CARBON RECYCLING - a Nature Based Solution for Climate Change Mitigation

.G Carbon-Recycling Initiative
www.carbon-recycling.eco

Carbon-recycling is a technological approach for climate change mitigation, proposed to be recognized as a **Removal by Sinks (Paris Agreement Paragraph 4.1)** and **CCS – Carbon Capture and Storage** (Section 11.3.6 of IPCC WGIII AR6, page 11.36)[1].

The carbon recycling is proposed by the ".G Initiative" to be implemented within Cooperative Approaches registered at UNFCCC Paris Agreement Paragraphs 6.2 and 6.4 Mechanisms, generating tangible and measurable amounts of **Carbon Dioxide Removals – CDR** and **Certified Emissions Reductions – CERs** for being appropriated as emissions allowances for national or international carbon offset market mechanisms, as will be described below.

Besides, it will also be demonstrated below that carbon-recycling cooperative approaches allow income generation for every participating community members: from the renewable feedstock generation (the "waste-pickers" and "forest-keepers"), throughout a chain of actors involved in the processing, logistical arrangements, and final storage or energetic utilization of the recycled carbon. Therefore, the network is intended to promote a fair and just intragenerational and intergenerational distribution of duties and earnings for harvesting and recycling excess CO_2 accumulated in the earth atmosphere by the historical emissions. As such, the initiative may promote a just transition to correct the historical failure of the market economy based on linearity of material flows, that resulted in the global warming, moving forward to a fair and sustainable economic approach based on circularity of the material flows.

The heart of the technology is the carbonization (slow pyrolysis), which is described below in more details. The starting feedstocks are renewable biomass from diverse sources, separated in two distinct primary sources (AFOLU or Wastes Routes). The processed feedstocks (pyrolyzed outputs, which we are naming "biocarbon" and "pyrocarbon") are inert and stable for being stored for centuries or millennia as artificially produced carbon and energy reserves for the future generations.

Carbon-recycling is proposed to be practiced in two separate routes:

(i) **BCCCS: Biocarbon Capture and Storage (from the AFOLU Route)**
(ii) **PCCCS: Pyrocarbon Capture and Storage (from the Wastes route)**

Both routes result in negative emissions (removal or reversals of CO_2 emissions, measurable in tons of CO_2 removed and stored) and emissions reductions of greenhouse gases (GHGs): methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2), that would otherwise be formed and emitted to the atmosphere, are avoided by the chemical conversion. Carbon Recycling is thus a technological approach resulting in **Certified Emissions Reductions (CERs)** and **Certified Carbon Dioxide Removals (CDRs)** (as per IPCC WGIII AR6 Section 12.6, page 12.35).

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[1] References are made for IPCC Report on Mitigation of Climate Change (IPCC WGIII AR6, 2022), Paris Agreement (2015) and Glasgow Accords (COP 26, 2021).

AFOLU Route (BCCS)

The Biocarbon route (“Forest keepers”) is based on the technologies for climate mitigation described in **Chapter 7 (Agriculture, Forestry and Land Use - AFOLU)** and **Chapter 8 (Urban Systems and other Settlements)** of the IPCC WGIII AR6 Report, 2022. Each participating land for generating the renewable biomass (see the modalities below) is described for their geographic location within a network (a Project Activity – PA or Programme of Activities - PoA). The PAs and PoAs are supervised by a Coordinating Management Entity – CME, and registered as a Cooperative Approach under the **Glasgow Accords** (CMA 3 Decision 2 – Guidance to Paragraph 6.2 and Decision 3 – Modalities and Procedures for Paragraph 6.4 of the Paris Agreement). Once registered, the PAs and PoAs will be able to generate carbon credits up to the duration of the PAs and PoAs (may last up to 45 years). The carbon credits are tradable within the implementation of National Determined Contributions – NDCs of the countries or within the Voluntary Market as **Internationally Transferred Mitigation Outcomes (ITMOs).**

Modalities for AFOLU renewable biomass generating activities:

