Supplementary Material

1 Supplementary Figures

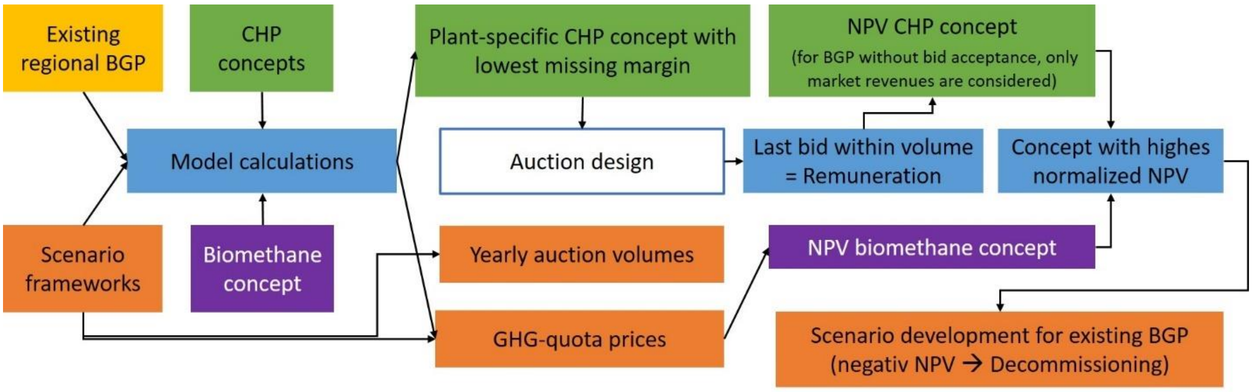

Figure S 1 Flow chart for modeling and scenario methodology including the auction design.

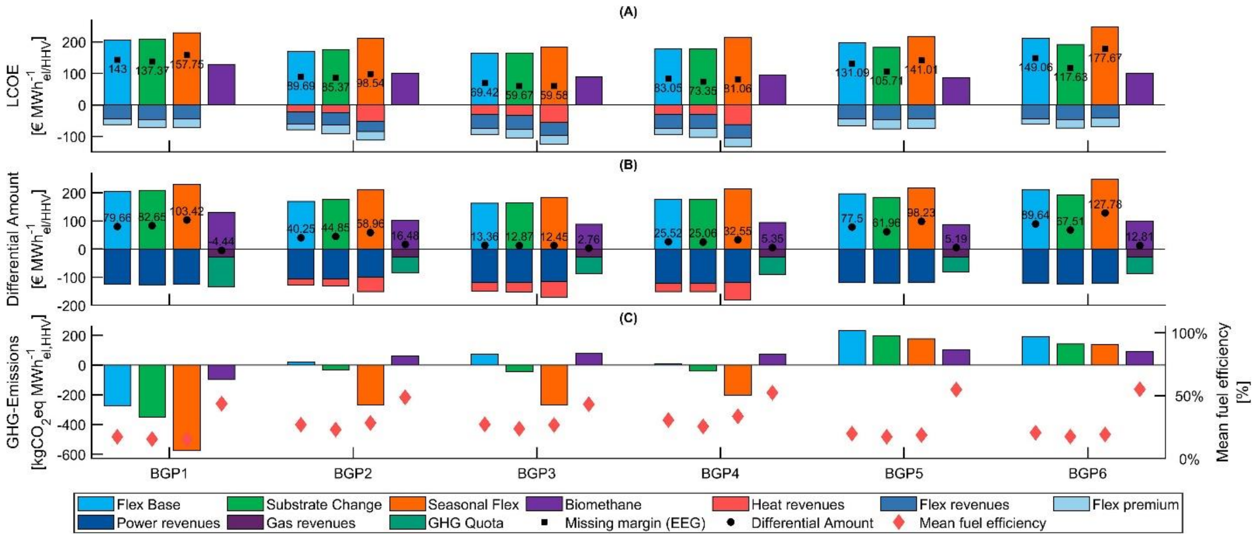

Figure S 2 Comparison of investments (A), NPV and normalized NPV (B) for the follow-up concepts of representative BGP in the Flex++ scenario.

