi_{i,t}$ multiplied with marginal costs $mc_{i,t}$, for each option at each time-point.

$$\varepsilon_{tot} = a \cdot \varepsilon_{max}, \quad a \in [0,1] \tag{5}$$

$$C_{tot} = \sum_{i,t} \kappa_{i,t}^{endo} \cdot I_{i,t}^{+} + \pi_{i,t} \cdot mc_{i,t} \tag{6}$$

The temporally high resolution RLDC data can be aggregated in order to reduce the computational time, and are in the standard setting divided into $\hat{j}$=50 slices ($j \in \{1,2,3,...,\hat{j}\}$) within each year. ERE production (cumulated negative residual load) is assumed as an input for power-to-X, with the additional option to add the electricity mix as an electricity source.

Processes based on biomass crops, biomass residues and electricity (PtX) are included. In order to capture the complexities involved in a sufficient detail, an intra-annual temporal resolution is required. Electrolyser capacities are endogenously adapted in order to capture the cost trade-off between electrolyser standing production capacity and their achievable capacity factor which is determined by the aggregated ERE curve (Eqn. 7), where $\hat{E}_j$ is the ERE limit at slice j in year t, and $E_{i,j,t}$ is the ERE used by technology i at the same time point.

$$\hat{E}_{j,t} \geqslant \sum_{i} E_{i,j,t} \tag{7}$$

The capacity restriction is given by Eqn. 8, where the available production capacity $\kappa_{i,t}$ [GW] of technology i is multiplied by the hours per slice (hours per year divided by the set number of intra-year slices $\hat{j}$), which cannot be surpassed by the production at slice j, given by the conversion efficiency $\eta_{i,t}$ of technology i in year t, multiplied by the ERE used by technology i at the same time point, $E_{i,j,t}$ [PJ].

$$\kappa_{i,t} \frac{8760}{\hat{j}} \frac{3.6}{1000} \geqslant \eta_{i,t} \cdot E_{i,j,t} \tag{8}$$

The electricity demand which is not covered by PV, wind or hydro is set as an upper demand for dispatchable power options. The demand is divided into 50 intra-year steps, similarly to the ERE. This is again done in order to more accurately capture the cost of covering the peak residual loads. The biomass and hydrogen used for dispatchable power decreases the renewable fuel production potential for transport (and vice versa). The optimal usage is determined endogenously within the model.

The production $\pi_{i,t}$ for option i in year t is the sum of production in all sectors s (Eqn. 9), with a total demand $\delta_{s,t}$ [PJ] for each sector which sets an upper limit for the total production of all options for each sector in each time point, but does not have to be met (Eqn. 10). The production cannot surpass the capacity available $\kappa_{i,t}$ (Eqn. 11).

$$\pi_{i,t} = \sum_{s} \pi_{i,s,t} \quad \forall (i,s,t) \in (I,S,T) \tag{9}$$

$$\delta_{s,t} \geqslant \sum_{i \in s} \pi_{i,s,t} \quad \forall (i,s,t) \in (I,S,T) \tag{10}$$

$$\pi_{i,t} \leqslant \kappa_{i,t} \quad \forall (i,t) \in (I,T) \tag{11}$$

The production capacity of each option (Eqn 12) is the sum of the capacity in the previous year, $\kappa_{i,t}$ [PJ] and new capacities $\kappa_{i,t+1}^{+}$, minus the capacities $\kappa_{i,t-\hat{t}_i}^{+}$ which have reached the end of their life time $\hat{t}_i$ years. Capacities available at the beginning κ_0 are gradually decommissioned linearly over the time span of one plant life time.

$$\kappa_{i,t+1} = \kappa_{i,t} + \kappa_{i,t+1}^{+} - \kappa_{i,t-\hat{t}_i}^{+} \quad \forall (i,t) \in (I,T) \tag{12}$$

Capacity expansion is subject to the sum of a constant ramp factor r_{min}^{GW} and the product of standing capacity and r_f^{cap} (Eqn. 13), and cannot surpass r_{max}^{GW} (Eqn. 14).