- **Afforestation and Reforestation (A/R) projects: applying UNFCCC CDM or Voluntary Markets methodologies**
- **Reduced Deforestation and Forest Degradation (REDD+) projects (see for example www.un-redd.org)**
- **Sustainable Forest Management (see Section 7.6.3 of IPCC WGIII AR6, page 7.108)**
- **Agricultural Residues and Bioenergy (see Box 7.7 of IPCC WGIII AR6, page 7.79)**
- **Urban Green and Blue Infrastructure (see Section 8.4.4 of IPCC WGIII AR6, page 8.63)**
- **Bioeconomy mitigation and adaptation opportunities (see Cross-Working Group Box 3 on IPCC WGIII AR6, page 12-112)**

The AFOLU modalities above are primarily targeted to achieve the removal/reversal of CO_2 emissions by increasing carbon stocks in the living ecosystems (the carbon pools above ground, below ground, and soil organic carbon). Secondly, the modalities are also designed to deliver to the market the locally produced goods from ecosystems managed or cultivated: food, fibers, wood, biofuels, etc. to the bioeconomy market chains. The carbon-recycling by means of slow pyrolysis, producing biocarbon (similarly to the **Biochar**, see section 7.4.3.2, IPCC WGIII AR6, page 7.63) is however implemented by our cooperative approaches to manage and make useful gains from the remaining non-marketable biomass harvested from the participant lands. In that sense, all land managed by the cooperative approaches are continuously capturing CO_2 from the atmosphere and converting it into the primary carbon stocks (living biomass), marketable secondary harvests (bioeconomic products) and biocarbon. The biocarbon itself may also be used as a renewable source of energy for industrial and energy sectors (zero emissions bioenergy or thermo-reducing agent for iron and steel plants). The remaining biocarbon, which is a stable mineralized product artificially produced, may be safely handled or logistically distributed at low cost, low environmental risks, without hazardous effects to water, soil and atmosphere. Finally, the biocarbon may be safely and quantitatively stored under controlled and auditable conditions at reverse mining sites (BCCCS, see below), allowing the issuance of a certificate (ITMO) of negative emissions by permanent removal and storage of the biocarbon.