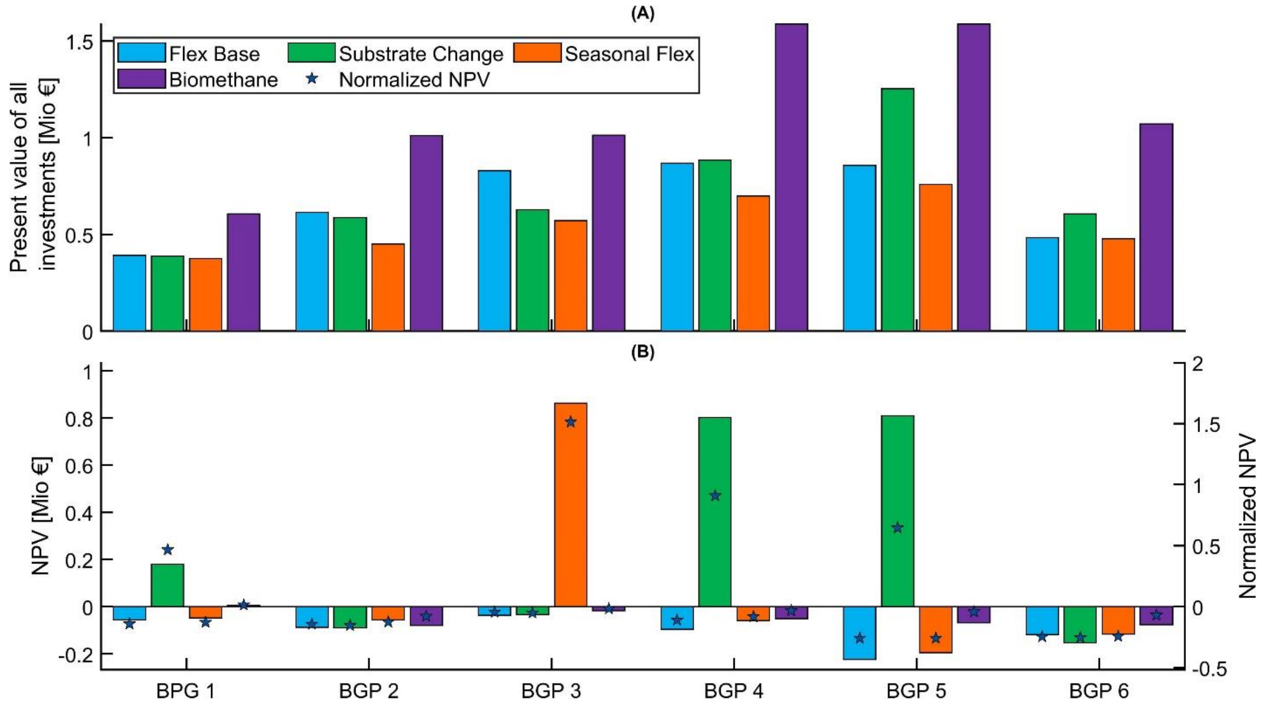

Figure S 3 Comparison of investments (A), NPV and normalized NPV (B) for the follow-up concepts of representative BGP in the EEG-MOD scenario.

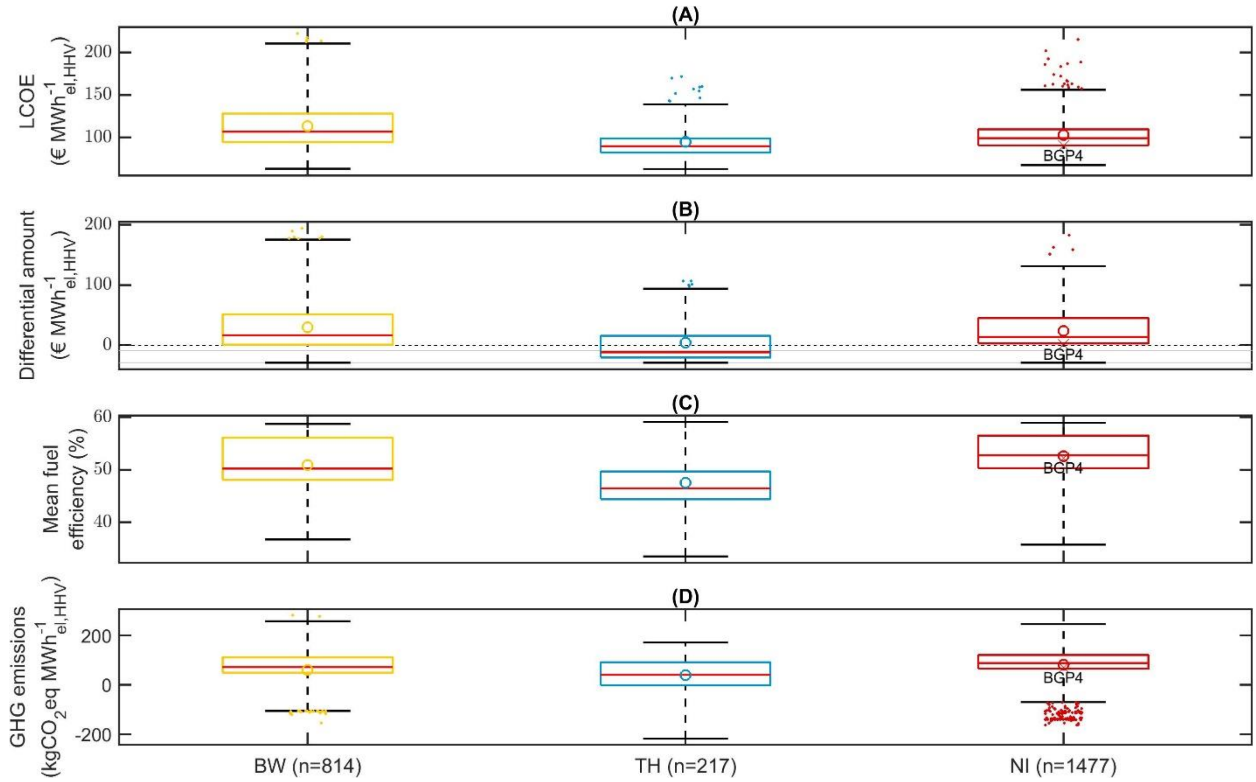

Figure S 4 Regional differences and distribution of KPIs (A-D) for the biomethane concept in the EEG-MOD scenario; BGP4 is additionally marked; Boxplots with a whisker value of 2.5; Circle = Mean value; Dots = Outliers.

