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Pre-feasibility Study (Croatia)

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Short Description
The document contains the prefeasibility study for Power2Gas (P2G) hubs for Croatia, in three basic configuration options: collocated with renewable energy or industrial plants or as a greenfield investment. Optimization tool V2.0 is used for obtaining all the results in this pre-feasibility study.

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1. METHODOLOGY

Optimization tool (OT) for sizing and scheduling of power-to-gas (P2G) hubs (<https://www.danup2gas.eu/optimizationtool>) is used within this study for three specific cases in Croatia to assess the current business potential of investments in P2G hubs. The P2G hubs are configured as either a greenfield investment or collocated with an existing renewable energy plant or with an existing industrial plant. In each of these three cases the situation is explored along two axes – one is the level of subsidy for the P2G hub investment (0% or 50%) and the other is the price of natural gas (1x the current price, 10x the current price). All arising 3x2x2=12 situations and results obtained by the optimization tool are analysed and commented.

2. CASE STUDIES

Three locations for potential P2G investments are considered for the case of Croatia. The first one is industrial plant Petrokemija Kutina (eng. petrochemistry Kutina), which is the largest petrochemical industry in Croatia, with a large consumption of natural gas. In the following it is denoted as Industrial Plant or IP in short. The second location considered is Tvornica ulja Čepin (eng. oil factory Čepin), which is a factory that has a photovoltaic plant within its facilities – it is noted as Renewable energy plant in the following, or REP in short. Advantage of this facility is its own biowaste which is an opportunity for P2G processes deployment. The third one is a greenfield location (noted as GF in short) at the location Karlovac-Dubovac. On this location there is a possibility to connect both to the electricity and gas networks nearby.

3. RESULTS

3.1 SUMMARY

For each one of case studies (IP, REP and GF), variations of methane prices and subsidies are considered. The considered cases are summarized in Table 1, with a short summary of the result obtained by the optimization tool applied in each.

Table 1. Simulation cases

	Conservative prices of methane			Higher prices of methane		
	No increase IP	No increase REP	No increase GF	10x increase IP	10x increase REP	10x increase GF
No subsidy	Combined heat and power, Fig. 1	No investment, Fig. 2	No investment, Fig. 3	Continuous production of biomethane (smaller during summer) Fig. 7	Periodic production of biomethane (only in winter), Fig. 8	Periodic production of biomethane (only in winter), Fig. 9
Subsidy of 50 %	Combined heat and power, Fig. 4	Combined heat and power in summer, Fig. 5	Combined heat and power in summer, Fig. 6	Continuous production of biomethane (smaller during summer) Fig. 10	Periodic production of biomethane (only in winter), Fig. 11	Periodic production of biomethane (only in winter), Fig. 12

Every solution from Table 1 is obtained using the simulation period of one complete year and electrical consumption/production sampling of 24h. Varying simulation periods and electrical sampling could give slightly different solutions. Optimization tool is in the background using GLPK free linear programming solver to solve the created optimization problems in the mentioned cases.

Increases of methane prices noted as “10x increase” refer to the increases in the “Gas price without grid/operator fees, including taxes”, which is an attribute in the Gas prices section of the Excel interface of the OT. Its conservative value (“1x”) is set to be 0.1 €/kWh for the winter period and 0.06 €/kWh for the summer period. Grid fees and taxes of gas price are not affected with this increase. All set inputs for the case studies may be checked in the annexed OT Excel interface documents for all the considered 12 scenarios. They are given in a zip file with Excel names clearly indicating each of the 12 simulation cases. Detailed results of simulations are given and analysed in the following sections.

3.2 RESULTS WITH CURRENT GAS PRICES WITHOUT SUBSIDIES

In Figures 1 to 3, results for cases with current gas prices without any subsidies are depicted. With conservative prices of methane, best investment option is building combined heat and power (CHP) plant for P2G next to industrial plant. It is shown that biomethane production is not economically feasible with current gas prices as it is shown in Figures 1 to 3.

Investment specifications		
Element	Cost	Size
Processes	Dry anaerobic digester	0,00 € 0,000000 kg/s
	Wet anaerobic digester	0,00 € 0,000000 kg/s
	Dry biomass to biochar plant	0,00 € 0,000000 kg/s
	Wet biomass to biochar plant	0,00 € 0,000000 kg/s
	Combined heat and power (CHP)	30.000.000,00 € 10.000,00 kWe
	Carbon capture plant	0,00 € 0,000000 mol/s
	Gasification + water gas shift plant	0,00 € 0,000000 kg/s
	Methanation reactor	0,00 € 0,000000 mol/s
	Electrolyser	0,00 € 0,00 kW
	Demineralizer	0,00 € 0,000000 mol/s
	Precipitation collector	0,00 € 0,00 m ²
	Heat exchanger	1.250.000,00 € 12.500,00 kW
	Gas compressor station	0,00 € 0,0000 kWe
	Total for processes	31.250.000,00 €
Storages	Dry biomass storage	0,00 € 0,00 kg
	Wet biomass storage	0,00 € 0,00 kg
	Biochar storage	0,00 € 0,00 kg
	Biogas storage	0,00 € 0,00 kg
	Hydrogen storage tank	0,00 € 0,00 kg
	Oxygen storage tank	0,00 € 0,00 kg
	Methane storage tank	0,00 € 0,00 kg
	Syngas storage tank	0,00 € 0,00 kg
	Carbon dioxide storage tank	0,00 € 0,00 kg
	Water storage tank	0,00 € 0,00 m ³
	Total for storages	0,00 €
Connections enlargement	Electrical connection	0,00 € 0,00 MW
	Gas connection	0,00 € 0,00 MW
	Water connection	0,00 € 0,00 m ³ /h
	Total for connections	0,00 €
Total investment		31.250.000,00 €
Payoff period		10,44 years

Operational costs for selected period		
	Cost	Amount
Electrical energy	Produced by REP	0,00 € 0,00 MWh
	Consumed by IP	34.259.995,00 € 102.200,00 MWh
	Net consumption without investment	34.259.995,00 € 102.200,00 MWh
	Mean peak power without investment	490.000,00 € 11,67 MW
	Consumed by P2G	-24.827.752,21 € -87.600,00 MWh
	Net consumption with investment	4.894.285,00 € 14.600,00 MWh
	Mean peak power with investment	70.000,00 € 1,67 MW
Heat	Produced by REP	0,00 € 0,00 MWh
	Produced IP	0,00 € 678.900,00 MWh
	Net production without investment	0,00 € 678.900,00 MWh
	Consumed by P2G	0,00 € -109.500,00 MWh
	Net production with investment	0,00 € 788.400,00 MWh
Gas (methane) to/from the grid	Produced by REP	0,00 € 0,00 MWh
	Consumed by IP	558.309.253,75 € 6.057.529,54 MWh
	Net consumption without investment	558.309.253,75 € 6.057.529,54 MWh
	Produced by P2G	-20.310.905,90 € -220.368,75 MWh
	Net consumption with investment	578.620.159,64 € 6.277.898,29 MWh
Water	Water from the grid consumed by P2G	0,00 € 0,00 m ³
	Collected precipitation consumed by P2	n/a € 0,00 m ³
Input materials	Dry biomass bought	0,00 € 0,00 t
	Wet biomass bought	0,00 € 0,00 t
	Biochar bought	0,00 € 0,00 t
	Total cost of input materials	0,00 €
Additional sales	Hydrogen sold (in bottles)	0,00 € 0,00 t
	Oxygen sold (in bottles)	0,00 € 0,00 t
	Methane sold (in bottles)	0,00 € 0,00 t
	Biochar sold	0,00 € 0,00 t
	Total revenue from additional sales	0,00 €
Residues	Residue from dry anaerobic digester	0,00 € 0,00 t
	Residue from wet anaerobic digester	0,00 € 0,00 t
	Tar from gasification + water gas shift p	0,00 € 0,00 t
	CO2 emitted	2.168.100,00 € 43.362,00 t
	Total cost of residues	2.168.100,00 €
	Total operational cost without investment	593.059.248,75 €
Total operational cost with investment		585.752.544,64 €
Savings with introduction of P2G		7.306.704,11 €

Fig. 1 Results for optimal P2G hub next to IP with conservative prices of methane and no subsidy (Results sheet of the Optimization tool)

This case shows that optimal scenario for current prices of gas and IP nearby is building combined heat and power plant of maximal available size defined in the tool (10 MW). Electricity produced is used for IP directly since production from CHP is cheaper than buying electricity from the grid with parameters used. Apart from investment in CHP, investment in heat exchanger is necessary to accommodate the heat produced. That investment would become profitable after 10.44 years.