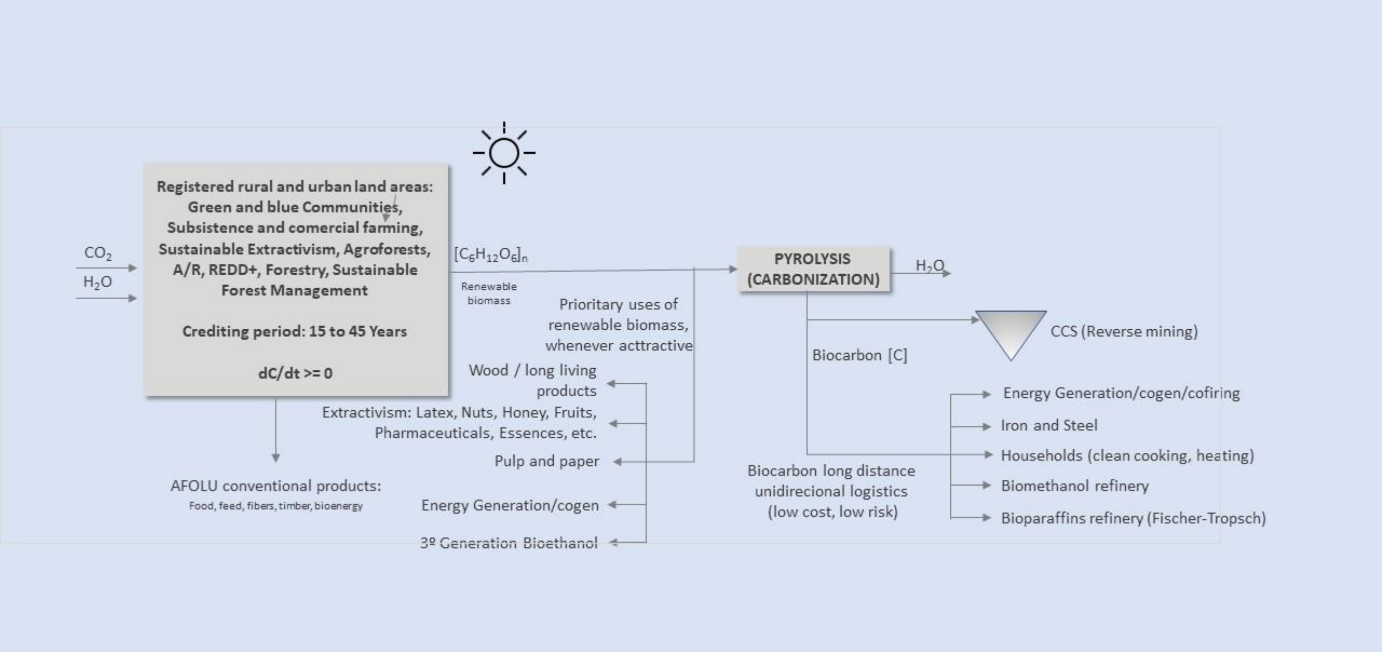

Figure 1: The AFOLU route and Biocarbon production, use and/or storage

A. Wastes Route (PCCS)

The urban wastes and residues route (the "waste pickers route") is based on the technologies for climate mitigation by means of circular economy and material efficiency[2] described in **Chapter 5 (Demand, services and social aspects of mitigation), Chapter 11 (Industry)** and **Chapter 12 (Cross-sectoral perspectives)** of the IPCC WGIII AR6 Report, 2022. Each participating community, locality or urban settlement is described for their geographic location within a network (a Project Activity – PA or Programme of Activities - PoA). The PAs and PoAs are supervised by a Coordinating Management Entity – CME, and registered as a Cooperative Approach under the **Glasgow Accords** (CMA 3 Decision 2 – Guidance to Paragraph 6.2 and Decision 3 – Modalities and Procedures for Paragraph 6.4 of the Paris Agreement). Once registered, the PAs and PoAs will be able to generate carbon credits tradable within the implementation of National Determined Contributions – NDCs of the countries or as **Internationally Transferred Mitigation Outcomes (ITMOs).**

Similarly to the biocarbon route, the activity starts with the collection of renewable biomasses associated with the urban wastes (domestic and commercial sources), as well as industrial wastes, and biosolids from wastewater treatment plants. These material flows also contain biobased carbon from vegetal or animal origins in the leftovers (food wastes, paper and wood, leather, cotton and natural fibers textiles, etc.). However, unlike the AFOLU route, these waste-based biomass products are usually in mixed composition with non-biobased polymers (plastics all kind, rubber, synthetic polymers, etc.) and other inert fractions or minerals (glass, metals, etc.). Therefore, the waste route is a different and separate technological course of actions: the wastes are primarily subject to the conventional segregation for the commercially viable, for example:

- **Reuse and/or Repair, Refurbish, Repurpose** for life-extension of useful goods;
- **Anaerobic Biodigestion** for production of biogas and/or biosolids;

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[2] According to the Netherlands Environmental Assessment Agency ten strategies for circularity are possible: Refuse (R0), Rethink (R1), Reduce (R2), Reuse (R3), Repair (R4), Refurbish (R5), Remanufacture (R6), Repurpose (R7), Recycle (R8), and Recover energy (R9).

- **Composting** for agricultural utilization of the compost;
- **Industrial recycling** for remanufacture of plastics, paper and cards, glass, metals, e-wastes, etc.

Carbon-recycling and PCCS:

The above recycling routes are not always commercially viable at all localities for different reasons, e.g.: gaps in the local capacity of wastes processing/segregation, gaps in the reverse logistic chains to bring the recyclables back to the industrial sector, or absence of technical viability of the recycling route for certain wastes. In all situations, the participant communities **will not** make use of conventional solid wastes disposal sites (SWDS). They will use instead the **slow pyrolysis** as a technology to process the wastes rich in carbon (either the organic biogenic or 'wet wastes' and plastic containing and or 'mixed wastes'). By means of the slow pyrolysis, carbon is artificially mineralized (made inert to biological or biochemical decay) allowing the storage at controlled sites in the reverse mining process called **"Pyrocarbon Capture and Storage – PCCS"**. The PCCS allows for quantitative measurement of climate mitigation outcomes (carbon credits for national or international markets) measured as the tons of equivalent emissions reductions or negative removals of CO_2 resulting from the following effects:

- Negative emissions (**CO_2 removals or reversals**) for the biogenic carbon content in the stored pyrocarbon wastes;
- Emissions reductions due to the **avoided combustion** or open burning of non-biogenic carbon that would otherwise be processed by the baseline waste management system;
- Emissions reductions by the **avoided methane** formation by the anaerobic biochemical decay of the wastes at the pre-existing waste management and disposal site/landfill;
- Emissions reductions by the **avoided leachates** formation and the corresponding avoidance of methane formation for the anaerobic decay or treatment or discharge of the leachates at the baseline waste management and disposal site/landfill;
- Emissions reductions by the **avoided nitrous oxide (N_2O)** formation at the biochemical anoxic decay of the organic nitrogen content of the wastes which would otherwise be processed by the pre-existing waste management system in the participant community.

