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Energy and Emissions in Transportation Systems

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Abstract

The aim of the project is performing a feasibility analysis on the supply chain of eFuels starting from urban unsorted wastes disposal. Starting point of the analysis is the production of electrical and thermal energy from a Waste to Energy plant, sized based on the Copenhagen plant built in the recent years. Once the electricity is produced, it will be analyzed what can be done using that energy: most of it will be used for electrolysis and for producing hydrogen, which will be considered as a self-standing energy vector or then used for eFuels synthesis throught Fischer Tropsch process. Fischer Tropsch reactor's syngas required gas mixture will be fed using Solid Oxide for hydrogen demand and Calcium Looping for Carbon Capture and Storage, reducing also the carbon emissions impact of the Waste to energy plant. The comparison between the different scenarios will be used as a benchmark for the economic analysis. Analyzed energy vectors were Electricity, Hydrogen and eFuels. Among the alternatives, the most effective has been identified in eFuels synthesis. eFuels production isn't meant to be the best performing on the economical perspective. In fact, previous stages of the supply chain may produce economically better performing solutions. However, as the final purpose of the supply chain in the considered study area is transportation, it must be considered the available demand, which is unbalanced and strictly related to traditional fuels.

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Acronyms

CCS Carbon Capture and Storage

ETS Emissions Trading System

FT Fischer Tropsch

GHG Green House Gasses

ICE Internal Combustion Engine

LCOE Levelized Cost Of Electricity

LCOF Levelized Cost Of Fuel

RWGS Reverse Water Gas Shift

SOEC Solid Water Electrolyzer Cell

TtW Tank to Wheel

WLTP Worldwide harmonized Light vehicles Test Procedure

WtE Waste to Energy

WtT Well to Tank

WtW Well to Wheel

1 Introduction and State of the art

Albanian mobility market is homogeneously composed by internal combustion engine vehicles. As private cars are the main mean of transport used by the population, public transport is not very developed in the most of the Country. Both public transport coaches and the low number of trains are using diesel traction engines. Freight transport is also based on diesel cycle vehicles. Considering the nature of the Country, the difficult scenario in many locations, the cost of the life and also the electric grid, a green mobility transition is a topic which is hardly possible to face in the low term future.

The private mobility market is mainly characterized by imported old vehicles from Central Europe, mostly sedan and station wagon vehicles. All these vehicles run on gasoline or diesel, reducing the electric vehicles' share to less than 1% of the total vehicles, mostly concentrated in the capital city of Tirana, where electric vehicles serve as taxis. The willingness to buy an electric vehicle is very low, as the infrastructure doesn't exist yet and issues on the electricity network are not related to charging vehicles. In these conditions, electricity as an energy vector for mobility cannot be considered.

Waste disposal is a big problem in the region: as many non-European Union countries, Albania doesn't have a proper regulation and management of the wastes even though the population is paying wastes collection taxes. Total production of wastes in the country is estimated in 750 thousand tons per year, of which 80% don't have a tracking through the final destination. Even though what happens to the majority of the wastes is unknown, also what happens to the remaining fraction cannot be considered as a sustainable alternative: about 30% of the wastes is buried in the most remote areas of the countryside, irremediably polluting the soil and just postponing the pollution problem to the future. A significant fraction of urban wastes is set on fire outside the cities, without any sort of control on emissions of carbon monoxide and dioxide, particulates, dioxins and other dangerous flue gases. The country has no currently working waste to energy plants and a business in Albania is import of wastes from bordering countries. In the latest years, Government planned building a waste to energy plant close to the capital. As today, dumps in the country are filled more than the nominal capacity and some of them were also closed.

The country has about 800 thousand officially registered vehicles, which don't include a significant number of vehicles permanently or occasionally sojourning in the Country having foreign registration plates (mostly United Kingdom, Switzerland, Italy, Germany and Kosovo), mostly composed of late 2000s and early 2010s sedan and station wagon vehicles imported from Central European countries. Public transport vehicles also have a previous use in other European countries.

All of the mentioned information is referred to the entire country. The capital city, Tirana, has an average younger vehicles fleet composition despite the high number of daily travelers from the rest of the country. Also waste management is better performed in the city, where the local government is trying to introduced fractioned collection and promote reuse and recycling generally.

In order to realize the project plant, it is necessary to develop a big construction site.

First choice was building the plant in Durres, close to Porto Romano, the new industrial site close to the harbor of the city, where main refineries and chemical industries are building big plants. Due to the location and the high complexity desalination plant required for cleaning the marine water, a more proper location has been found close to the city of Elbasan.

Figure 1: Kombinati Metalurgjik in Elbasan.

The archive image displays the former plant named "Kombinati Metalurgjik Elbasan", built during the socialist regime in the country which has been abandoned after the anarchy of 1995, as Chinese investors left the site. Nowadays, the location is considered as an industrial archeological location, as only a few buildings are left as ruins.
The site is located close to a river that can provide easily the required quantity of water for the whole duration of the year, and the closeness to the city of Elbasan and to other industrial sites gives the opportunity of synergies for both final unused products (oxygen and carbon dioxide) but also thermal energy, as most of the plant is working on exothermic reactions.

2 Supply chain analysis

Analyzed supply chain consists in three different series connected processes, each one briefly described in the following paragraphs. As each one of the processes requires a main plant and some auxiliary smaller systems, the auxiliary systems are described in the main plant section.