Investment specifications			
	Element	Cost	Size
Processes	Dry anaerobic digester	0,00 €	0,000000 kg/s
	Wet anaerobic digester	0,00 €	0,000000 kg/s
	Dry biomass to biochar plant	0,00 €	0,000000 kg/s
	Wet biomass to biochar plant	0,00 €	0,000000 kg/s
	Combined heat and power (CHP)	0,00 €	0,00 kWe
	Carbon capture plant	0,00 €	0,000000 mol/s
	Gasification + water gas shift plant	0,00 €	0,000000 kg/s
	Methanation reactor	0,00 €	0,000000 mol/s
	Electrolyser	0,00 €	0,00 kW
	Demineralizer	0,00 €	0,000000 mol/s
	Precipitation collector	0,00 €	0,00 m ²
	Heat exchanger	0,00 €	0,00 kW
	Gas compressor station	0,00 €	0,0000 kWe
	Total for processes	0,00 €	
Storages	Dry biomass storage	0,00 €	0,00 kg
	Wet biomass storage	0,00 €	0,00 kg
	Biochar storage	0,00 €	0,00 kg
	Biogas storage	0,00 €	0,00 kg
	Hydrogen storage tank	0,00 €	0,00 kg
	Oxygen storage tank	0,00 €	0,00 kg
	Methane storage tank	0,00 €	0,00 kg
	Syngas storage tank	0,00 €	0,00 kg
	Carbon dioxide storage tank	0,00 €	0,00 kg
	Water storage tank	0,00 €	0,00 m ³
	Total for storages	0,00 €	
Connections engagement	Electrical connection	0,00 €	0,00 MW
	Gas connection	0,00 €	0,00 MW
	Water connection	0,00 €	0,00 m ³ /h
	Total for connections	0,00 €	
	Total investment	0,00 €	
	Payoff period	n/a	years

Operational costs for selected period			
		Cost	Amount
Electrical energy	Produced by REP	700.902,18 €	2.473,00 MWh
	Consumed by IP	0,00 €	0,00 MWh
	Net consumption without investment	-700.902,18 €	-2.473,00 MWh
	Mean peak power without investment	0,00 €	0,00 MW
	Consumed by P2G	0,00 €	0,00 MWh
	Net consumption with investment	-700.902,18 €	-2.473,00 MWh
	Mean peak power with investment	0,00 €	0,00 MW
Heat	Produced by REP	0,00 €	0,00 MWh
	Produced IP	0,00 €	0,00 MWh
	Net production without investment	0,00 €	0,00 MWh
	Consumed by P2G	0,00 €	0,00 MWh
	Net production with investment	0,00 €	0,00 MWh
Gas (methane) to/from the grid	Produced by REP	0,00 €	0,00 MWh
	Consumed by IP	0,00 €	0,00 MWh
	Net consumption without investment	0,00 €	0,00 MWh
	Net consumption with investment	0,00 €	0,00 MWh
Water	Water from the grid consumed by P2G	0,00 €	0,00 m ³
	Collected precipitation consumed by P2G	n/a	0,00 m ³
Input materials	Dry biomass bought	0,00 €	0,00 t
	Wet biomass bought	0,00 €	0,00 t
	Biochar bought	0,00 €	0,00 t
	Total cost of input materials	0,00 €	
Additional sales	Hydrogen sold (in bottles)	0,00 €	0,00 t
	Oxygen sold (in bottles)	0,00 €	0,00 t
	Methane sold (in bottles)	0,00 €	0,00 t
	Biochar sold	0,00 €	0,00 t
	Total revenue from additional sales	0,00 €	
Residues	Residue from dry anaerobic digester	0,00 €	0,00 t
	Residue from wet anaerobic digester	0,00 €	0,00 t
	Tar from gasification + water gas shift plant	0,00 €	0,00 t
	CO ₂ emitted	0,00 €	0,00 t
	Total cost of residues	0,00 €	
Total operational cost without investment		-700.902,18 €	
Total operational cost with investment		-700.902,18 €	
Savings with introduction of P2G		0,00 €	

Fig. 2 Results for optimal P2G hub next to REP with conservative prices of methane and no subsidy

For the scenario with current prices of gas and without subsidies, P2G hub next to REP is not economically feasible for investment. With payoff period set to 20 years and investment prices used for the OT, optimal solution is not to invest. Only revenues in this case come from electricity produced from REP which is then sold to the grid.

Investment specifications			
	Element	Cost	Size
Processes	Dry anaerobic digester	0,00 €	0,000000 kg/s
	Wet anaerobic digester	0,00 €	0,000000 kg/s
	Dry biomass to biochar plant	0,00 €	0,000000 kg/s
	Wet biomass to biochar plant	0,00 €	0,000000 kg/s
	Combined heat and power (CHP)	0,00 €	0,00 kWe
	Carbon capture plant	0,00 €	0,000000 mol/s
	Gasification + water gas shift plant	0,00 €	0,000000 kg/s
	Methanation reactor	0,00 €	0,000000 mol/s
	Electrolyser	0,00 €	0,00 kW
	Deminerallizer	0,00 €	0,000000 mol/s
	Precipitation collector	0,00 €	0,00 m ²
	Heat exchanger	0,00 €	0,00 kW
	Gas compressor station	0,00 €	0,0000 kWe
	Total for processes	0,00 €	
Storages	Dry biomass storage	0,00 €	0,00 kg
	Wet biomass storage	0,00 €	0,00 kg
	Biochar storage	0,00 €	0,00 kg
	Biogas storage	0,00 €	0,00 kg
	Hydrogen storage tank	0,00 €	0,00 kg
	Oxygen storage tank	0,00 €	0,00 kg
	Methane storage tank	0,00 €	0,00 kg
	Syngas storage tank	0,00 €	0,00 kg
	Carbon dioxide storage tank	0,00 €	0,00 kg
	Water storage tank	0,00 €	0,00 m ³
	Total for storages	0,00 €	
Connections enlargement	Electrical connection	0,00 €	0,00 MW
	Gas connection	0,00 €	0,00 MW
	Water connection	0,00 €	0,00 m ³ /h
	Total for connections	0,00 €	
	Total investment	0,00 €	
	Payoff period	n/a	years