To calculate the net effects, the process monitored by sampling and determination of the fractions of biogenic and non-biogenic carbon and nitrogen in the processed wastes, and storage will be quantitatively measured by the weight final mineralized wastes deposited in the storage site. The methodologies for monitoring the mitigation outcomes will follows the requirements of the **Supervisory Body (SB)** of Paris Agreement Paragraph 6.4 Mechanism. The recycling routes (all recycling technologies used at the participant communities, together with the carbon-recycling and PCCS route) will thus be able to generate carbon credits for use in the national or in international carbon mitigation markets.

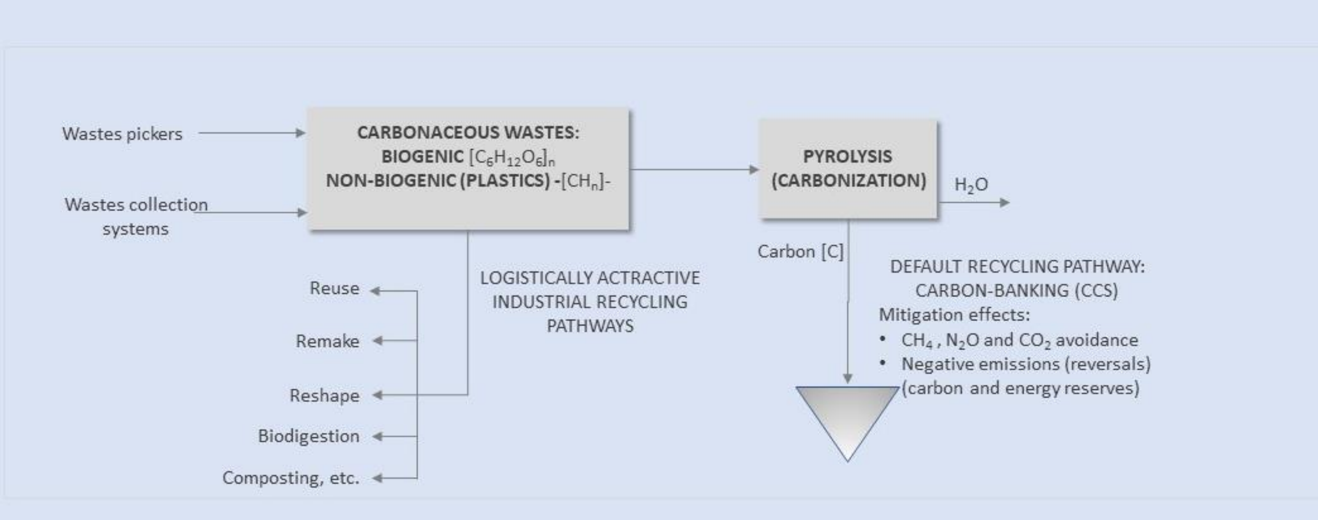

Figure 2: The urban wastes and plastic pollution route and pyrocarbon production and storage

B. Renewable Energy generation

As indicated above, both routes of carbon-recycling generate the stable and throughout pyrolysis mineralized or inert-made **Biocarbon** from the AFOLU sector, or the **Pyrocarbon** from the waste route. The biocarbon, besides being able to be stored for achieving the negative emissions (reversals), may also be a clean and safe source of **zero emissions energy source** for different industrial or energy processes. Biocarbon may be easily transported for long distances at low-cost, low-environmental risks logistic arrangements, for being water-compatible (don't causing water contamination) and able to floating transportation in rivers and oceans. Therefore, according to the market conditions, it may be used as **thermo-reductant** agent at iron and steel plants, or as **solid biofuel or co-firing** in coal or woodfuel power plants, or as carbon feedstock for **synthetic biofuels** production. For example, the biocarbon can be converted through gasification and **Fischer-Tropsch synthesis into bio-paraffin synfuel** for aviation or diesel engines, or **bio-methanol synfuel** for spark-ignition engines.