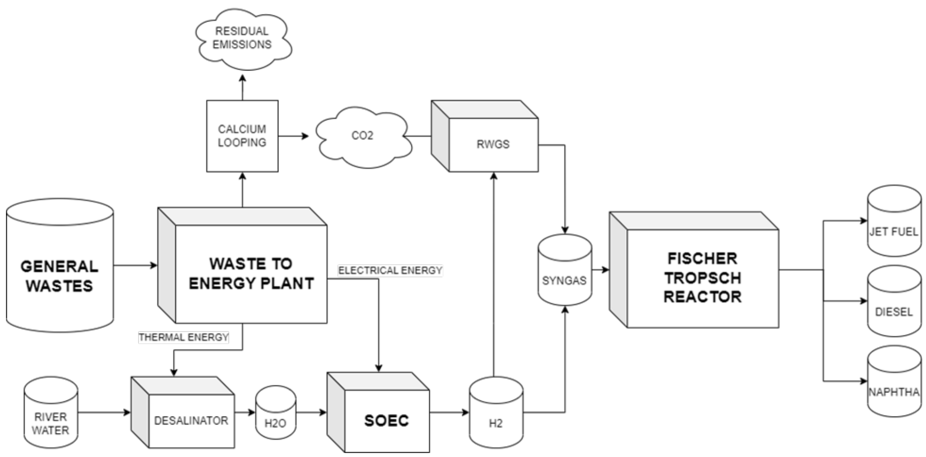

Figure 2: Supply chain scheme.

The supply chain flow algorithm is the following:

1. After the garbage collection in the study area, the general wastes are brought to the Waste to Energy plant (described in dedicated section), where electricity and thermal energy are produced as output. Carbon dioxide is collected by the CCS using carbon looping technology. 85% of the produced CO_2 is captured through calcium looping, of which 10% is then used for the supply chain.

2. WtE thermal energy is partially used by the desalination plant, which cleans the water obtained from the near river and provides distilled water as final product. Reverse osmosis technology was also considered but water purity was not compatible with electrolysis requirements.

3. WtE electrical energy is almost completely used by SOEC plant (described in dedicated section), which produces output of oxygen and pure hydrogen. Hydrogen is used in the supply chain, most of the oxygen is not used so it is emitted to the atmosphere.

4. Part of the hydrogen produced is combined with approximately 10% of the carbon dioxide obtained from the calcium looping. Through Reverse Water Gas Shift technology, carbon monoxide is produced.

5. The produced carbon monoxide and the remaining hydrogen are combined in the syngas, which is used as input for the Fischer Tropsch reactor (described in dedicated section). Final output of the process are jet fuel, naphtha and diesel, while intermediate products such as waxes are subject to cracking in order to have desired products. Methane produced during the process is used for producing electrical energy for an internal turbine, in order to reduce the FT reactor's net energy requirement.

As garbage input is approximately 1700 tons of general wastes per day, the supply chain output is meant to be:

- 25 tons of jet fuel, which is meant to be sold to air traffic companies.
- 15 tons of diesel, which is meant to be used partially by garbage collection and then sold through the national fuel companies.
- 14 tons of naphtha, which is used for tractors and ships.

As is clear from the supply chain scheme in figure 2, some of the intermediate products of the complete eFuels producing supply chain can be considered as final products, which can be already sold on both energy market and transportation vectors market. In the economic analysis, the comparison on the results will be performed and will be suggested the better-performing among the three vectors. As starting point of the supply chain is the garbage collected, the analysis will be performed as a well to tank analysis and then as a following tank to wheel analysis. The supply chain analysis is split in two in order to allow the comparison between the current scenario and the project scenario. An additional analysis will be performed comparing the disposal of the garbage through waste to energy plants (combined with carbon capture and storage systems) against current garbage disposal solutions. It is known that the suggested supply chain cannot be considered as a carbon neutral solution: waste to energy plant and Fischer Tropsch reactor have a significant impact on emissions. Considering a differential analysis, based on the current scenario, is the only possibility for evaluating the feasibility of the project.

2.1 Waste to energy

First part of the supply chain is the waste to energy production. As the Albanian country doesn't have a fractioned wastes collection, it is hardly possible to perform a differentiated recycling and reuse process based on the different composition. A significant proportion of the wastes is composed by biomass. However, as they're collected combined with the rest of the industrial and urban wastes, the more valuable biomass fraction will be used in the waste to energy plant in order to stabilize the combustion of the wastes.

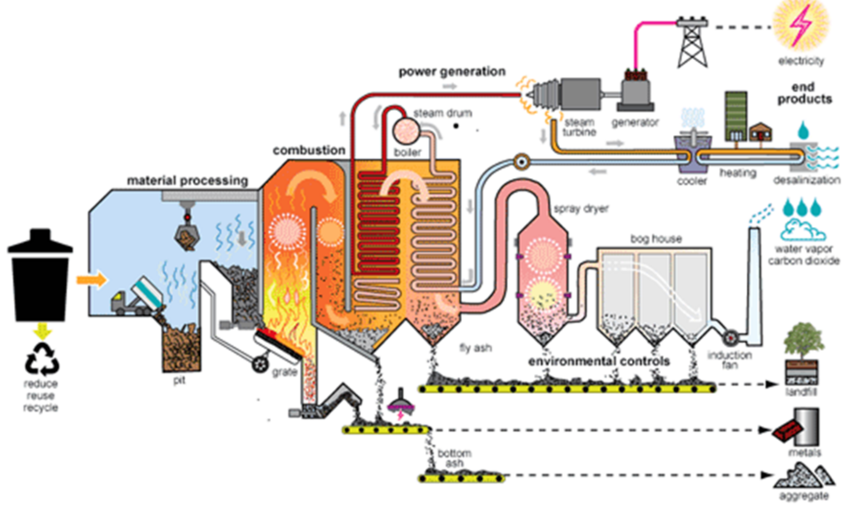

Figure 3: Waste to Energy plant.