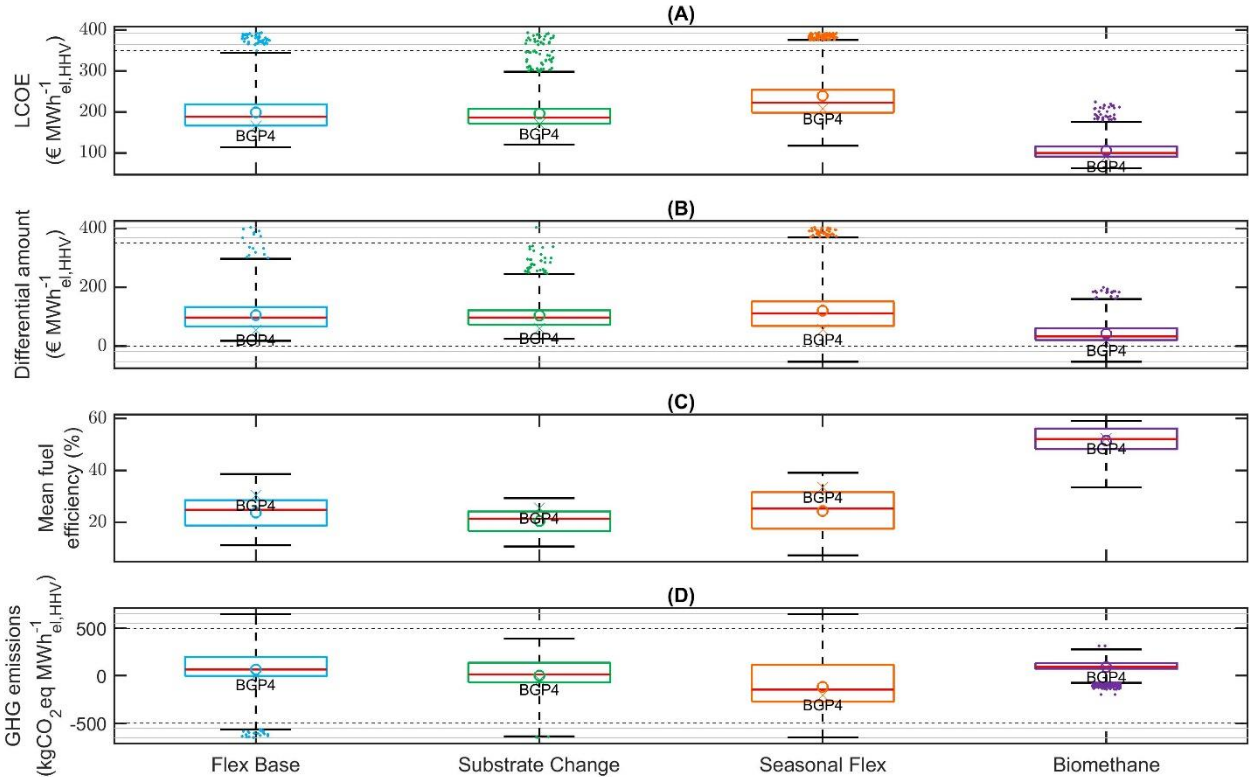

Figure S 5 Comparison of follow-up concepts and distribution of KPI (A-D) in the REF scenario; BGP4 is additionally marked; Boxplots with a whisker value of 2,5; Circle = Mean value; Dots = Outliers.