C. Reverse Mining and Carbon-Banking: intergenerational justice

The carbon-recycling approach for climate mitigation is based on a fundamental principle of circularity in the economic flows. The currently level of CO_2 in the earth atmosphere is caused by the historical failure of the market regulations during the last two hundred years of the industrial revolution, based on linear material flows: minerals all kinds and fossil fuels reserves were mobilized to feed the industrial and energetic consumption of the industrialized and developing countries, the emissions and wastes released or disposed without taking proper care of the consequences. Now, carbon-recycling may be pursued as a technologic pathway to promote the circularity by means of Carbon-Dioxide Removal – CDR. The excess CO_2 in the atmosphere may be harvested by a collective and cooperative initiative, worldwide, to capture it as biocarbon and/or pyrocarbon reserves to be stored safely and in tangible and physically registered way, creating artificially made reserves of carbon and energy for the future generations.

The proposal of ".G Initiative" is to start accumulating the recycled carbon in the open pits of exhausted mining sites (e.g. iron, cupper, asbests, gold, coal, and diverse available open caves). The biocarbon, which is made of carbon captured by the AFOLU sector, may safely deposited in those sites, without damaging the surficial water bodies and underground soil. After restoring the mining site to a desired topographic condition as close as possible of the pre-existing before the start of the mining activity, the resulting "reverse mine" will be covered by natural soils and revegetated. At the end, a new reserve of carbon (and energy) is created, and the ecological situation of the impacted mine sites restored close to the original undisturbed condition. Besides, the mining site is now containing an exactly known amount and quality of biocarbon reserves, able to be used by the future generations, when the climate and economic conditions allow or require this utilization. The carbon stored is thus belonging to the climate governance and registered as a reserve of what we may name “carbon-coins”: the global reserves of recycled biocarbon achieved by the cooperative approaches.

Similarly, the pyrocarbon from the carbon recycling routes based on urban and industrial wastes will be accumulated in properly designed and managed disposal sites, under stable and safe conditions. They will also constitute available reserves of carbon and energy, however, the level of presence of extraneous elements in the processed wastes will be indicative of potential risks if these reserves are used for energy, because there is a potential to formation of hazardous pollutants if the pyrocarbon is combusted for energy. In other words, pyrocarbon is not able to receive the label of a “recycled fuel” and, if used for energy, shall be by means of incineration plants, taking proper care of the atmospheric emissions and of the resulting ashes. However, the intention of the cooperative approaches is to promote the education of the participant communities, the urban waste route will thus progressively improve the level of segregation of the wastes.