Operational costs for selected period			
		Cost	Amount
Electrical energy	Produced by REP	0,00 €	0,00 MWh
	Consumed by IP	0,00 €	0,00 MWh
	Net consumption without investment	0,00 €	0,00 MWh
	Mean peak power without investment	0,00 €	0,00 MW
	Consumed by P2G	0,00 €	0,00 MWh
	Net consumption with investment	0,00 €	0,00 MWh
	Mean peak power with investment	0,00 €	0,00 MW
Heat	Produced by REP	0,00 €	0,00 MWh
	Produced IP	0,00 €	0,00 MWh
	Net production without investment	0,00 €	0,00 MWh
	Consumed by P2G	0,00 €	0,00 MWh
	Net production with investment	0,00 €	0,00 MWh
Gas (methane) to/from the grid	Produced by REP	0,00 €	0,00 MWh
	Consumed by IP	0,00 €	0,00 MWh
	Net consumption without investment	0,00 €	0,00 MWh
	Net consumption with investment	0,00 €	0,00 MWh
Water	Water from the grid consumed by P2G	0,00 €	0,00 m ³
	Collected precipitation consumed by P2G	n/a	0,00 m ³
Input materials	Dry biomass bought	0,00 €	0,00 t
	Wet biomass bought	0,00 €	0,00 t
	Biochar bought	0,00 €	0,00 t
	Total cost of input materials	0,00 €	
Additional sales	Hydrogen sold (in bottles)	0,00 €	0,00 t
	Oxygen sold (in bottles)	0,00 €	0,00 t
	Methane sold (in bottles)	0,00 €	0,00 t
	Biochar sold	0,00 €	0,00 t
	Total revenue from additional sales	0,00 €	
Residues	Residue from dry anaerobic digester	0,00 €	0,00 t
	Residue from wet anaerobic digester	0,00 €	0,00 t
	Tar from gasification + water gas shift plant	0,00 €	0,00 t
	CO ₂ emitted	0,00 €	0,00 t
	Total cost of residues	0,00 €	
	Total operational cost without investment	0,00 €	
	Total operational cost with investment	0,00 €	
	Savings with introduction of P2G	0,00 €	

Fig. 3 Results for optimal P2G hub as GF with conservative prices of methane and no subsidy

Building P2G hub as GF investment shows, as in the previous case with REP, that it is not profitable with conservative prices of gas and without any subsidies since no investment would become profitable in the selected maximum payoff period of 20 years and for the parameters used.

3.3 RESULTS WITH CURRENT GAS PRICES WITH SUBSIDIES

Subsidies are common with big investments in green energy and infrastructure. Following figures show results for scenarios where subsidies are included. Although the OT can use different subsidies for each part of the P2G hub, Figures 4 to 6 show results for scenarios with current gas prices and subsidies on all investment in amount of 50%.

Investment specifications			
	Element	Cost	Size
Processes	Dry anaerobic digester	0,00 €	0,000000 kg/s
	Wet anaerobic digester	0,00 €	0,000000 kg/s
	Dry biomass to biochar plant	0,00 €	0,000000 kg/s
	Wet biomass to biochar plant	0,00 €	0,000000 kg/s
	Combined heat and power (CHP)	15.000.000,00 €	10.000,00 kWe
	Carbon capture plant	0,00 €	0,000000 mol/s
	Gasification + water gas shift plant	0,00 €	0,000000 kg/s
	Methanation reactor	0,00 €	0,000000 mol/s
	Electrolyser	0,00 €	0,00 kW
	Demineralizer	0,00 €	0,000000 mol/s
	Precipitation collector	0,00 €	0,00 m ²
	Heat exchanger	625.000,00 €	12.500,00 kW
	Gas compressor station	0,00 €	0,0000 kWe
	Total for processes	15.625.000,00 €	
Storages	Dry biomass storage	0,00 €	0,00 kg
	Wet biomass storage	0,00 €	0,00 kg
	Biochar storage	0,00 €	0,00 kg
	Biogas storage	0,00 €	0,00 kg
	Hydrogen storage tank	0,00 €	0,00 kg
	Oxygen storage tank	0,00 €	0,00 kg
	Methane storage tank	0,00 €	0,00 kg
	Syngas storage tank	0,00 €	0,00 kg
	Carbon dioxide storage tank	0,00 €	0,00 kg
	Water storage tank	0,00 €	0,00 m ³
	Total for storages	0,00 €	
Connections enlargement	Electrical connection	0,00 €	0,00 MW
	Gas connection	0,00 €	0,00 MW
	Water connection	0,00 €	0,00 m ³ /h
	Total for connections	0,00 €	
	Total investment	15.625.000,00 €	
	Payoff period	7,72 years	

Operational costs for selected period			
		Cost	Amount
Electrical energy	Produced by REP	0,00 €	0,00 MWh
	Consumed by IP	34.259.995,00 €	102.200,00 MWh
	Net consumption without investment	34.259.995,00 €	102.200,00 MWh
	Mean peak power without investment	490.000,00 €	11,67 MW
	Consumed by P2G	-24.827.752,21 €	-87.600,00 MWh
	Net consumption with investment	4.894.285,00 €	14.600,00 MWh
	Mean peak power with investment	70.000,00 €	1,67 MW
Heat	Produced by REP	0,00 €	0,00 MWh
	Produced IP	0,00 €	678.900,00 MWh
	Net production without investment	0,00 €	678.900,00 MWh
	Consumed by P2G	0,00 €	-109.500,00 MWh
	Net production with investment	0,00 €	788.400,00 MWh
Gas (methane) to/from the grid	Produced by REP	0,00 €	0,00 MWh
	Consumed by IP	558.309.253,75 €	6.057.529,54 MWh
	Net consumption without investment	558.309.253,75 €	6.057.529,54 MWh
	Produced by P2G	-20.310.905,90 €	-220.368,75 MWh
	Net consumption with investment	578.620.159,64 €	6.277.898,29 MWh
Water	Water from the grid consumed by P2G	0,00 €	0,00 m ³
	Collected precipitation consumed by P2	n/a	0,00 m ³
Input materials	Dry biomass bought	0,00 €	0,00 t
	Wet biomass bought	0,00 €	0,00 t
	Biochar bought	0,00 €	0,00 t
	Total cost of input materials	0,00 €	
Additional sales	Hydrogen sold (in bottles)	0,00 €	0,00 t
	Oxygen sold (in bottles)	0,00 €	0,00 t
	Methane sold (in bottles)	0,00 €	0,00 t
	Biochar sold	0,00 €	0,00 t
	Total revenue from additional sales	0,00 €	
Residues	Residue from dry anaerobic digester	0,00 €	0,00 t
	Residue from wet anaerobic digester	0,00 €	0,00 t
	Tar from gasification + water gas shift p	0,00 €	0,00 t
	CO2 emitted	2.168.100,00 €	43.362,00 t
	Total cost of residues	2.168.100,00 €	
	Total operational cost without investment	593.059.248,75 €	
	Total operational cost with investment	585.752.544,64 €	
	Savings with introduction of P2G	7.306.704,11 €	

Fig. 4 Results for optimal P2G hub next to IP with conservative prices of methane and subsidy of 50%

For the case of IP collocation, adding subsidy did not change the optimal size of the P2G hub comparing to the case without subsidies. Figure 4 shows that adding subsidies when investing in P2G next to IP provided same size of CHP as in the scenario for IP without subsidy which is shown in Figure 1. The only major difference is in the investment costs which are now 50% smaller and that reduces the payoff period significantly.

Investment specifications			
	Element	Cost	Size
Processes	Dry anaerobic digester	0,00 €	0,000000 kg/s
	Wet anaerobic digester	0,00 €	0,000000 kg/s
	Dry biomass to biochar plant	0,00 €	0,000000 kg/s
	Wet biomass to biochar plant	0,00 €	0,000000 kg/s
	Combined heat and power (CHP)	15.000.000,00 €	10.000,00 kWe
	Carbon capture plant	0,00 €	0,000000 mol/s
	Gasification + water gas shift plant	0,00 €	0,000000 kg/s
	Methanation reactor	0,00 €	0,000000 mol/s
	Electrolyser	0,00 €	0,00 kW
	Demineralizer	0,00 €	0,000000 mol/s
	Precipitation collector	0,00 €	0,00 m ²
	Heat exchanger	625.000,00 €	12.500,00 kW
	Gas compressor station	0,00 €	0,0000 kWe
	Total for processes	15.625.000,00 €	
Storages	Dry biomass storage	0,00 €	0,00 kg
	Wet biomass storage	0,00 €	0,00 kg
	Biochar storage	0,00 €	0,00 kg
	Biogas storage	0,00 €	0,00 kg
	Hydrogen storage tank	0,00 €	0,00 kg
	Oxygen storage tank	0,00 €	0,00 kg
	Methane storage tank	0,00 €	0,00 kg
	Syngas storage tank	0,00 €	0,00 kg
	Carbon dioxide storage tank	0,00 €	0,00 kg
	Water storage tank	0,00 €	0,00 m ³
	Total for storages	0,00 €	
Connections enlargement	Electrical connection	987.550,35 €	7,60 MW
	Gas connection	251.562,50 €	25,16 MW
	Water connection	0,00 €	0,00 m ³ /h
	Total for connections	1.239.112,85 €	
	Total investment	16.864.112,85 €	
	Payoff period	13,71 years	