The process is set to use a slightly oversized plant of the current plant installed in Copenhagen, as the available wastes quantity is higher than the available in the Danish city. Waste to energy plant will be equipped with a Carbon Capture and Storage system based on calcium looping, which is supposed to reduce the overall efficiency of the plant of 10%, giving a carbon dioxide capture rate of above 90%. About 10% of the captured carbon dioxide will be used by the following plants in the supply chain. The process occurs according to the following chemical reaction:

$$CaCO_3 \longleftrightarrow CaO + CO_2$$

Calcium looping has been chosen among the different alternatives as overperforming the other alternatives, in particular MDEA filter was not compatible with a waste to energy plant.

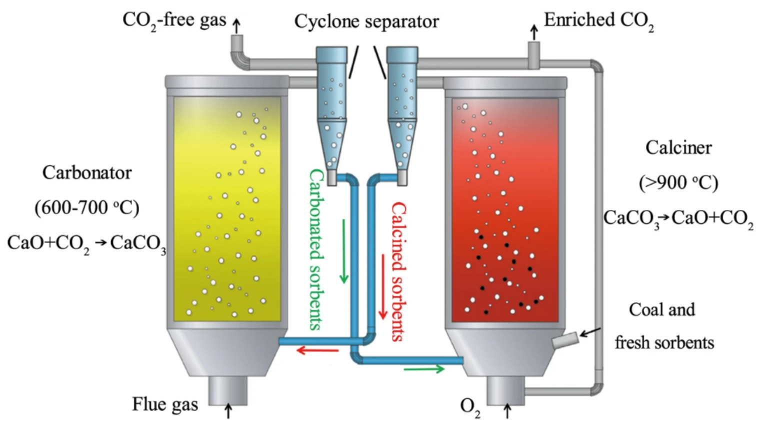

Figure 4: Calcium looping working principle.

Waste to Energy is known for not being the greenest solution to waste disposal. However, considered the current scenario, reducing the quantity of buried wastes can be an important step towards a better implementation of wastes management. The huge amount of thermal energy produced by the plant is only partially used by the rest of the supply chain. The remaining energy can be used (in the future) for district heating of the city of Elbasan, close to the plant.

Input		
Wastes	613200	tons/year
Nominal	521220	tons/year

Output		
Electric power	62.70	MW
Electric energy	549.25	GWh/year
Thermal power	190	MW
Thermal energy	1498	GWh/year
CO_2 emissions	429	ktons/year
CO_2 captured	365	Ktons/year

Table 1: Waste to Energy plant input and output values.

In table 3 the nominal wastes have been used to perform the energy power output in order to take into account the equivalent hours of plant operation, while CO_2 emissions are computed starting from total wastes.

Garbage trucks' consumption and emissions will be computed separately from the current scenario. It is assumed that in the current scenario every garbage collection vehicle is used for a length of approximately 50 km per day, having a consumption of 30 L of diesel per day. Assumed 10 tons of load per each truck and one ride per day, 150 trucks can be assumed for capable of managing the whole garbage collection in the analysis area. Total consumption for the garbage collection can be estimated as 689 tons of diesel per year (821 thousand liters per year).

Waste to energy plants have a garbage mass reduction ratio of the between 75% and 90%, reducing significantly the size of disposal sites.

2.2 Water electrolysis

In order to produce high purity hydrogen in a high efficiency plant, a Solid Oxide Electrolyzer Cell system has been chosen for hydrogen separation from water. The choice among different technologies lead to the use of SOEC also in order to use at least partially the thermal energy produced as output in the waste to energy plant. The solid oxide technology is still under development for high scale plants, but it is assumed to be ready for the year of the realization of the plant.

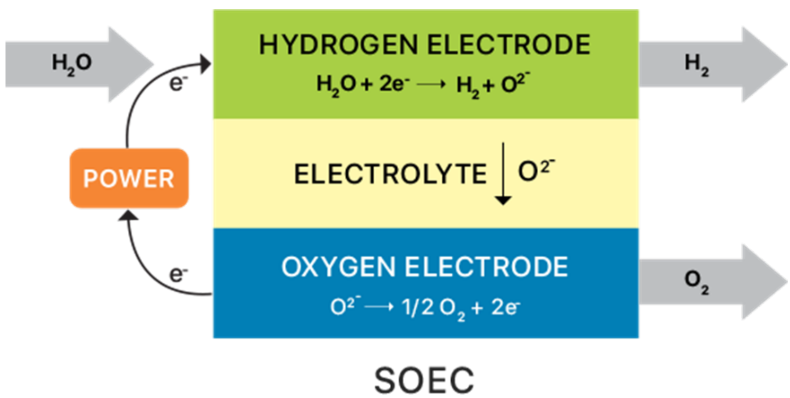

Figure 5: Solid Oxide Electrolyzer Cell working principle.

Water electrolysis is the main bottleneck of the whole supply chain: as it is a very energy consuming process, the sizing of the whole supply chain is based on the energy consumption of SOEC. As the water inlet to the electrolyzer must consist in distilled water, it is necessary to install also a desalination system close to the plant. Outbound pure water from other plants is supposed to be used by the desalination system in order to reduce the impact of the onsite river. Desalination process has a thermal energy consumption of 15 GWh/year, while SOEC thermal energy consumption is 180 GWh/year.