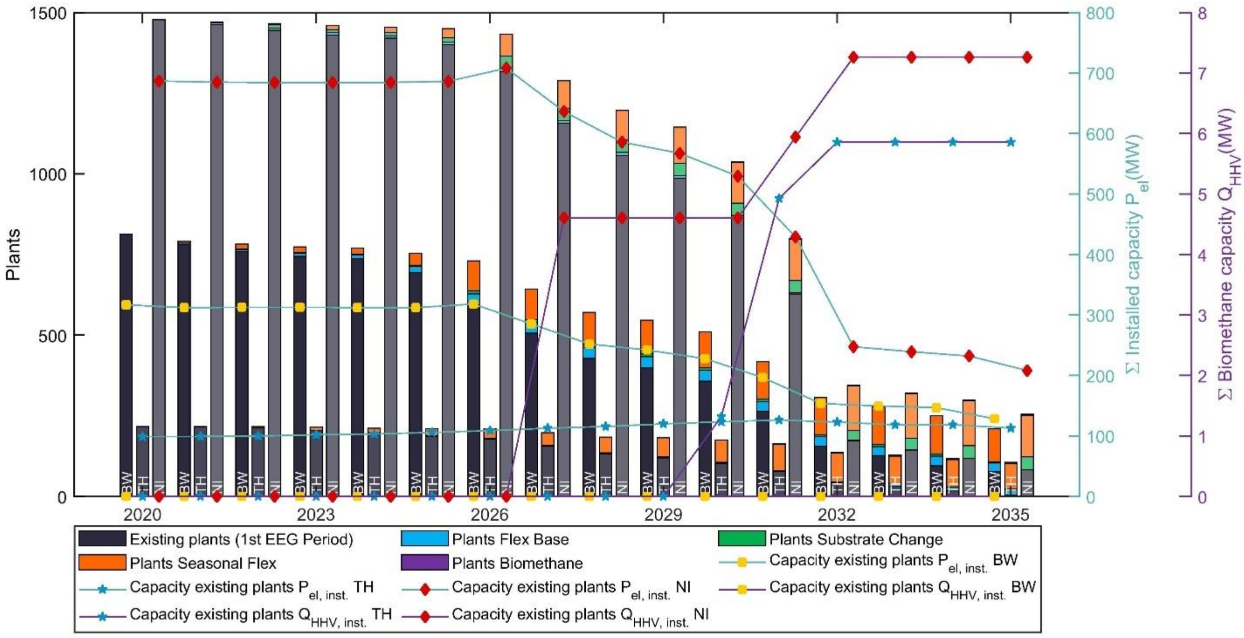

Figure S 6 Regional development of existing plants until 2035 in the REF scenario. Showing distribution of plant-specific implemented follow-up concept, installed electric capacity, and biomethane capacity.

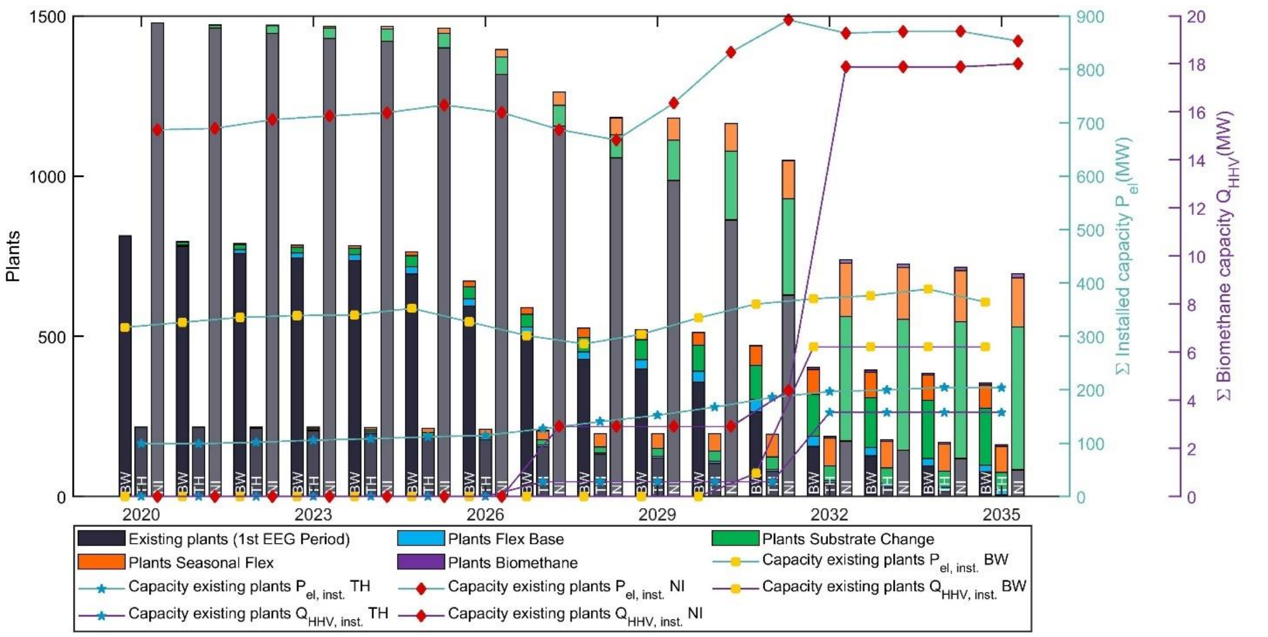

Figure S 7 Regional development of existing plants until 2035 in the Flex++ scenario. Showing distribution of plant-specific implemented follow-up concept, installed electric capacity, and biomethane capacity.