Operational costs for selected period			
		Cost	Amount
Electrical energy	Produced by REP	700.902,18 €	2.473,00 MWh
	Consumed by IP	0,00 €	0,00 MWh
	Net consumption without investment	-700.902,18 €	-2.473,00 MWh
	Mean peak power without investment	0,00 €	0,00 MW
	Consumed by P2G	-12.447.886,73 €	-43.920,00 MWh
	Net consumption with investment	-13.148.788,91 €	-46.393,00 MWh
	Mean peak power with investment	0,00 €	0,00 MW
Heat	Produced by REP	0,00 €	0,00 MWh
	Produced by IP	0,00 €	0,00 MWh
	Net production without investment	0,00 €	0,00 MWh
	Consumed by P2G	0,00 €	-54.900,00 MWh
	Net production with investment	0,00 €	54.900,00 MWh
Gas (methane) to/from the grid	Produced by REP	0,00 €	0,00 MWh
	Consumed by IP	0,00 €	0,00 MWh
	Net consumption without investment	0,00 €	0,00 MWh
	Produced by P2G	-7.861.096,69 €	-110.486,25 MWh
	Net consumption with investment	7.861.096,69 €	110.486,25 MWh
Water	Water from the grid consumed by P2G	0,00 €	0,00 m ³
	Collected precipitation consumed by P2	n/a	0,00 m ³
Input materials	Dry biomass bought	0,00 €	0,00 t
	Wet biomass bought	0,00 €	0,00 t
	Biochar bought	0,00 €	0,00 t
	Total cost of input materials	0,00 €	
Additional sales	Hydrogen sold (in bottles)	0,00 €	0,00 t
	Oxygen sold (in bottles)	0,00 €	0,00 t
	Methane sold (in bottles)	0,00 €	0,00 t
	Biochar sold	0,00 €	0,00 t
	Total revenue from additional sales	0,00 €	
Residues	Residue from dry anaerobic digester	0,00 €	0,00 t
	Residue from wet anaerobic digester	0,00 €	0,00 t
	Tar from gasification + water gas shift p	0,00 €	0,00 t
	CO ₂ emitted	1.087.020,00 €	21.740,40 t
	Total cost of residues	1.087.020,00 €	
	Total operational cost without investment	-700.902,18 €	
	Total operational cost with investment	-4.200.672,22 €	
	Savings with introduction of P2G	3.499.770,04 €	

Fig. 5 Results for optimal P2G hub next to REP with conservative prices of methane and subsidy of 50%

Adding subsidies for the P2G hub next to REP shows that in this case there is a profitable investment. Equally as in the case of P2G next to IP, optimal investment is in CHP of maximum size allowed in parameters (10 MW). Unlike in the case with IP, this solution also requires electricity and gas connection enlargements for the CHP. Since there are different prices of gas during winter and summer, CHP in this scenario is only profitable during summer when gas price is cheaper comparing to the winter price. That is why CHP is operating only during summer. Payoff period for this scenario is 13.71 years.

Investment specifications			
	Element	Cost	Size
Processes	Dry anaerobic digester	0,00 €	0,000000 kg/s
	Wet anaerobic digester	0,00 €	0,000000 kg/s
	Dry biomass to biochar plant	0,00 €	0,000000 kg/s
	Wet biomass to biochar plant	0,00 €	0,000000 kg/s
	Combined heat and power (CHP)	15.000.000,00 €	10.000,00 kWe
	Carbon capture plant	0,00 €	0,000000 mol/s
	Gasification + water gas shift plant	0,00 €	0,000000 kg/s
	Methanation reactor	0,00 €	0,000000 mol/s
	Electrolyser	0,00 €	0,00 kW
	Demineralizer	0,00 €	0,000000 mol/s
	Precipitation collector	0,00 €	0,00 m ²
	Heat exchanger	625.000,00 €	12.500,00 kW
	Gas compressor station	0,00 €	0,0000 kWe
	Total for processes	15.625.000,00 €	
Storages	Dry biomass storage	0,00 €	0,00 kg
	Wet biomass storage	0,00 €	0,00 kg
	Biochar storage	0,00 €	0,00 kg
	Biogas storage	0,00 €	0,00 kg
	Hydrogen storage tank	0,00 €	0,00 kg
	Oxygen storage tank	0,00 €	0,00 kg
	Methane storage tank	0,00 €	0,00 kg
	Syngas storage tank	0,00 €	0,00 kg
	Carbon dioxide storage tank	0,00 €	0,00 kg
	Water storage tank	0,00 €	0,00 m ³
	Total for storages	0,00 €	
Connections enlargement	Electrical connection	1.618.967,67 €	10,00 MW
	Gas connection	264.517,48 €	25,16 MW
	Water connection	0,00 €	0,00 m ³ /h
	Total for connections	1.883.485,16 €	
	Total investment	17.508.485,16 €	
	Payoff period	14,24 years	

Operational costs for selected period			
	Cost	Amount	
Electrical energy	Produced by REP	0,00 €	0,00 MWh
	Consumed by IP	0,00 €	0,00 MWh
	Net consumption without investment	0,00 €	0,00 MWh
	Mean peak power without investment	0,00 €	0,00 MW
	Consumed by P2G	-12.447.886,73 €	-43.920,00 MWh
	Net consumption with investment	-12.447.886,73 €	-43.920,00 MWh
	Mean peak power with investment	0,00 €	0,00 MW
Heat	Produced by REP	0,00 €	0,00 MWh
	Produced IP	0,00 €	0,00 MWh
	Net production without investment	0,00 €	0,00 MWh
	Consumed by P2G	0,00 €	-54.900,00 MWh
	Net production with investment	0,00 €	54.900,00 MWh
Gas (methane) to/from the grid	Produced by REP	0,00 €	0,00 MWh
	Consumed by IP	0,00 €	0,00 MWh
	Net consumption without investment	0,00 €	0,00 MWh
	Produced by P2G	-7.903.523,41 €	-110.486,25 MWh
	Net consumption with investment	7.903.523,41 €	110.486,25 MWh
Water	Water from the grid consumed by P2G	0,00 €	0,00 m ³
	Collected precipitation consumed by P2G	n/a	0,00 m ³
Input materials	Dry biomass bought	0,00 €	0,00 t
	Wet biomass bought	0,00 €	0,00 t
	Biochar bought	0,00 €	0,00 t
	Total cost of input materials	0,00 €	
Additional sales	Hydrogen sold (in bottles)	0,00 €	0,00 t
	Oxygen sold (in bottles)	0,00 €	0,00 t
	Methane sold (in bottles)	0,00 €	0,00 t
	Biochar sold	0,00 €	0,00 t
	Total revenue from additional sales	0,00 €	
Residues	Residue from dry anaerobic digester	0,00 €	0,00 t
	Residue from wet anaerobic digester	0,00 €	0,00 t
	Tar from gasification + water gas shift p	0,00 €	0,00 t
	CO2 emitted	1.087.020,00 €	21.740,40 t
	Total cost of residues	1.087.020,00 €	
	Total operational cost without investment	0,00 €	
	Total operational cost with investment	-3.457.343,32 €	
	Savings with introduction of P2G	3.457.343,32 €	

Fig. 6 Results for optimal P2G hub as GF with conservative prices of methane and subsidy of 50%

Like in the previous case with REP, adding subsidies on the investment costs for GF showed the optimal result that includes an investment into a CHP of maximal size allowed by the current setting in the OT. Again, electricity is sold to the grid during summer only and this scenario becomes profitable after somewhat more than 14 years.