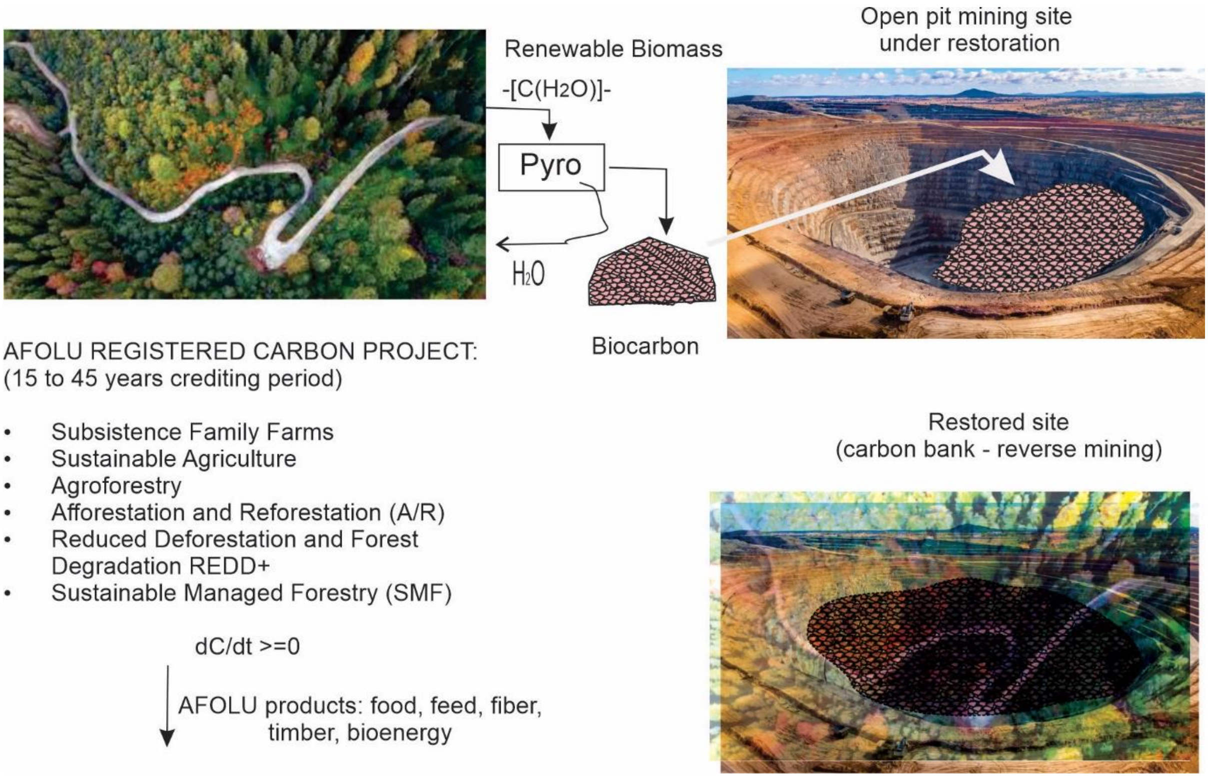

Figure 3: The reverse mining and carbon-banking approach for the biocarbon from AFOLU sector