$$\kappa_{i,t+1}^{+} \geqslant r_{min}^{GW} + r_f^{cap} \cdot \kappa_{i,t} \quad \forall (i,t) \in (I,T) \tag{13}$$

$$\kappa_{i,t+1}^{+} \leqslant r_{max}^{GW} \quad \forall (i,t) \in (I,T) \tag{14}$$

The required land for each option is given by the production, divided by yield $Y_{i,t}$ [PJ$_{feed}$ Mha^{-1}] times conversion efficiency $\eta_{i,t}$ [PJ_{fuel} PJ_{feed}^{-1}]. The total land use cannot surpass Λ_t at any time point (Eqn. 15).

$$\Lambda_t \geqslant \sum_{i,f \in \Lambda,s} \pi_{i,f,s,t} \left(Y_{f,t} \cdot \eta_{i,f,t}\right)^{-1} \quad \forall (i,f,s,t) \in (I,F,S,T) \tag{15}$$

The land use $\lambda_{f,t+1}$ by any given crop type at time $(t+1)$ can be maximally increased by $r_{min,\Lambda} + r_\Lambda \cdot \lambda_{f,t}$ (Eqn. 16).

$$\lambda_{f,t+1} \leqslant r_{min}^{\Lambda} + r_f^{\Lambda} \cdot \lambda_{f,t} \quad \forall (f,t) \in (F,T) \tag{16}$$

The usage of biomass residues $\phi_{f,t}$ is restricted by their given potential, and the production potential restricted by the conversion efficiency (Eqn. 17), which is individual for each process-feedstock combination.

$$\phi_{f,t} \geqslant \sum_{i,f \in \Phi,t} \pi_{i,f,s,t} \cdot \eta_{i,f,t}^{-1} \quad \forall (i,s,t) \in (I,S,T) \tag{17}$$

Levelized investment costs for endogenously installed capacities $I_{i,t}^{+}$ (Eqn. 18) and marginal costs $mc_{i,t}$ (Eqn. 19) are summed in the total costs (Eqn. 20). $I_{i,t}^{+}$ are levelized based on a discount rate q and capacity factor $C_f^{i,t}$, which changes over time. The investment costs (capex) for capacities available in the beginning are assumed as sunk costs. Marginal costs (opex) include all input costs (biomass, electricity, H_2, CO_2, secondary feedstocks and heat) and byproduct income $p_{f,t}$ [€ $unit_{in}^{-1}$] times $\dot{m}_{f,i,t}$ [$unit_{in}$ $unit_{out}^{-1}$], operation and maintenance, personnel and infrastructure costs $c_{i,t}^{o,m,l}$.

$$I_{i,t}^{+} = \frac{I_{i,t}^{cap}}{3.6 \cdot C_f^{i,t}} \frac{q(1+q)^T}{(1+q)^T - 1} \quad \forall (i,t) \in (I,T) \tag{18}$$

$$mc_{i,t} = c_{i,t}^{o,m,l} + \sum_f p_{f,t} \dot{m}_{f,i,t} \quad \forall (i,f,t) \in (I,F,T) \tag{19}$$

$$C_{i,t} = I_{i,t}^{+} + mc_{i,t} \quad \forall (i,t) \in (I,T) \tag{20}$$

Sets, parameters and decision variables are summarised in Tables 1, 2 and 3, respectively.

Sets

Table 1: Sets in the modelling. I=tech option, F=feedstock, S=market/sector, T=year/time

Name	Domains	Description
market	*	energy markets
marketCONV	market	
passenger	market	
CH4market	market	
H2market	market	
fuel	*	fuel type options
tech	*	technology options
techDiesel	tech	tech options diesel
techEtOH	tech	tech options ethanol
techCH4fuel	tech	tech options methane fuel
techLNG	tech	tech options LNG fuel
techH2	tech	tech options H_2 fuel
techEV	tech	tech options battery electric vehicle
techCONVth	tech	technlogies in the sector CONVth
techCH4in	tech	technologies that require methane
techInter	tech	technologies that require intermediate CH_4 or H_2
feed	*	feed options
feedResidue	feed	feed options residues
feedCrop	feed	feed options crop based
powerMix	feed	feedstock electricity mix
powerRes	feed	feedstock excess electricity
cat	*	feedstock price categories
year	*	global year time
t	year	model year time points
d	*	model time steps intra year

Parameters

Table 2: Parameters in the modelling.