All cases with current prices of gas show similar results that biomethane production is not profitable. Instead of that, using gas from the grid to produce electricity with CHP is profitable, especially in case with IP where the produced electrical energy is used directly at the site. If electricity is not used directly but instead sold to the grid like in cases with REP and GF investments, without subsidies no investment is profitable in under 20 years. After adding 50% of subsidies, investment in CHP is profitable but only for prices of gas during summer which are significantly cheaper than the prices of gas during winter.

3.4 RESULTS WITH INCREASED GAS PRICES WITHOUT SUBSIDIES

Since gas prices are increasing rapidly in last years, scenarios with gas price increase are observed. For the next 6 scenarios (Figures 7 to 12), 10x increase in gas price is used in the OT. Such an abrupt change is made to explore the optimal investment cases that occur when the gas prices outweigh the electricity prices.

Figures 7 to 9 show scenarios for IP, REP and GF without subsidy and Figures 10 to 12 show scenarios with 50% subsidy on the investment cost.

Results show that after this significant gas price increase, biomethane production becomes economically profitable.

Investment specifications				Operational costs for selected period				
Processes	Element	Cost	Size	Electrical energy		Cost	Amount	
	Dry anaerobic digester	2.443.910,26 €	0,116377 kg/s		Produced by REP	0,00 €	0,00 MWh	
	Wet anaerobic digester	2.443.910,26 €	0,116377 kg/s		Consumed by IP	34.259.995,00 €	102.200,00 MWh	
	Dry biomass to biochar plant	0,00 €	0,000000 kg/s		Net consumption without investment	34.259.995,00 €	102.200,00 MWh	
	Wet biomass to biochar plant	0,00 €	0,000000 kg/s		Mean peak power without investment	490.000,00 €	11,67 MW	
	Combined heat and power (CHP)	0,00 €	0,00 kWe		Consumed by P2G	28.643.119,26 €	85.444,46 MWh	
	Carbon capture plant	0,00 €	0,000000 mol/s		Net consumption with investment	62.903.114,26 €	187.644,46 MWh	
	Gasification + water gas shift plant	14.028,80 €	0,014029 kg/s		Mean peak power with investment	899.749,02 €	21,42 MW	
	Methanation reactor	3.205.426,05 €	7,542179 mol/s		Heat	Produced by REP	0,00 €	0,00 MWh
	Electrolyser	11.430.026,35 €	4.572,01 kW			Produced IP	0,00 €	678.900,00 MWh
	Demineralizer	1.156,05 €	11,560518 mol/s			Net production without investment	0,00 €	678.900,00 MWh
	Precipitation collector	2.000,00 €	1.000,00 m ²			Consumed by P2G	0,00 €	-17.298,91 MWh
	Heat exchanger	227.944,10 €	2.279,44 kW			Net production with investment	0,00 €	696.198,91 MWh
	Gas compressor station	202.112,95 €	252,6412 kWe		Gas (methane) to/from the grid	Produced by REP	0,00 €	0,00 MWh
	Total for processes	19.970.514,82 €				Consumed by IP	4.916.743.244,83 €	6.057.529,54 MWh
Storages	Dry biomass storage	100.000,00 €	10.000,00 kg	Net consumption without investment		4.916.743.244,83 €	6.057.529,54 MWh	
	Wet biomass storage	50.000,00 €	10.000,00 kg	Produced by P2G		34.425.075,97 €	47.431,04 MWh	
	Biochar storage	15.000,00 €	1.000,00 kg	Net consumption with investment		4.877.092.883,32 €	6.010.098,50 MWh	
	Biogas storage	0,00 €	0,00 kg	Water	Water from the grid consumed by P2G	648,02 €	5.445,57 m ³	
	Hydrogen storage tank	0,00 €	0,00 kg		Collected precipitation consumed by P2G	n/a €	867,19 m ³	
	Oxygen storage tank	0,00 €	0,00 kg		Input materials	Dry biomass bought	24.839,02 €	3.650,00 t
	Methane storage tank	0,00 €	0,00 kg	Wet biomass bought		27.995,44 €	2.962,00 t	
	Syngas storage tank	0,00 €	0,00 kg	Biochar bought		0,00 €	0,00 t	
	Carbon dioxide storage tank	0,00 €	0,00 kg	Total cost of input materials		52.834,46 €		
	Water storage tank	0,00 €	0,00 m ³	Additional sales		Hydrogen sold (in bottles)	0,00 €	0,00 t
Total for storages	165.000,00 €		Oxygen sold (in bottles)		25.550,00 €	365,00 t		
Connections enhancement	Electrical connection	0,00 €	0,00 MW		Methane sold (in bottles)	0,00 €	0,00 t	
	Gas connection	0,00 €	0,00 MW		Biochar sold	21.960,00 €	183,00 t	
	Water connection	23,12 €	0,75 m ³ /h		Total revenue from additional sales	47.510,00 €		
	Total for connections	23,12 €		Residues	Residue from dry anaerobic digester	0,00 €	109,50 t	
	Total investment	20.135.537,94 €			Residue from wet anaerobic digester	0,00 €	444,30 t	
	Payoff period	7,10 years			Tar from gasification + water gas shift plant	0,00 €	22,06 t	
					CO2 emitted	0,00 €	0,00 t	
					Total cost of residues	0,00 €		
				Total operational cost without investment			4.951.493.239,83 €	
				Total operational cost with investment			4.940.901.719,08 €	
				Savings with introduction of P2G			10.591.520,75 €	

Fig. 7 Results for optimal P2G hub next to IP with higher prices of methane and no subsidy

P2G hub next to IP with large methane consumption can be highly profitable with increased gas prices. Optimal result for this scenario is producing as much biomethane as it is possible with constraints of the OT to fulfil the IP's needs for gas. In this scenario, both wet and dry biomass inputs are limited to 10 tonnes per day and that is the amount of dry biomass bought each day by the P2G hub. Wet biomass sources which are more

expensive in this scenario are bought in smaller amounts during summer. That biomass is used in anaerobic digestors (AD) which are sized to allow the acceptance of all the biomass available. Biogas produced from ADs is going to the methanation reactor sized accordingly to the biogas input. CO₂ from biogas needs H₂ in the methanation reactor and that hydrogen is supplied from the electrolyser. Biochar that is a by-product of AD is sold during summer period and during winter when gas price is high, biochar is used in gasification and water gas shift plant (GWGS) to produce syngas which also supplies the methanation reactor. Other investments include demineralizer and precipitation collector for water to supply the electrolyser, gas compression station and heat exchanger. Since gas is more expensive during the winter period, biomass storage is being filled during summer and emptied during winter to increase intake of the anaerobic digestors and therefore methane production in the winter period. Biomass storages are set to their maximal allowed size in the OT.

Investment for P2G hub next to the REP shows a similar investment as in the scenario with the P2G hub next to the IP.