Input		
H_2O	316	m^3/day
Electrical Power	58	MW
Electrical Energy	504	GWh/year
Compressor	22	GWh/year

Output		
H_2	35	tons/day

Table 2: SOEC input and output values.

2.3 Fischer Tropsch process

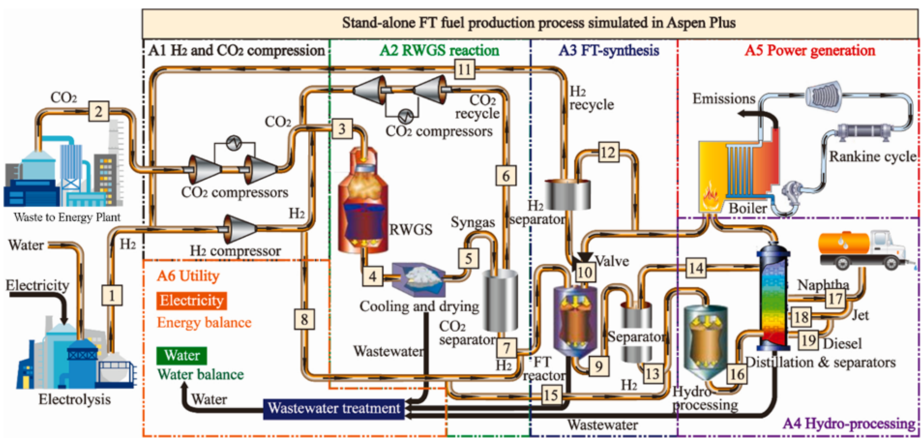

Figure 6: Fischer Tropsch reactor plant working principle, from CO_2 and hydrogen to fuels.

Final product of the supply chain is produced by the Fischer Tropsch reaction, based on carbon monoxide and hydrogen.

$$(2n + 1)\,H_2 + nCO \longrightarrow C_nH_{(2n+2)} + nH_2O$$

The plant has been downscaled from an existing simulation [9] in order to have clear numbers on what are the real consumption and not only the theoretical energy and prime material consumptions. As FT synthesis is an exothermal reaction, also this component will lead to unused thermal energy.

Fischer Tropsch synthesis uses carbon monoxide and pure hydrogen. Carbon monoxide can be obtained from carbon dioxide through Reverse Water Gas Shift process, which is performed on a portion of the carbon dioxide emissions of the waste to energy plant.

$$CO + H_2O \longleftrightarrow CO_2 + H_2$$

The mentioned process requires a hydrogen input, so the hydrogen required by the whole system will be higher than the stoichiometric coefficients of the Fischer Tropsch standard process.

Fischer Tropsch synthesis has a hydrocarbon output consisting in different final products. As some unwanted products are also produced (including waxes), they are processed through cracking and the only significant outputs of the synthesis are meant to be diesel, naphtha and jet fuel. Among the unwanted outputs, a different case is represented by methane: methane is an undesired output of the whole process but the fraction will supply a turbine included in the plant: the turbine electricity production is meant to be used by the Fischer Tropsch plant for reducing the energy input.

Input		
H_2	35	tons/day
CO_2	376	tons/day
Electrical Energy	13	MWh/day

Output		
Naphtha	14	tons/day
Diesel	15	tons/day
Jet Fuel	26	tons/day

Table 3: Fischer Tropsch reactor input and output.

3 Energy vectors comparison

The reported supply chain passes through different raw materials and pure energy vectors. Analysis is performed on electricity, hydrogen and eFuels as energy vectors.

Among the different alternatives, three alternative energy vectors and three related supply chain schemes have been compared in the analysis:

- Electricity production: final product is the electricity produced by the WtE plant.
- Hydrogen production: the electricity produced by the WtE plant is used to perform electrolysis through a SOEC plant and final product is then hydrogen.
- eFuels production: the hydrogen is combined with the captured carbon dioxide outcoming from the WtE plant, which undergoes RWGS process, and is finally mixed with the hydrogen produced during SOEC. The gaseous mix (syngas) is then used by the FT reactor and final products are diesel, naphtha and jet fuel.

All the different alternatives but current scenario assume an 85% carbon dioxide capture efficiency performed through calcium looping systems.

3.1 Current scenario

Current scenario is assumed as half of the collected garbage is free fire burned, which means uncontrolled emissions and no further use of the heat produced. Residual wastes are then half of the starting collected garbage. OPEX for a wildfire are assumed as negligible. Emissions analysis also considers the WtW emissions due to production of the fuels and their usage. Garbage collection emissions are discounted of 50% as the current scenario has shorter trips for garbage collection trucks.

3.2 Electricity

Electricity scenario analysis is performed as energy is produced by the WtE plant. As the final purpose of this energy cannot be assumed as mobility or transportation purpose, the value of the energy is assumed as the LCOE. OPEX include the operational expenses of the WtE plant. Emissions from average European mix for the same amount of energy are then deducted from the total of emissions, as the market is experiencing substitution process. WtW emissions due to fossil fuels are the same as the current scenario as the transportation demand is still the same.

3.3 Hydrogen

Hydrogen scenario has same OPEX of the Electricity scenario plus those related to the operational phase of the SOEC system. Value of the produced hydrogen is assumed for the given pressure for grey hydrogen, as the not-green source of electricity implies the lower value of the product. As the hydrogen transportation market in Albania isn't developed, the offer for the product is not existent and the final purpose is chemical/refinery use. Emissions are the same as electricity scenario without the deduction for energy production. If the product would be used for transportation purpose, a compression is necessary as the pressure is too low.