Name	Symbol	Unit	Description
rampF	r_f^{cap}	-	capacity expansion ramp per year
rampMinGW	r_{min}^{GW}	GW	minimum capacity expansion ramp per year
rampMin	r_{min}^{PJ}	PJ	minimum capacity expansion ramp per year
rampC_GW	r_{max}^{GW}	PJ	maximum capacity expansion ramp per year
rampMinVehicles	r_{min}^{veh}	PJ	minimum vehicle expansion ramp per year
landF	r_f^{land}	-	land use expansion ramp per year
rampFvehicles	r_f^{veh}	-	vehicle fuel type expansion per year
landMin	r_{min}^{Λ}	ha	minimum land use expansion per year
lifeTvehicles	$\hat{t}_{veh}$	a	Vehicle life time
ghgTarget	ε_{tot}	$\mathrm{ktCO_2eq\ PJ^{-1}}$	GHG target
dMax	$\hat{j}$	-	number of time steps intra year
ghgRefCO2	$\varepsilon_{in}^{CO_2}$	$\mathrm{ktCO_2eq\ MtCO_2^{-1}}$	GHG reference for input CO_2 (1000 or zero)
pwrMixMax	$\hat{E}_{el}^{mix}$	PJ	Maximum electricity usage from mix for EVs and H_2 production
landMax	Λ_t	ha	arable land limit
demand	$\delta_{s,t}$	PJ	demand matrix
costInvLevel	$\mathrm{I}_{i,t}^{+}$	$\mathrm{M€\ GW^{-1}}$	investment cost levelized
costMarg	$\mathrm{mc}_{i,t}$	$\mathrm{M€\ PJ^{-1}}$	marginal cost
capF	C_f	-	capacity factor development
cap0	κ_0	GW	initial capacity (continuously decommissioned)
landDmdPJ	$Y_{f,t}^{-1}$	$\mathrm{ha\ PJ_{feed}^{-1}}$	Land demand
feedLandUseInit	$\lambda_{f,t=0}$	ha	Feed land use initial
convEta	$\eta_{i,t}$	$\mathrm{PJ\ PJ_{feed}^{-1}}$	Energetic conversion efficiency feed to main energy carrier
convEtaBiomSpec	$\eta_{i,f,t}$	$\mathrm{PJ\ PJ_{feed}^{-1}}$	Energetic conversion efficiency feed to main energy carrier for each feed type
bioResPot	$\phi_{f,t}$	$\mathrm{PJ_{feed}}$	feed residue potential
bioResPotImport	$\phi_{f,t}^{imp}$	$\mathrm{PJ_{feed}}$	feed residue potential
resImportMax	$\hat{\phi}_t^{imp}$	PJ	Maximal residual feed import
feedPrice	$\mathrm{p}_{t,f,cat}$	$\mathrm{M€\ PJ_{feed}^{-1}}$	feed price
feedPriceImport	$\mathrm{p}_{t,f}^{imp}$	$\mathrm{M€\ PJ_{feed}^{-1}}$	feed price import
heatByprod	$\eta_{t,i}^{th}\ \eta_{t,i}^{-1}$	$\mathrm{PJ_{th}\ PJ^{-1}}$	Heat byproduct per unit of main product
lifeT	$\hat{t}$	a	capacity lifetime for each technology
powerPrice	$\mathrm{p}_{t,i}^{el}$	$\mathrm{M€\ MWh^{-1}}$	electricity price for each sector
heatPrice	p_t^{th}	$\mathrm{M€\ MWh^{-1}}$	heat price development
powerInput	$\dot{m}_i^{el}$	$\mathrm{MWh_{el}\ PJ^{-1}}$	electricity input
heatInput	$\dot{m}_i^{el}$	$\mathrm{MWh_{th}\ PJ^{-1}}$	heat input
CO2input	$\dot{m}_i^{CO_2}$	$\mathrm{MtCO_2\ PJ^{-1}}$	CO_2 feedstock input
CO2price	$\mathrm{p}_t^{CO_2}$	$\mathrm{M€\ MtCO_2}$	CO_2 feedstock price
H2input	$\dot{m}_{t,i}^{H_2}$	$\mathrm{PJ_{H_2}\ PJ^{-1}}$	H2 feedstock input
H2Max	$\delta_{s,t}^{H_2}\ \delta_{s,t}^{-1}$	-	Maximal H_2 share development in each sector
CH4Max	$\delta_{s,t}^{CH_4}\ \delta_{s,t}^{-1}$	-	Maximal CH_4 share development in each sector
LCH4Max	$\delta_{s,t}^{LCH_4}\ \delta_{s,t}^{-1}$	-	Maximal LCH_4 (LNG) share development in each sector
CO2source	$\hat{\dot{m}}_t^{CO_2}$	$\mathrm{MtCO_2}$	CO_2 feedstock maximum source
ghgEmisFeed	$\varepsilon_{f,t}$	$\mathrm{ktCO_2eq\ PJ_{feed}^{-1}}$	Feedstock CO_2 emissions
ghgEmisT1	ε_t^{trans}	$\mathrm{ktCO_2eq\ PJ^{-1}}$	Transport CO_2 emissions
ghgEmisGateWheel	$\varepsilon_{i,t}$	$\mathrm{ktCO_2eq\ PJ^{-1}}$	Gate to tank CO_2 emissions
powerMixEmis	$\varepsilon_t^{el,mix}$	$\mathrm{ktCO_2eq\ PJ_{el}^{-1}}$	Electricity mix emissions
ghgRef	$\varepsilon_{sub,t,s}$	$\mathrm{ktCO_2eq\ PJ^{-1}}$	GHG reference (fossil substitute)
historicFuelDemand	$\delta_{t,fuel}$	PJ	Fuel demand development constraint based on past fleet
newVehicSharePass	(t)	-	share of new vehicles yearly in the passenger road sector
residualLoad	$\hat{E}_{j,t}$	PJ	residualLoad
posResLoad	$\delta_{j,t}^{el}$	PJ	positive residual load = demand for dispatchable power
vehicleKMroadTot	δ_{v-km}	10^9 vehicle-km	total vehicle km in passenger road sector
MJperKMavgICEV	-	PJ (10^9 vehicle-km)$^{-1}$	fuel economy baseline passenger road sector
relativeFuelEconomy	ω_i	-	relative fuel economy between fuels in passenger road sector