Investment specifications			
	Element	Cost	Size
Processes	Dry anaerobic digester	2.443.910,26 €	0,116377 kg/s
	Wet anaerobic digester	2.443.910,26 €	0,116377 kg/s
	Dry biomass to biochar plant	0,00 €	0,000000 kg/s
	Wet biomass to biochar plant	0,00 €	0,000000 kg/s
	Combined heat and power (CHP)	0,00 €	0,00 kWe
	Carbon capture plant	0,00 €	0,000000 mol/s
	Gasification + water gas shift plant	13.968,97 €	0,013969 kg/s
	Methanation reactor	3.204.939,13 €	7,541033 mol/s
	Electrolyser	11.427.366,74 €	4.570,95 kW
	Demineralizer	1.074,96 €	10,749593 mol/s
	Precipitation collector	2.000,00 €	1.000,00 m ²
	Heat exchanger	227.906,30 €	2.279,06 kW
	Gas compressor station	48.512,84 €	60,6410 kWe
	Total for processes	19.813.589,45 €	
Storages	Dry biomass storage	100.000,00 €	10.000,00 kg
	Wet biomass storage	50.000,00 €	10.000,00 kg
	Biochar storage	887,80 €	59,19 kg
	Biogas storage	0,00 €	0,00 kg
	Hydrogen storage tank	0,00 €	0,00 kg
	Oxygen storage tank	0,00 €	0,00 kg
	Methane storage tank	0,00 €	0,00 kg
	Syngas storage tank	0,00 €	0,00 kg
	Carbon dioxide storage tank	0,00 €	0,00 kg
	Water storage tank	71.195,47 €	3.236,16 m ³
	Total for storages	222.083,27 €	
Connections enlargement	Electrical connection	751.877,58 €	5,78 MW
	Gas connection	60.705,32 €	6,07 MW
	Water connection	21,50 €	0,70 m ³ /h
	Total for connections	812.604,40 €	
	Total investment	20.848.277,11 €	
	Payoff period	8,19 years	

Operational costs for selected period			
		Cost	Amount
Electrical energy	Produced by REP	700.902,18 €	2.473,00 MWh
	Consumed by IP	0,00 €	0,00 MWh
	Net consumption without investment	-700.902,18 €	-2.473,00 MWh
	Mean peak power without investment	0,00 €	0,00 MW
	Consumed by P2G	16.286.321,54 €	48.583,25 MWh
	Net consumption with investment	15.460.179,80 €	46.110,25 MWh
	Mean peak power with investment	237.078,78 €	5,64 MW
Heat	Produced by REP	0,00 €	0,00 MWh
	Produced IP	0,00 €	0,00 MWh
	Net production without investment	0,00 €	0,00 MWh
	Consumed by P2G	0,00 €	-9.994,51 MWh
	Net production with investment	0,00 €	9.994,51 MWh
Gas (methane) to/from the grid	Produced by REP	0,00 €	0,00 MWh
	Consumed by IP	0,00 €	0,00 MWh
	Net consumption without investment	0,00 €	0,00 MWh
	Produced by P2G	23.916.794,89 €	27.365,91 MWh
	Net consumption with investment	-23.916.794,89 €	-27.365,91 MWh
Water	Water from the grid consumed by P2G	357,97 €	3.008,18 m ³
	Collected precipitation consumed by P2	n/a €	711,72 m ³
Input materials	Dry biomass bought	60,29 €	1.944,86 t
	Wet biomass bought	5.491,83 €	1.830,00 t
	Biochar bought	0,00 €	0,00 t
	Total cost of input materials	5.552,12 €	
Additional sales	Hydrogen sold (in bottles)	0,00 €	0,00 t
	Oxygen sold (in bottles)	16.145,21 €	230,65 t
	Methane sold (in bottles)	0,00 €	0,00 t
	Biochar sold	957,71 €	7,98 t
	Total revenue from additional sales	17.102,92 €	
Residues	Residue from dry anaerobic digester	0,00 €	58,35 t
	Residue from wet anaerobic digester	0,00 €	274,50 t
	Tar from gasification + water gas shift	0,00 €	21,97 t
	CO ₂ emitted	0,00 €	0,00 t
	Total cost of residues	0,00 €	
	Total operational cost without investment	-700.902,18 €	
	Total operational cost with investment	-8.230.729,13 €	
	Savings with introduction of P2G	7.529.826,95 €	

Fig. 8 Results for optimal P2G hub next to REP with higher prices of methane and no subsidy

Unlike with IP, P2G hub next to REP is selling the produced gas to the grid (distribution grid, not the transmission grid like for the IP case) and price increase was not sufficient

to produce gas and sell it to the grid during summer. Methane is produced mostly during winter and sold to the grid while during summer there is a small intermittent biomethane production. Methane produced during summer is following the amounts of electrical energy produced by REP which is used to support the P2G hub processes and no additional electricity is bought from the grid in summer. Additional electrical energy is bought from the grid during winter to maximize the biomethane production in that period.

Investment specifications			
	Element	Cost	Size
Processes	Dry anaerobic digester	2.443.910,26 €	0,116377 kg/s
	Wet anaerobic digester	2.443.910,26 €	0,116377 kg/s
	Dry biomass to biochar plant	0,00 €	0,000000 kg/s
	Wet biomass to biochar plant	0,00 €	0,000000 kg/s
	Combined heat and power (CHP)	0,00 €	0,00 kWe
	Carbon capture plant	0,00 €	0,000000 mol/s
	Gasification + water gas shift plant	2.327,53 €	0,002328 kg/s
	Methanation reactor	3.110.197,69 €	7,318112 mol/s
	Electrolyser	10.909.871,48 €	4.363,95 kW
	Deminerizer	837,70 €	8,376969 mol/s
	Precipitation collector	2.000,00 €	1.000,00 m ²
	Heat exchanger	220.549,90 €	2.205,50 kW
Storages	Gas compressor station	196.108,48 €	245,1356 kWe
	Total for processes	19.329.713,30 €	
	Dry biomass storage	100.000,00 €	10.000,00 kg
	Wet biomass storage	50.000,00 €	10.000,00 kg
	Biochar storage	15.000,00 €	1.000,00 kg
	Biogas storage	0,00 €	0,00 kg
	Hydrogen storage tank	0,00 €	0,00 kg
	Oxygen storage tank	0,00 €	0,00 kg
	Methane storage tank	0,00 €	0,00 kg
	Syngas storage tank	0,00 €	0,00 kg
	Carbon dioxide storage tank	0,00 €	0,00 kg
	Water storage tank	9.725,39 €	442,06 m ³
Connections enlargement	Total for storages	174.725,39 €	
	Electrical connection	1.710.257,14 €	10,56 MW
	Gas connection	61.944,60 €	5,89 MW
	Water connection	50,26 €	0,54 m ³ /h
	Total for connections	1.772.252,00 €	
	Total investment	21.276.690,69 €	
	Payoff period	8,54 years	

Operational costs for selected period			
	Cost	Amount	
Electrical energy	Produced by REP	0,00 €	0,00 MWh
	Consumed by IP	0,00 €	0,00 MWh
	Net consumption without investment	0,00 €	0,00 MWh
	Mean peak power without investment	0,00 €	0,00 MW
	Consumed by P2G	15.468.288,50 €	46.143,00 MWh
	Net consumption with investment	15.468.288,50 €	46.143,00 MWh
	Mean peak power with investment	221.841,37 €	5,28 MW
Heat	Produced by REP	0,00 €	0,00 MWh
	Produced IP	0,00 €	0,00 MWh
	Net production without investment	0,00 €	0,00 MWh
	Consumed by P2G	0,00 €	-9.368,27 MWh
	Net production with investment	0,00 €	9.368,27 MWh
Gas (methane) to/from the grid	Produced by REP	0,00 €	0,00 MWh
	Consumed by IP	0,00 €	0,00 MWh
	Net consumption without investment	0,00 €	0,00 MWh
	Produced by P2G	22.665.104,06 €	25.732,24 MWh
	Net consumption with investment	-22.665.104,06 €	-25.732,24 MWh
Water	Water from the grid consumed by P2G	285,38 €	2.378,21 m ³
	Collected precipitation consumed by P2G	n/a	976,73 m ³
Input materials	Dry biomass bought	14.690,80 €	1.830,00 t
	Wet biomass bought	13.874,20 €	1.830,00 t
	Biochar bought	0,00 €	0,00 t
	Total cost of input materials	28.565,00 €	
Additional sales	Hydrogen sold (in bottles)	0,00 €	0,00 t
	Oxygen sold (in bottles)	12.740,00 €	182,00 t
	Methane sold (in bottles)	0,00 €	0,00 t
	Biochar sold	21.960,00 €	183,00 t
	Total revenue from additional sales	34.700,00 €	
Residues	Residue from dry anaerobic digester	0,00 €	54,90 t
	Residue from wet anaerobic digester	0,00 €	274,50 t
	Tar from gasification + water gas shift plant	0,00 €	3,66 t
	CO ₂ emitted	0,00 €	0,00 t
	Total cost of residues	0,00 €	
	Total operational cost without investment	0,00 €	
	Total operational cost with investment	-6.980.823,80 €	
	Savings with introduction of P2G	6.980.823,80 €	

Fig. 9 Results for optimal P2G hub as GF with higher prices of methane and no subsidy

Similar results are obtained with gas price increase on the scenario with GF investment as with the REP collocation scenario. Methane is produced only during the winter period. Biomass storage is being emptied throughout the winter period and before the winter tariff starts again it is being refilled. Here, transmission gas grid is used for connection which requires higher gas compressor station power than for the case of P2G collocation with REP.