3.4 eFuels

eFuels scenario includes the full analysis: as a consequence, OPEX include all auxiliary and primary plants involved in the supply chain. WtT emissions are limited to WtE plant, TtW emissions are the same as the rest of the cases.

3.5 Power to X

Power to X analysis was performed in the three scenarios. Assuming an electricity input of 504 GWh/year from the WtE plant, based on Lower Heating Values of the fuels, it is reported that:

- Hydrogen production has a total energy value of 428 GWh/year, having an electricity-to-hydrogen efficiency of 85%.
- eFuels production has a total energy value of 260 GWh/year, having an electricity-to-fuel efficiency of 52%, computed using yearly flows of fuels and corresponding lower heating values.

3.6 X to Wheel

In order to have some insights on final usage of the energy vectors, a comparison between Electricity, Hydrogen and eFuels has been computed. As the produced eFuels are used for different purposes, the estimation are calculated using only diesel fraction of the final products. As a consequence, electricity and hydrogen reference values have been reduced to 27% of the total production, in order to make it comparable to diesel. Potential losses due to transmission and distribution have been considered for electricity scenario.

In order to compute a more effective analysis, comparison has been run considering a vehicle already existing in all three alternatives, reference values from WLTP consumptions. Electric consumption of the vehicle has been computed considering pure electric drive of the reference vehicle, which is a plug-in hybrid vehicle.

	Adjusted Availability	Consumption	Vehicle Information	Range (km/day)
Electricity	240 MWh/day	0.24 kWh/km	BMW G05 X5 xDrive50e	1019925
Hydrogen	10 ton/day	0.0119 kg/km	BMW G05 iX5 Hydrogen	802139
Diesel	17647 L/day	0.061 L/km	BMW G05 X5 xDrive30d	289296

Table 4: Theoretical range available related to daily production.

As predicted, electric alternative is giving a longer available theoretical range. However, the electric and the hydrogen alternatives are not feasible in the Albanian scenario as there is no demand for these energy vectors.

4 Emissions analysis

The three alternatives analyzed include the following components for the emissions analysis:

- The emissions of electrical energy production only include the emissions due to WtE plant. It is assumed no transport emissions and total consumption.
- As the electrolysis process has no emissions, the emissions are the same of the previous alternative.
- Final alternative of the supply chain has the same figures of the previous, deducted by the not emitted pollutants due to the production of the sold fuels, i.e., fractioned distillery emissions are deducted as the fuels would have been consumed anyway.

Emissions analysis is performed also comparing to the current scenario, where fuel is produced through standard refinery. Analysis don't compare a scenario where vehicles are electric motor vehicles or fuel cell vehicles as their presence on the Albanian market is not realistic in the short term. As a consequence, the emissions due to the final produced fuels are not computed as consisting in the same values for all the available alternatives.

Emissions for garbage collection are assumed as previously mentioned in the project scenarios, and halved in the current scenario as garbage collection is performed on lower distances currently.

Energy vector	Well to Tank	Contribution
Current scenario	231 kton CO_{2eq}	Garbage collection, naked flame emissions, fuels production
Electricity	81 kton CO_{2eq}	Garbage collection, WtE emissions, fuels production
Hydrogen	81 kton CO_{2eq}	Garbage collection, WtE emissions, fuels production
eFuels	64 kton CO_{2eq}	Garbage collection, WtE emissions

Table 5: Yearly emissions comparison between energy vectors and current scenario. Garbage collection emissions are included in WtT.

Emissions analysis shows how electricity alternative is not sustainable, as emissions due to production in base conditions are way lower than in WtE production. Also, Albanian energy mix is mostly supported by hydroelectric/marine energy, which is very low emitting. Value is also expected to decrease as trends for 2030 are decreasing, giving an even clearer situation.

4.1 Well to Tank

Well to Tank analysis emissions in the project scenario are coming from the waste to energy plant, as the Fischer Tropsch reactor's emissions are reused in the process itself.

Current scenario garbage disposal, which is assumed being performed 50% by open air combustion of garbage, is assumed (downscaling approximation) emitting the lower bound emissions value of a WtE plant, which is 690 $kgCO_2$/ton of waste.

WtE plant has 429 ktons of CO_2 output per year, of which:

- 365 ktons are captured using CCS and accounted as avoided externalities and accounted as of carbon credit value.
- 137 ktons are used for the Fischer Tropsch
- Final emissions for Waste to Energy plant are 64 ktons.

Electrolysis plant and FT reactor don't have direct or non-negligible atmosphere emissions, as FT reactor's CO_2 emissions are directly recycled for the process itself.

In current scenario, the same amount of eFuels is produced in standard refineries. These amounts are producing a 17 kton of CO_2eq output per year.

The WtT analysis also includes emissions due to garbage transportation, which are estimated as 1800 tons per year in the three project scenarios and 900 tons per year in the current scenario, assuming EURO4 diesel trucks as average garbage collection fleet.

126 kton CO_{2eq} /year are saved in the project scenarios during the supply chain.

4.2 Tank to Wheel

As the analysis' focus is the supply chain, Tank to Wheel analysis hasn't been performed in none of the reference scenarios. If electricity and/or hydrogen would have been a used energy vector in the Albanian mobility and transportation market, it would have been interesting the results of the analysis. Given the assumption that the market shares of different fuels remain the same in all the scenarios, Tank to Wheel analysis would report the same results regarding every analyzed scenario.