Variables

Table 3: Decision variables in the modelling.

Name	Symbol	Unit	Description
cost	C_{tot}	M€	Total system cost
costAnnual	$C_{tot,t}$	M€ a^{-1}	Total system cost yearly
ghgAbatement	ε_{tot}	ktCO_2eq PJ^{-1}	Total GHG abatement
ghgAbateTech	$\varepsilon_{i,t}^{tot}$	ktCO_2eq a^{-1}	technology GHG abatement
inst	$\kappa_{i,t}^{+}$	GW	new installed capacity
cap	$\kappa_{i,t}$	GW	capacity
capNew	$\kappa_{i,t}^{endo}$	GW	endogenously installed standing capacity minus decommissioned capacity
prd	$\pi_{i,s,t}$	PJ	production
prdDaily	$E_{i,j,t,s}$	PJ	dispatchable power production
feedUse	$\dot{m}_{t,i,f,cat}$	PJ	feed used
residualLoadUse	$E_{j,t}$	PJ	residualLoad use
dispatchPrd	$P_{j,t}$	PJ	dispatchable power production
CO2use	$\dot{m}_{t}^{CO_2}$	MtCO_2	CO_2 used
powerUseDaily	$\dot{m}_{t,d,i,f}^{el}$	PJ	electricity used daily
feedUseImport	$\dot{m}_{t,i,f}^{imp}$	PJ	feed import used
newVehicles	$\delta_{t,s,fuel}^{+}$	PJ	new vehicle fuel demand development
vehiclePark	$\delta_{t,s,fuel}$	PJ	vehicle park demand per fuel
decomVehicles	$\delta_{t,s,fuel}^{-}$	PJ	vehicle fuel type decommission
costTech	$C_{t,i}$	M€ a^{-1}	technology cost incl. CAPEX and OPEX

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