3.5 RESULTS WITH INCREASED GAS PRICES WITH SUBSIDIES

Investment specifications			
	Element	Cost	Size
Processes	Dry anaerobic digester	1.221.955,13 €	0,116377 kg/s
	Wet anaerobic digester	1.221.955,13 €	0,116377 kg/s
	Dry biomass to biochar plant	0,00 €	0,000000 kg/s
	Wet biomass to biochar plant	0,00 €	0,000000 kg/s
	Combined heat and power (CHP)	0,00 €	0,00 kWe
	Carbon capture plant	0,00 €	0,000000 mol/s
	Gasification + water gas shift plant	7.014,40 €	0,014029 kg/s
	Methanation reactor	1.602.713,02 €	7,542179 mol/s
	Electrolyser	5.715.013,18 €	4.572,01 kW
	Demineralizer	578,03 €	11,560518 mol/s
	Precipitation collector	1.000,00 €	1.000,00 m ²
	Heat exchanger	113.972,05 €	2.279,44 kW
	Gas compressor station	101.056,48 €	252,6412 kWe
	Total for processes	9.985.257,41 €	
Storages	Dry biomass storage	50.000,00 €	10.000,00 kg
	Wet biomass storage	25.000,00 €	10.000,00 kg
	Biochar storage	7.500,00 €	1.000,00 kg
	Biogas storage	0,00 €	0,00 kg
	Hydrogen storage tank	0,00 €	0,00 kg
	Oxygen storage tank	0,00 €	0,00 kg
	Methane storage tank	0,00 €	0,00 kg
	Syngas storage tank	0,00 €	0,00 kg
	Carbon dioxide storage tank	0,00 €	0,00 kg
	Water storage tank	0,00 €	0,00 m ³
	Total for storages	82.500,00 €	
Connections engagement	Electrical connection	0,00 €	0,00 MW
	Gas connection	0,00 €	0,00 MW
	Water connection	23,12 €	0,75 m ³ /h
	Total for connections	23,12 €	
Total investment		10.067.780,53 €	
Payoff period		6,05 years	

Operational costs for selected period			
	Cost	Amount	
Electrical energy	Produced by REP	0,00 €	0,00 MWh
	Consumed by IP	34.259.995,00 €	102.200,00 MWh
	Net consumption without investment	34.259.995,00 €	102.200,00 MWh
	Mean peak power without investment	490.000,00 €	11,67 MW
	Consumed by P2G	28.643.119,26 €	85.444,46 MWh
	Net consumption with investment	62.903.114,26 €	187.644,46 MWh
	Mean peak power with investment	899.749,01 €	21,42 MW
Heat	Produced by REP	0,00 €	0,00 MWh
	Produced by IP	0,00 €	678.900,00 MWh
	Net production without investment	0,00 €	678.900,00 MWh
	Consumed by P2G	0,00 €	-17.298,91 MWh
	Net production with investment	0,00 €	696.198,91 MWh
Gas (methane) to/from the grid	Produced by REP	0,00 €	0,00 MWh
	Consumed by IP	4.916.743.244,83 €	6.057.529,54 MWh
	Net consumption without investment	4.916.743.244,83 €	6.057.529,54 MWh
	Produced by P2G	34.425.075,97 €	47.431,04 MWh
	Net consumption with investment	4.877.092.883,32 €	6.010.098,50 MWh
Water	Water from the grid consumed by P2G	648,02 €	5.445,57 m ³
	Collected precipitation consumed by P2G	n/a €	867,19 m ³
Input materials	Dry biomass bought	24.839,02 €	3.650,00 t
	Wet biomass bought	27.995,44 €	2.962,00 t
	Biochar bought	0,00 €	0,00 t
	Total cost of input materials	52.834,46 €	
Additional sales	Hydrogen sold (in bottles)	0,00 €	0,00 t
	Oxygen sold (in bottles)	25.550,00 €	365,00 t
	Methane sold (in bottles)	0,00 €	0,00 t
	Biochar sold	21.960,00 €	183,00 t
	Total revenue from additional sales	47.510,00 €	
Residues	Residue from dry anaerobic digester	0,00 €	109,50 t
	Residue from wet anaerobic digester	0,00 €	444,30 t
	Tar from gasification + water gas shift	0,00 €	22,06 t
	CO ₂ emitted	0,00 €	0,00 t
	Total cost of residues	0,00 €	
Total operational cost without investment		4.951.493.239,83 €	
Total operational cost with investment		4.940.901.719,08 €	
Savings with introduction of P2G		10.591.520,75 €	

Fig. 10 Results for optimal P2G hub next to IP with higher prices of methane and subsidy of 50%

Subsidy did not significantly affect the optimal sizing for the scenario with increased prices of gas and P2G hub next to the IP. Again, biomethane is produced throughout the year with slightly smaller production during summer. The only significant difference is in the investment cost which is now roughly 50% lower and the payoff period is thus shorter.

Investment specifications			
	Element	Cost	Size
Processes	Dry anaerobic digester	1.221.955,13 €	0,116377 kg/s
	Wet anaerobic digester	1.221.955,13 €	0,116377 kg/s
	Dry biomass to biochar plant	0,00 €	0,000000 kg/s
	Wet biomass to biochar plant	0,00 €	0,000000 kg/s
	Combined heat and power (CHP)	0,00 €	0,00 kWe
	Carbon capture plant	0,00 €	0,000000 mol/s
	Gasification + water gas shift plant	6.984,48 €	0,013969 kg/s
	Methanation reactor	1.602.469,57 €	7,541033 mol/s
	Electrolyser	5.713.683,37 €	4.570,95 kW
	Demineralizer	537,48 €	10,749593 mol/s
	Precipitation collector	1.000,00 €	1.000,00 m ²
	Heat exchanger	113.953,15 €	2.279,06 kW
	Gas compressor station	24.256,42 €	60,6410 kWe
Storages	Total for processes	9.906.794,72 €	
	Dry biomass storage	50.000,00 €	10.000,00 kg
	Wet biomass storage	25.000,00 €	10.000,00 kg
	Biochar storage	443,90 €	59,19 kg
	Biogas storage	0,00 €	0,00 kg
	Hydrogen storage tank	0,00 €	0,00 kg
	Oxygen storage tank	0,00 €	0,00 kg
	Methane storage tank	0,00 €	0,00 kg
	Syngas storage tank	0,00 €	0,00 kg
	Carbon dioxide storage tank	0,00 €	0,00 kg
Connections enlargement	Water storage tank	35.597,73 €	3.236,16 m ³
	Total for storages	111.041,63 €	
	Electrical connection	751.877,58 €	5,78 MW
	Gas connection	60.705,32 €	6,07 MW
	Water connection	21,50 €	0,70 m ³ /h
	Total for connections	812.604,40 €	
	Total investment	10.830.440,76 €	
	Payoff period	6,66 years	