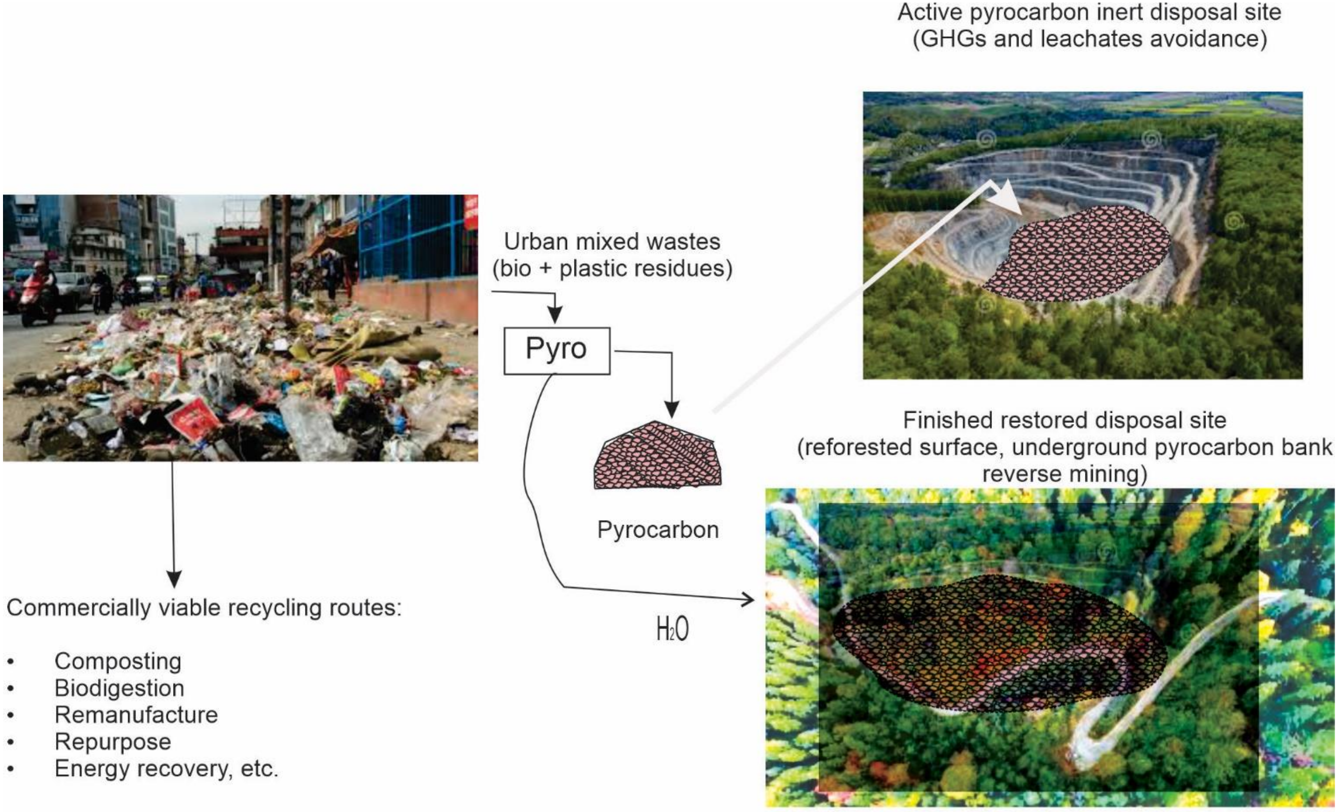

Figure 4: The pyrocarbon recycling route, based on mixed urban and industrial wastes

D. Universal income generation: intragenerational justice

As a newly introduced economic activity, the carbon-recycling routes may be shaped by the new markets for climate mitigation as a just transition, not only for its circularity in the management of material flows, but also in regard to the fair and just remuneration of the participant communities, worldwide. The carbon-recycling is a network where all the individual participants of the cooperative approaches, starting from the homework done by each waste or biomass generating activities: households wastes separated for the pyrocarbon route, farms and AFOLU activities producing renewable biomass for the biocarbon route, waste-pickers collecting plastic and other carbon wastes from the contaminated landscapes and water bodies, forest-keepers promoting the restauration or the conservation of natural ecosystems in individual or collective associations, etc. will be able to formally join the initiatives, and be recognized and remunerated for their efforts based on the primary activity of harvesting and making the harvest carbon feedstocks available to the cooperative approach, which follows the requirements set by the global climate governance (the Paris Agreement Paragraph 6.4 governance and the Monitoring, Reporting and Verification - MRV procedures). At the end, each verified amount of carbon recycled by the cooperative approach will be physically identified, and give rise to the corresponding **Certified Emissions Reductions – CERs** and/or **Certified Carbon Dioxide Removals – CCDRs**, which are remunerated by the market based on the carbon pricing representing the demand and offer of necessary CO_2 mitigation outcomes to be achieved towards the Paris Agreement joint mitigation goals for the National Determined Contributions – NDCs. Therefore, if the carbon pricing is set as a market value of each ton of CO2,eq. proportional to the debt between the current overall GHG global emissions and the deficit we have to cover to achieve the required pathway for the Paris goal (1.5 °C), the whole economic chain for the carbon recycling routes will be profiting and remunerated by the distribution of the financial flows from the demanding to the supply of mitigation outcomes.

At the bottom of the pyramid, the waste-pickers and forest-keepers will receive a share of the paid amount of money for the CERs and CCDRs achieved by the cooperative approach, proportional to the quantity and quality of the renewable biomass or carbon-containing wastes they deliver as primary feedstock. Similarly, the pyrolysis processing plants, the in the logistic involved transportation services, the biocarbon utilizing activity, or the carbon-banking activity will be implemented as regular businesses, with their market sustainability based on the carbon price that is a measure of the value paid by the demanding countries/entities interested in the carbon emissions allowances generated by the "carbon-coins" physically produced by the cooperative approaches, and certified under the Paris 6.4 Mechanism.

The intention of the ".G Initiative" is that each individual participant person, member of the communities involved in the cooperative approaches, are **individual account holders** in the carbon-banking system, applying fintech tools and blockchain carbon-tokens to identify and tackle the individual carbon-coins produced within the network. The carbon-coins will thus be permanently accounted for their current status as a physical asset, which is either deposited and kept stored in a reverse mining carbon-bank, or which has been sold and used for energy generation with the corresponding generation of CERs for displacing fossil carbon sources. Each carbon-coin is thus also accounted in the global carbon stocks, under an unique registry by the climate governance under UNFCCC Paris 6.4 asset account, the UNFCCC thus playing the role of a Central Carbon-Bank for the entire carbon-recycling activities.