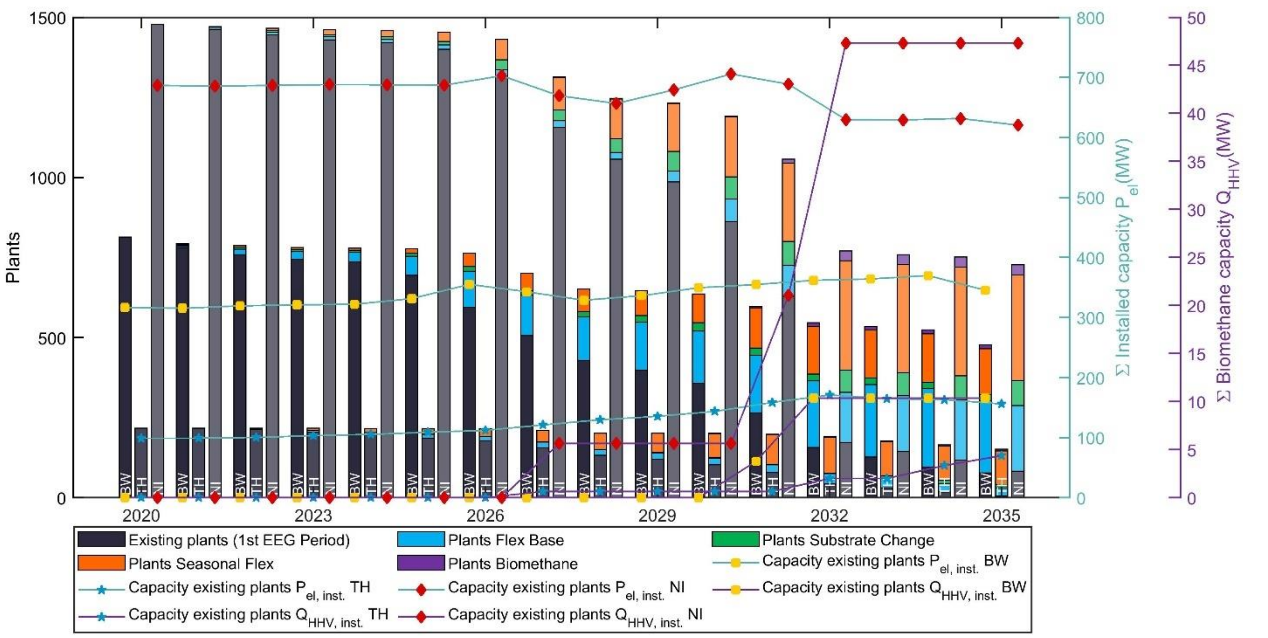

Figure S 8 Regional development of existing plants until 2035 in the EEG-MOD scenario. Showing distribution of plant-specific implemented follow-up concept, installed electric capacity, and biomethane capacity.

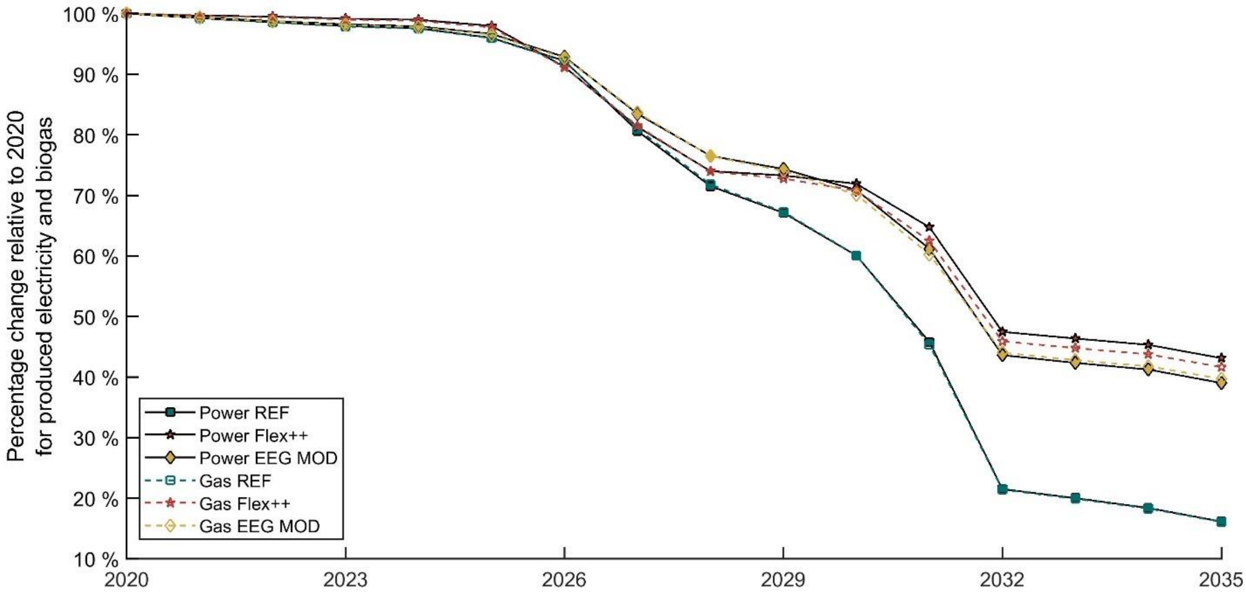

Figure S 9 Development of electricity and biogas production until 2035 in all three regions comparing the three scenarios. Showing relative values to the year 2020.