5 Economic analysis

Economic analysis is performed on both sides of Capital Expenses and Operational Expenses. Instead of being directly computed on the energy vectors side, the economic analysis is performed on the components and then aggregated for alternative energy vectors.

Hypothesis for economic analysis include:

- Carbon dioxide externalities are computed using ETS values (80 $/ton), final products' values are computed on the market value of the resources.
- Feedstock cost is zero in eFuels scenario as hydrogen and carbon dioxide are self-produced.
- Cost for the plants is assumed on the estimations from 2025-2028, when the SOEC and CCS technologies are supposed to be fully developed.
- Waste collection and disposal taxes are equal to 40 M$/year in the whole country.
- Diesel value is assumed as the same for both usage and market: the amount of money saved as part of the production is used for garbage trucks is capitalized at the same market price.
- As using WtE as electricity source for hydrogen production is not associated to a hydrogen "color", reference price for produced hydrogen is 2.5 $/kg, which is an average between grey and blue.
- Carbon credits has been chosen against carbon dioxide sale as raw material as the whole analysis is oriented to a low emissions impact. Also, given market price of CO_2 the sale would have been less profitable.
- Thermal energy value is not accounted as considered a residual product.

	WtE plant	Electrolysis plant	FT Reactor
CAPEX	737 M$	23 M$	75 M$
CAPEX criteria	Scaled plant w.r.t. Copenhagen plant	Sized on capacity @ 400 $/kW	Scaled plant w.r.t. simulation plant
Auxiliary CAPEX	3 M$	22 M$ + 8M$	7 M$
Notes	Calcium looping CAPEX costs already included, additional pipelines	Desalination plant, additional pipelines	Additional pipelines
OPEX (per year)	38 M$	6.5 M$	6.6 M$ having no feedstock cost
Product output	Electricity	Hydrogen	Naphtha + Diesel + Jet Fuel
Raw materials market value (per year)	40 M$ w.r.t. LCOE	32 M$ w.r.t LCOH	8.5 M$ + 3.5 M$ + 5 M$ (naphtha + jet fuel + diesel) w.r.t market value of raw materials

Table 6: Well to Tank plants economic summary.

	Current scenario	Electricity	Hydrogen	eFuels
CAPEX	-	740 M$	793 M$	875 M$
OPEX	-	38 M$/year	44.5 M$/year	51 M$/year
ETS value	-	29 M$/year	29 M$/year	18 M$/year
CCS cost	-	13 M$/year	13 M$/year	13 M$/year
Taxes income	40 M$/year	50 M$/year	50 M$/year	50 M$/year

Table 7: Well to Tank energy vectors aggregated economic analysis comparison.

5.1 CAPEX analysis detail for Fischer Tropsch Reactor

Reaction Area	**Major Type of Equipment**	**Major Equipment Installed Cost**	**Inst. Factor**	**Scaling Exp**	**Scaled Installed Cost**
A1: H_{2} and CO_{2} compression	CO_{2} compressor 01	$ 11,807,922.00	247	65	$ 3,324,234.08
	CO_{2} compressor 02	$ 17,388,504.00	247	80	$ 3,653,810.86
	H_{2} compressor	$ 2,547,995.00	247	60	$ 790,790.52
	RWGS reactor	$ 22,972,192.00	247	60	$ 7,129,602.54
	Syngas preheater	$ 6,248,204.00	247	60	$ 1,939,179.82
	CO_{2} separator	$ 32,995,221.00	247	60	$ 10,240,329.33
A2: RWGS reaction	Syngas cooler	$ 4,186,906.00	323	70	$ 886,161.09
	Flash separator	$ 807,728.00	182	70	$ 255,432.64
	Dryer	$ 75,501.00	200	70	$ 22,350.79
	Syngas compressor	$ 11,461,600.00	247	65	$ 3,226,735.52
	FT synthesis reactor	$ 36,681,585.00	275	80	$ 7,073,320.61
	Wax separator	$ 144,155.00	302	60	$ 39,655.79
	Gas/liquid separator	$ 6,595,713.00	169	70	$ 2,196,859.52
	Flue gas heat exchanger	$ 1,626,125.00	152	70	$ 583,343.88
	Flue gas cooler	$ 980,551.00	203	70	$ 287,265.98
A3: FT-synthesis	Dryer	$ 123,670.00	302	60	$ 34,020.54
	Flue gas compressor	$ 718,300.00	247	80	$ 150,934.91
	PSA H_{2} separator	$ 7,495,642.00	247	60	$ 2,326,332.13
	Wax preheater	$ 969,104.00	152	70	$ 347,649.10
	Wax cooler	$ 29,456.00	233	70	$ 7,835.85
	Wax dryer	$ 21,715.00	302	60	$ 5,973.61
	Liquid cooler and dryer	$ 50,244.00	152	70	$ 18,024.16
	Wax hydrocracking	$ 33,067,253.00	247	65	$ 9,309,283.17
	Gas separator	$ 411,911.00	247	65	$ 115,963.55
A4: Hydro-processing	Naphtha distillation	$ 585,966.00	247	65	$ 164,964.52
	Jet fuel distillation	$ 326,304.00	247	65	$ 91,862.98
	Diesel distillation	$ 178,050.00	247	65	$ 50,125.66
	Naphtha dryer and cooler	$ 223,100.00	499	70	$ 34,824.94
	Boiler steam generator	$ 27,883,640.00	180	60	$ 10,463,260.03
A5: Power generation	Steam turbine	$ 11,065,762.00	180	60	$ 4,152,397.08
	Boiler auxiliary device	$ 6,015,366.00	180	60	$ 2,257,249.72
	Wastewater treatment	$ 1,779,507.00	141	60	$ 773,124.24
A6: Utility	Cooling tower	$ 2,929,758.00	150	60	$ 1,226,473.16
	Fuel storage	$ 7,405,996.00	302	65	$ 1,829,574.52
Total		$ 257,800,644.00			$ 75,008,946.82

Table 8: Scaled CAPEX for Fischer Tropsch Reactor. CAPEX scaled on available hydrogen flow using general exponent scaling equation.