Operational costs for selected period			
		Cost	Amount
Electrical energy	Produced by REP	700.902,18 €	2.473,00 MWh
	Consumed by IP	0,00 €	0,00 MWh
	Net consumption without investment	-700.902,18 €	-2.473,00 MWh
	Mean peak power without investment	0,00 €	0,00 MW
	Consumed by P2G	16.286.321,54 €	48.583,25 MWh
	Net consumption with investment	15.460.179,80 €	46.110,25 MWh
	Mean peak power with investment	237.078,78 €	5,64 MW
Heat	Produced by REP	0,00 €	0,00 MWh
	Produced by IP	0,00 €	0,00 MWh
	Net production without investment	0,00 €	0,00 MWh
	Consumed by P2G	0,00 €	-9.994,51 MWh
	Net production with investment	0,00 €	9.994,51 MWh
Gas (methane) to/from the grid	Produced by REP	0,00 €	0,00 MWh
	Consumed by IP	0,00 €	0,00 MWh
	Net consumption without investment	0,00 €	0,00 MWh
	Produced by P2G	23.916.794,89 €	27.365,91 MWh
Water	Net consumption with investment	-23.916.794,89 €	-27.365,91 MWh
	Total cost of input materials	5.552,12 €	
Input materials	Water from the grid consumed by P2G	357,97 €	3.008,18 m ³
	Collected precipitation consumed by P2G	n/a €	711,72 m ³
	Dry biomass bought	60,29 €	1.944,86 t
	Wet biomass bought	5.491,83 €	1.830,00 t
Additional sales	Biochar bought	0,00 €	0,00 t
	Total revenue from additional sales	17.102,92 €	
Residues	Hydrogen sold (in bottles)	0,00 €	0,00 t
	Oxygen sold (in bottles)	16.145,21 €	230,65 t
	Methane sold (in bottles)	0,00 €	0,00 t
	Biochar sold	957,71 €	7,98 t
	Total cost of residues	0,00 €	
	Total operational cost without investment	-700.902,18 €	
	Total operational cost with investment	-8.230.729,13 €	
	Savings with introduction of P2G	7.529.826,95 €	

Fig. 11 Results for optimal P2G hub next to REP with higher prices of methane and subsidy of 50%

Similarly, subsidy did not change optimal size of the P2G hub next to REP for the considered case of higher natural gas prices. Biomethane is produced during winter and during summer the production is small and intermittent just to accommodate the electrical energy produced by REP.

Investment specifications			
	Element	Cost	Size
Processes	Dry anaerobic digester	1.221.955,13 €	0,116377 kg/s
	Wet anaerobic digester	1.221.955,13 €	0,116377 kg/s
	Dry biomass to biochar plant	0,00 €	0,000000 kg/s
	Wet biomass to biochar plant	0,00 €	0,000000 kg/s
	Combined heat and power (CHP)	0,00 €	0,00 kWe
	Carbon capture plant	0,00 €	0,000000 mol/s
	Gasification + water gas shift plant	6.982,60 €	0,013965 kg/s
	Methanation reactor	1.602.454,25 €	7,540961 mol/s
	Electrolyser	5.713.599,71 €	4.570,88 kW
	Deminerallizer	463,78 €	9,275541 mol/s
	Precipitation collector	1.000,00 €	1.000,00 m ²
	Heat exchanger	113.951,96 €	2.279,04 kW
	Gas compressor station	101.040,16 €	252,6004 kWe
	Total for processes	9.983.402,72 €	
Storages	Dry biomass storage	50.000,00 €	10.000,00 kg
	Wet biomass storage	25.000,00 €	10.000,00 kg
	Biochar storage	0,00 €	0,00 kg
	Biogas storage	0,00 €	0,00 kg
	Hydrogen storage tank	0,00 €	0,00 kg
	Oxygen storage tank	0,00 €	0,00 kg
	Methane storage tank	0,00 €	0,00 kg
	Syngas storage tank	0,00 €	0,00 kg
	Carbon dioxide storage tank	0,00 €	0,00 kg
	Water storage tank	4.862,70 €	442,06 m ³
	Total for storages	79.862,70 €	
Connections enlargement	Electrical connection	1.775.109,45 €	10,96 MW
	Gas connection	63.830,91 €	6,07 MW
	Water connection	55,65 €	0,60 m ³ /h
	Total for connections	1.838.996,02 €	
	Total investment	11.902.261,43 €	
	Payoff period	6,97 years	

Operational costs for selected period			
	Cost	Amount	
Electrical energy	Produced by REP	0,00 €	0,00 MWh
	Consumed by IP	0,00 €	0,00 MWh
	Net consumption without investment	0,00 €	0,00 MWh
	Mean peak power without investment	0,00 €	0,00 MW
	Consumed by P2G	16.054.840,25 €	47.892,73 MWh
	Net consumption with investment	16.054.840,25 €	47.892,73 MWh
	Mean peak power with investment	230.253,51 €	5,48 MW
Heat	Produced by REP	0,00 €	0,00 MWh
	Produced IP	0,00 €	0,00 MWh
	Net production without investment	0,00 €	0,00 MWh
	Consumed by P2G	0,00 €	-9.684,41 MWh
	Net production with investment	0,00 €	9.684,41 MWh
Gas (methane) to/from the grid	Produced by REP	0,00 €	0,00 MWh
	Consumed by IP	0,00 €	0,00 MWh
	Net consumption without investment	0,00 €	0,00 MWh
	Produced by P2G	23.355.295,01 €	26.515,83 MWh
	Net consumption with investment	-23.355.295,01 €	-26.515,83 MWh
Water	Water from the grid consumed by P2G	316,00 €	2.633,31 m ³
	Collected precipitation consumed by P2	n/a €	976,73 m ³
Input materials	Dry biomass bought	14.690,80 €	1.830,00 t
	Wet biomass bought	13.874,20 €	1.830,00 t
	Biochar bought	0,00 €	0,00 t
	Total cost of input materials	28.565,00 €	
Additional sales	Hydrogen sold (in bottles)	0,00 €	0,00 t
	Oxygen sold (in bottles)	12.740,00 €	182,00 t
	Methane sold (in bottles)	0,00 €	0,00 t
	Biochar sold	0,00 €	0,00 t
	Total revenue from additional sales	12.740,00 €	
Residues	Residue from dry anaerobic digester	0,00 €	54,90 t
	Residue from wet anaerobic digester	0,00 €	274,50 t
	Tar from gasification + water gas shift p	0,00 €	21,96 t
	CO2 emitted	0,00 €	0,00 t
	Total cost of residues	0,00 €	
	Total operational cost without investment	0,00 €	
	Total operational cost with investment	-7.054.060,25 €	
	Savings with introduction of P2G	7.054.060,25 €	

Fig. 12 Results for optimal P2G hub as GF with higher prices of methane and subsidy of 50%

Finally, adding subsidy while gas prices are increased, did not change the optimal size of P2G as GF investment. Methane production occurs during winter and it is limited by biomass storages which define the maximal daily intake.

4. CONCLUSIONS

Prefeasibility studies for three characteristic location cases for a P2G hub investment in Croatia are presented. Maximum allowed return on investment period of 20 years is considered uniformly in all cases, however often the optimum economical setup of the investment yields much shorter return on investment periods. In scenarios with current gas prices in Croatia, biomethane production is not economically feasible. On the other hand, OT shows in case with P2G next to IP, combined heat and power plant is profitable with current electricity and gas prices. Adding subsidy makes CHP profitable for REP and GF but only during summer when prices of gas are lower. Increase of methane price enables investment in biomethane production within the P2G where hubs next to IP produce biomethane throughout the year while hubs next to REP and GF produce methane during winter when gas prices are much higher. With an additional increase in the gas price, production would become profitable throughout the year.