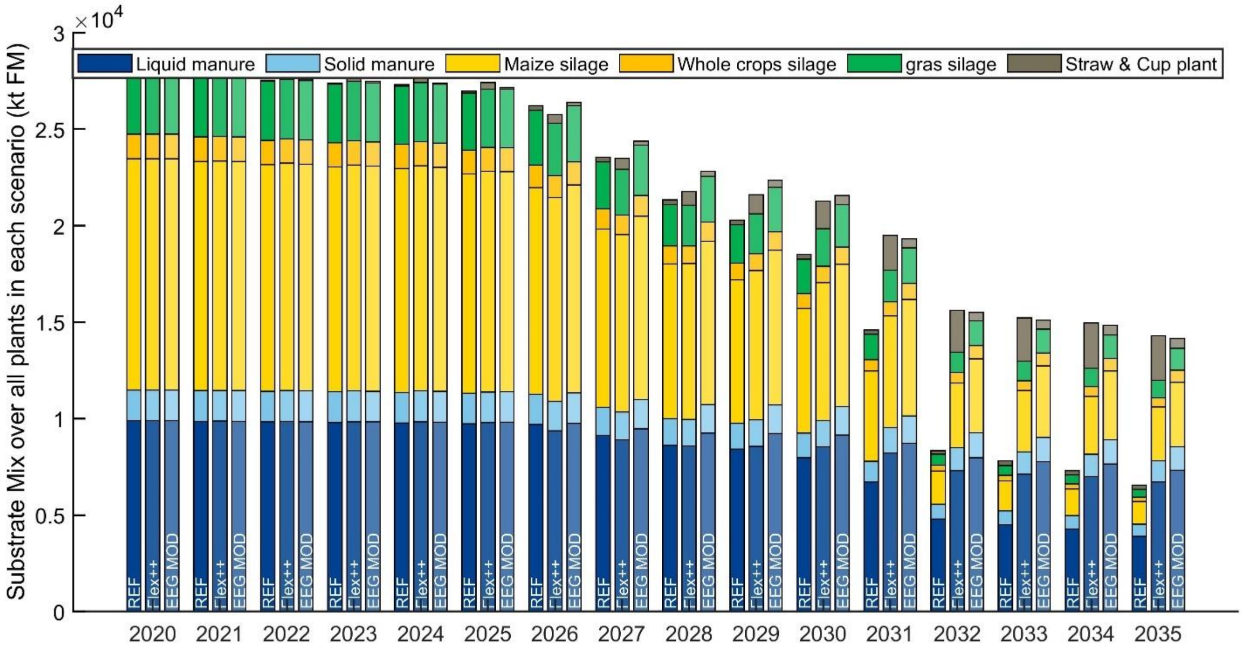

Figure S 10 Development of substrate mix and input until 2035 in all three regions comparing the three scenarios.

2 Supplementary Tables

Table S 1 Regional distribution of process stages according to the BGP size class (Härdtlein et al., 2013; TLL, 2015)

BGP-size class (rated power output)		1	2	3	4	Total
BW	Single stage	28%	30%	15%	13%	22%
	Two stages	72%	70%	85%	88%	78%
TH	Single stage	71%	32%	33%	44%	40%
	Two stages	29%	68%	67%	56%	60%
NI	Single stage	-	-	-	-	30%
	Two stages	-	-	-	-	70%

Table S 2 Regional digester sizes in according to the BGP size class (Härdtlein et al., 2013; TLL, 2015)

BGP-size class (rated power output)		1	2	3	4
BW	Mean	568	1245	1172	1577
	standard deviation	304	613	649	896
TH	Mean	1369	1966	2249	2863
	standard deviation	836	1087	1281	1688
NI	Mean (assumption)	1000	1500	2000	4000

Table S 3 Mean hydraulic retention time in BW according to BGP size class (Härdtlein et al., 2013)

BGP size class (rated power output)		1	2	3	4	Total
BW	Digester (in two stage Systems)	73	72	68	63	69
	Digester (in single stage Systems)	100	88	82	92	89
	Digester & secondary digester	118	121	110	103	113
	Gastight system	135	163	177	158	162

Table S 4 Mean hydraulic retention time for BPG in NI in relation to manure share (Liebetrau et al., 2011)

Manure share [%]		>=55	<55 & >=45	<45 & >=40	<40 & >=37	<37	Factor D/sec. D
NI	Digester (in two stage Systems)	40	50	75	105	120	1.6
	Digester (in single stage Systems)	40	50	75	105	120	1

Table S 5 Distribution of CHP types according to size class (Härdtlein et al., 2013; TLL, 2015)

BGP size class (rated power output)		1	2	3	4	Total
BW	spark-ignition/gas-otto engines	70%	81%	58%	66%	68%
	Duel-fuel engines	30%	19%	42%	34%	32%
TH	spark-ignition/gas-otto engines	50%	71%	91%	94%	83%
	Duel-fuel engines	40%	26%	6%	6%	14%
NI	spark-ignition/gas-otto engines	-	-	-	-	73%
	Duel-fuel engines	-	-	-	-	27%

Table S 6 Effect of the follow-up concept on the characteristic parameters of BGP4 in the Flex++ scenario

Parameter	Unit	Flex Base	Substrate Change	Seasonal Flex	Biomethane
Substrate mix (Manure: Energy crops:Others)	%	45:44:11	40:25:35	65:27:8	41:14:45
Rated power output	kW_{el}	430	429	206	-
Installed capacity	kW_{el}	1720	1717	819	-
Upgrading capacity	Nm^3/h	-	-	-	102
HRT in gas-tight system	d	245	229	365	236
LCOE	€/$MWh_{el,HHV}$	177.3	176.7	213.7	94.3
Missing Margin (EEG)	€/$MWh_{el,HHV}$	83	73	81	-
Differential Amount	€/$MWh_{el,HHV}$	25.5	25.1	32.5	5.3
Normalized NPV	-	-0.2433	-0.2584	-0.1379	-0.1097
Mean fuel efficiency	%	30.46%	25.55%	33.5%	52.24%
GHG-emissions	kg CO_2/ $MWh_{el,HHV}$	7.9	-42.33	-202.27	70.06