5.2 Levelized Cost of Fuel

The following analysis was run on the eFuels scenario, which has more complex cost items.

Levelized Cost of Fuel has been computed comparing the different results in three different scenarios. Calculations were then repeated using Generalized Reduced Gradient optimization method in order to perform sensitivity analysis and obtain an optimized result.

Depreciations were computed as follow, given the useful life of the plants. They were assumed as constant in the different scenario, as the plants are always the same. However, in order to simulate external financial contributions (which have the final effect of reducing the depreciation yield), values were included as variable in the sensitivity analysis.

Plant	**Value**	**Useful life**	**Depreciation**
Waste to Energy	740 M$	30 years	25 M$/year
SOEC	53 M$	20 years	2.7 M$/year
Fischer Tropsch reactor	82 M$	20 years	4 M$/year

Table 9: Depreciation.

Revenues	$ 16,855,853.56	Value of the fuels referring to raw materials
Tax income	$ 40,000,000.00	Total garbage collection taxes
ETS	$ 18,192,800.00	Value of the avoided CO_2 emissions
Costs	$ (97,715,000.00)	Depreciations, CCS and OPEX
Totals	$ (22,666,346.44)	

Table 10: LCOF items detail.

Using reference values previously computed, the supply chain gross loss is 22,7M$/year.

5.3 Sensitivity analysis

	eFuels	**Sensitivity Variations**
OPEX	51 M$/year	Fixed value
ETS value	18 M$/year	Fixed value
CCS cost	13 M$/year	Variable
Tax income	40 M$/year	Variable
Depreciations	32 M$/year	Variable

Table 11: Sensitivity analysis variables description.

	Production		Lower Bound Price	Price	Upper Bound Price	Reference value	Unit
Naphtha	5176	ton/year	650	673	900	650	$/ton
Diesel	5579	ton/year	883	908	1200	883	$/ton
Jet fuel	9432	ton/year	908	951	1500	908	$/ton
Taxes	1000000	$/year	40	50	50	40	$/year
CCS Cost	429000	ton	-40	-25	-25	-30	$/ton*year
ETS	227000	ton	80	80	80	80	$/ton*year
OPEX	1000000	$/year	-51	-51	-51	-51	$/year

Table 12: Results of simulation run using GRG algorithm.

	Reference	Maximum	Break Even
Revenues	$ 16,855,853.56	$ 25,502,658.03	$ 17,532,200.00
Tax income	$ 40,000,000.00	$ 50,000,000.00	$ 50,000,000.00
ETS	$ 18,192,800.00	$ 18,192,800.00	$ 18,192,800.00
Costs	$ (97,715,000.00)	$ (85,725,000.00)	$ (85,725,000.00)
Totals	$ (22,666,346.44)	$ 7,970,458.03	-

Table 13: Scenarios comparison. Reference scenario computed using reference values, Maximum using Upper Bound values, Break Even using GRG output values.

	Price [$/ton]	Price [$/L]
Naphtha	674	0.607
Diesel	909	0.759
Jet fuel	951	0.761

Table 14: Break even prices before taxes of fuels in the simulation scenario.

Sensitivity analysis on LCOF price was run on the following cost items:

- Raw materials sale price was optimized between the raw material price and the green raw material price.
- Garbage collection tax was increased of the same percentage as local salaries have increased in 2023.
- CCS cost was optimized between upper and lower bound of the current reference values, which were estimated based on current research and development estimations.

- Proportions of produced fuels haven't been included in the optimization due to technical constraints: reference simulation used for the whole technical analysis had to undergo resizing if changing FT process' output.

Under given hypothesis, break-even point was computed having:

- Fuels sale prices of 674 \$/ton (naphtha), 908 \$/ton (diesel) and 951 \$/ton (jet fuel).
- Taxes of 50 M\$/year (was 40 M\$/year, reaching upper bound but bound lower than real cost of garbage collection).
- CCS cost reduced to 25 \$/ton (was 35 \$/ton, lower bound 25 \$/ton).
- Government investment of 13 M\$/year (reduction shown in the last row of the report). Government investment can be seen also as a possible increase in garbage collection taxes.
- External intervention is limited if products are sold at upper bound price: increase in the prices can partially cover the taxes increase.

Fuels sale price is not set to upper bound as the analysis aims to reach the break-even point and not generating profit. Further increase of those prices is possible as competitive prices of eFuels are higher than those reported in the analysis.

Using higher bound values for sale prices and lower bound for costs, supply chain is producing 8 M\$/year profit (Maximum scenario).

If following the given bounds on raw materials selling price, the most profitable change to accounted value is the impact of taxes.

Supply chain (and also garbage collection) becomes economically sustainable if taxes income is increased.

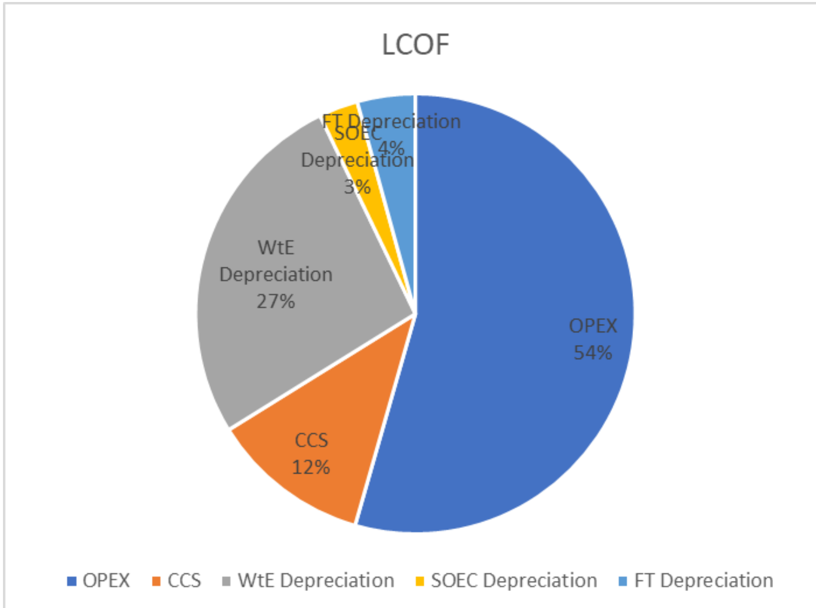

Figure 7: LCOF components after sensitivity analysis.

- Highest impact of the cost of the fuel is given by the operational phase (all plants included). CCS cost remains the same even if increased the capacity of FT reactor and SOEC.
- Waste to Energy plant's depreciation has a significant impact: if the investment cost is covered by external investments, the cost of the fuel can be further reduced.
- Cost of the fuel is significantly related to cost of Carbon Capture and Storage: if reduction is not possible as predicted by forecasts and sensitivity analysis, price may rise.

Reducing the taxes income to 25 M$/year, price of the fuel changes significantly.

	Price [$/ton]	**Price [$/L]**
Naphtha	1833	1.649
Diesel	2359	1.969
Jet fuel	2107	1.686

Table 15: Break even prices before taxes of the fuels in the simulation with reduced taxes income.

As shown in table 15, industrial prices pre-tax are almost equal to market price of traditional diesel, jet fuel and naphtha (of which the industrial price shown is higher than market price after taxes).

6 Conclusions

Despite the high complexity of the supply chain, the production of eFuels starting from wastes is an unexplored alternative in the current scenario. The main reason is the high cost of the electrolysis plants, which is expected to decrease in the next ten years reaching an acceptable price related to the rated power. It is well known that it is utopic to create a plant and use it in order to burn the totality of the waste produced in a country, but it is interesting to see what happens to the value of the different energy vectors when the supply chain becomes more complicated.

Given the current scenario of mobility in Albania (and more generally in the Eastern European countries), where green mobility and transition are not considered as important topics, eFuels can be considered an alternative, or at least a complement, to the traditional fossil fuel products available and required by the market offer. The current scenario is strictly dominated by all the remaining as there is not a proper garbage collection and disposal solution. Also, waste to energy plants construction is already in the plans of the Albanian Government.

It is clear that implementing a waste to energy plant in Albania as an energy source is economically unsustainable, but considering it as a waste disposal solution gives a way better alternative: although primary energy emissions are lower in the analyzed scenario, what happens to the wastes in the country is (probably on purpose) unclear and officially unmentioned. However, the suggested solution reduces of 80% the size of the residual wastes: having one fifth of the original size of the wastes makes it easier to manage the still big amount of garbage. The environmental impact of the waste to energy disposal solution is then significant. The current garbage collection taxes in Albania are not sufficient to cover the cost of the suggested plant. However, as in the last years the average salaries in the Albanian country are increasing, also an increase in the garbage collection taxes can be sustainable.

eFuels alternative has been elected as the most effective as, among the different scenarios analyzed. Considering the other analyzed alternatives, must be stated that:

- Electricity production alternative is the most cost effective: however, it is dominated by the internal market for energy due to emissions, as hydroelectrical plants are widespread in Albania and they're covering most of the demand and have none to negligible pollutants emissions.
- Hydrogen alternative isn't effective as there isn't and existing hydrogen market for mobility in the country and an even lower market value of the final product, which will extend the payback time to a too long period. Hydrogen needs mention as further development of the technology in the years may lead to massive use of hydrogen as energy vector for transportation. Implementing co-electrolysis can increase the overall efficiency of the supply chain.

eFuels alternative's products offer is completely absorbed by the internal demand of the country, as mobility and transportation markets are still running on diesel vehicles. Reaching a break-even solution in this scenario gives the possibility of reaching a low economic impact for garbage disposal. However, a lower taxes income requires higher market price of the final product, which becomes higher than traditional fuels price.

The supply chain is flexible and adaptable to fuel shifts in the future. Assuming that the fuel shift happens in the useful life of the plant, if the new fuels market requires different products, Fischer Tropsch synthesis output can be re-balanced in order to produce the most required final products, for example increasing jet fuel production and reducing diesel/naphtha yields. Considering the engineered supply chain, even in the worst-case scenario, (complete shift to electric and hydrogen vehicles, which happens to be the best-case scenario for the emissions reduction), Fischer Tropsch reactor can be switched off and removed from the supply chain, having as final output hydrogen and/or electricity.

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