Table S 7 Effect of the follow-up concept on the characteristic parameters of BGP4 in the EEG-MOD scenario

Parameter	Unit	Flex Base	Substrate Change	Seasonal Flex	Biomethane
Substrate mix (Manure: Energy crops:Others)	%	45:44:11	40:25:35	65:27:8	41:14:45
Rated power output	kW_{el}	424	424	206	-
Installed capacity	kW_{el}	1290	1288	819	-
Upgrading capacity	Nm^3/h	-	-	-	102
HRT in gas-tight system	d	245	229	365	236
LCOE	$€/MWh_{el,HHV}$	167.78	172.01	205.4	90.34
Missing Margin (EEG)	$€/MWh_{el,HHV}$	89.75	94.06	86.85	-
Differential Amount	$€/MWh_{el,HHV}$	34.83	39.15	38.35	1.37
Normalized NPV	-	-0.2433	-0.2584	-0.1379	-0.1097
Mean fuel efficiency	%	30.15%	25.29%	33.49%	52.24%
GHG-emissions	kg CO_2/ $MWh_{el,HHV}$	8.08	-43.01	-202.61	70.06

Table S 8 Perspectives of the market and framework conditions of the follow-up concepts groups on-site CHP and biomethane upgrading

	On-site CHP	Biomethane upgrading
Trends	• Demand for flexibility rises ➢ Nuclear and coal phase-out ➢ Mandatory expansion of fluctuating renewable energies • Participation in markets is facilitated & harmonized (e.g. regarding balancing power, intraday trading)	• Federal bioenergy strategy towards fuel and process energy • Rising GHG reduction quota in fuel sector (4% to 6% in 2020) • Increasing minimum requirements for permissible „green“ fuels • Rising demand for bio-CNG/LNG in heavy-duty transport and public transport (also due to exhaust emission values) • Associations and major industry are looking for new "green gas" business areas • -European market & exchange is growing
Opportunities	• Auction volumes extended and raised • Degression of maximum bid limit halted • Improvements for small plants (see EEG-MOD scenario) • KWKG improvements lead to an alternative funding path for BGP	• Simpler products compared to electricity market diversification • Revenues from high GHG emission reduction can compensate for economies of scale (e.g. for smaller BGP)
Risks	• No extension of EEG auctions • Complex business models (more markets, more volatility) • Competition from other flexibility options, e.g. batteries with focus balance power → Flex value decreases	• Fuel market volume (CNG) rather small, a saturation of "GHG reduction" may be reached quickly • Market change from upgrading currently supplying EEG biomethane CHP leads to increasing supply → GHG quota price might decrease again
	• Rising substrate costs ➢ Declining yields due to progressing climate change (e.g. increase in droughts) ➢ Rising fertilizer & fuel costs (extension of CO_2 prices in other sectors) ➢ Additional requirements for agricultural practice (e.g. application of farm manure & digestate)	

Table S 9 **Evaluation results of the standardized expert survey (N=40), Criteria weighting and evaluation was done with a Likert-type scale with 5 points from 1 (unimportant) to 5 (very important).**

Evaluation Criteria		**Economic success**	**Acceptance among the population**	**Reduction of GHG emissions**	**Biodiversity**	**Area efficiency**	**Index**	**Rank**
Criteria Weight		4.45	3.36	3.28	2.93	3.28		
Biomethane upgrading	**Upgrading and grid injection**	3.80	2.70	3.00	2.26	2.62	**0.41**	**8**
	Upgrading and local fuel supply in the transport sector	3.73	3.45	3.15	2.23	2.56	**0.43**	**4**
	Pooling of BGPs via microgrids with central upgrading	3.80	3.13	3.10	2.43	2.46	**0.42**	**6**
Flexibilization	**Nationwide marketing of electricity**	3.80	2.60	2.45	2.18	2.33	**0.38**	**11**
	Regional marketing of electricity	3.73	3.65	2.78	2.44	2.46	**0.43**	**5**
	Future system services in the electricity sector	3.85	2.79	2.59	2.21	2.11	**0.39**	**10**
Heat utilization	**Seasonal flexibilization**	4.13	3.48	3.10	2.31	2.44	**0.44**	**3**
	Direct heat use in a gas boiler	3.67	3.15	3.01	2.06	2.09	**0.40**	**9**
Substrate Change	**Alternative energy crops**	3.44	3.79	2.87	3.82	3.38	**0.48**	**2**
	Agricultural residues & manure	4.11	3.58	3.42	3.19	3.39	**0.50**	**1**
Digestate processing		3.63	3.21	3.24	2.05	2.58	**0.42**	**7**

Table S 10 Time series of electricity prices, heat prices, CO_2-quota prices and gas prices, and auction volumes in the different scenarios

Scenario	Year/Parameter	Unit	2020	2025	2030	2035	Based on /Sources
REF	Auction volumes (for bioenergy in Germany)	MW_{el}	200	200	200	200	(Deutscher Bundestag, 2016)
FLEX++			200	500	2000	500	(BBE, 2019)
EEG-MOD			200	500	1500	500	(HBB, 2020)
REF	Ø-Spot price day-ahead -market	€ MWh_{el}^{-1}	34	44	51	65	(Prognos AG et al., 2014; Jenny Winkler, Frank Sensfuß, Martin Pudlik, 2015; Öko-Institut e.V. and Fraunhofer ISI, 2015; Afman et al., 2017; BMUB, 2017; Fernahl et al., 2017; Hermann et al., 2017; Kopiske et al., 2017; Pfluger et al., 2017; Danish Energy Agency, 2018; Lenz et al., 2018; dena, 2018; Nitsch, 2019; Matthes et al., 2019)
FLEX++/EEG-MOD			45	57	65	79	
REF	CO_2-Price outside fuel sector	€ t CO_2-eq $^{-1}$	13	24	33	46	
FLEX++/EEG-MOD			27	48	62	98	
REF	CO_2-quota price fuel sector	€ t CO_2-eq $^{-1}$	150	158	167	175	Assumptions
FLEX++/EEG-MOD			150	175	200	225	
REF/FLEX++/ EEG-MOD	Heat value/price	€ MWh_{th}^{-1}	55	60	64	69	(UBA, 2013)
REF	CO_2-emission for electricity – (internal auxiliary consumption)	kg MWh_{el}^{-1}	499	469	439	419	(Greiner and Hermann, 2016)
FLEX++/EEG-MOD			411	333	256	186	
REF	CO_2-emission for heat – substituted by heat supply via biogas	kg MWh_{th}^{-1}	287	269	252	240	(Thrän et al., 2015)
FLEX++/EEG-MOD			287	250	237	234	

Table S 11 Regional substrate properties & input parameters for the GHG balance of crops (Update of Table 4 in (Güsewell et al., 2019)). GHG emission are calculated according to presented method, Prices based on surveys (Schmehl et al., 2012; Härdtlein et al., 2013; Reinhold, 2015; TLL, 2015; 3N, 2017; Reinhold, 2017) and assumptions.

Typ	Class	DM	Methane yield	GHG emissions			Prices			Yield per area			Diesel usage for cultivation[c)]			Seeds	N demand according to DüV[d)]	N-Min[d)]		
Region				BW	TH	NI	BW	TH	NI	BW	TH	NI	BW	TH	NI			BW	TH	NI
Unit		%FM	Nm^3/t FM	[kg CO_{2eq}/t FM]			[€/t FM]			t FM/ha			l/ha			kg/ha	kg N /ha	kg N/ha		
Corn-Cob-Mix	Energy crop[b]	65	241.81	189.4	179.0	187.5	93	83	90	14	14	14	71.01	57.09	64.99	32.5	200	44	55	45
Grains	Energy crop[b)]	87	320.34	379.4	406.1	324.6	186	145	189	7.71	6.81	8.26	79.05	48.58	72.91	180	230	30	62	51
Whole crop silage	Others	35	109.26	93.8	93.4	80.0	37.21	36.50	36.50	30.55	27.24	34.17	36.02	32.6	33.86	180	230	30	62	44
Millet	Others	28	79.93	37.7	37.4	37.5		30.37[a)]		60	60	60	48.51	43.41	44.72	10	180	0	0	0
Maize silage	Energy crop[b)]	35	112.39	41.8	156.0	69.7	36.01	34.60	41.00	45.25	32.11	39.32	40.65	36.33	37.56	27.5	200	44	55	45
Sugar beet	Others	23	75.54	48.6	34.6	47.7	17.00[a)]	29.40	17.00[a)]	76.1	65.6	75.6	92.92	89.24	91.16	1.8	170	48	76	46
Arable fodder	Others	22	65.19	244.3	243.7	243.9	35.19	30.00[a)]		23	23	23	69.35	64.82	66.54	40	400	0	0	0
Gras silage	Others	35	100.17	133.5	139.5	140.4	28.88	24.10	24.10	17.9	25.4	27.5	69.35	64.82	66.54	40	310	0	43	0
Cup plant	Others	28	72.50	31.1	31.0	31.0	28.00	32.00	30.00	50	50	50	14.135	13.07	13.35	2.75	140	0	0	0
Wheat straw	Others	86	148.55	3.1	3.6	2.9		65.00[a)]		3.084	2.724	3.304	5.3	5.5	4.5	0	0	0	0	0
Maize straw	Others	51	72.57	7.8	8.9	7.3	35.00[a)]	7.8	8.9	5.1	4.6	4.7	5.3	5.5	4.5	0	0	0	0	0
Cow liquid manure	Manure	10	16.7	-54.3	-54.3	-54.3	1.23	4.00[a)]												
Pig liquid manure	Manure	6	12.1	-59.7	-59.7	-59.7	1.53	4.00[a)]												
Cow solid manure	Manure	25	52.6	-96.2	-96.2	-96.2	6.59	5.62[a)]												
Pig solid manure	Manure	25	52.8	-137.9	-137.9	-137.9	1.11	5.62[a)]												
Chicken manure	Manure	45	91.2	-56.0	-56.0	-56.0		17.59[a)]												

a) No regional data available, assumptions based on Germany-wide data (KTBL, 2013), b) according to the corn cap c) Sources: (KTBL, 2013, 2014) d) Sources: (Heckelmann, 2019; Heckelmann and Grimm, 2019; Matuschek, 2019; TLLLR, 2019)

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