E. Slow Pyrolysis and Carbonization: the "ugly duckling" among the technologies?

The heart of the technological approach is the pyrolysis plant used to convert biomass or solid wastes. Traditional charcoaling or carbonization is widespread technology practiced in all continents, mainly to produce charcoal for domestic application. The carbonization is however usually very criticized for being non-sustainable, causing deforestation, air and water pollution, and involving degrading and children work, notably in south America and in Africa.

However, the pyrolysis itself is not the cause or driver of these effects, on the opposite: the discrimination and criminalization, and the lack of any support or regulation for its proper development and utilization has turned into a "black-market" activity at the informal sector, processing unknown sources of biomass, using the simplest and less developed and less costly equipment and workforce as possible.

The traditional and simple charcoaling technologies are based on the ignition of the biomass in confined spaces with addition of small amount of air to make the reaction occur under expenses of the calorific value of the processed biomass, and without any recovery of the exhaust gases that are rich in several gases and organic vapors, including water and GHG e.g. methane.

Chemically, pyrolysis is a very complex chain of both homogeneous reactions (at solid phase) and heterogeneous solid-gas interface reactions. By just considering the input feedstock and output products, pyrolysis can be seen as a "destructive distillation" giving rise to three phases: a) the solid product rich in elemental carbon (here named biocarbon and pyrocarbon, but may be also called "char", "charcoal" or "biochar"), b) water physically released from the moisture content of the processed material, or chemically formed by the thermal decomposition of carbohydrates. When condensing this water, it will contain organic substances also originating from the process, water soluble, that are mostly oxygenates (alcohols, ketones, aldehydes, phenols), and may be named "liquor"; c) the non-soluble organic substances (named 'tars') that will be separated as an oily floating phase above the liquor, and d) the non-condensable gases encompassing methane, carbon dioxide, carbon monoxide, hydrogen, and other minor components.

The yield and the composition of each fraction are mainly determined by the time-temperature pattern during the process, being both the final temperature but in special the speed of temperature increase (the temperature ramp) the determinant factors. Fast and very fast also called “flash” pyrolysis will favor the condensable and gaseous products, whereas the slow pyrolysis will favor the solid phase as the main product. Pressure has also effects in the kinetics and the yields.

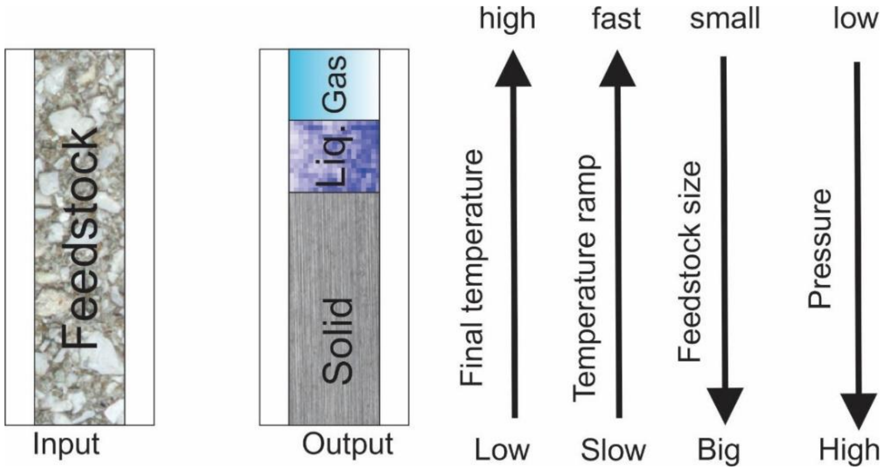

Figure 5: influence of manageable parameters on the yield of the main pyrolysis products: solid char, organic condensable vapors and tars, and gases.

As can be seen from the figure, the desired conditions to favor the solid biocarbon or pyrocarbon as the valuable product for climate mitigation are: low final temperature (but at least around 300°C are required to induce the thermal decomposition of the biomass), low heating rates, larger feedstock sizes, and higher pressures.

Pyrolysis may also be developed to focus on liquid and gaseous products, because they are also combustible, and possible substitutes or additives to the conventional gas and liquid fuels. In some instances, the fast pyrolysis process is named “bio-refinery” for producing a “second generation” biofuel or “bio-oil” to be further refined and gaseous fuels.

The carbon-recycling approach is however based on the most simple reactors for slow pyrolysis, the solid phase is the target product to be produced decentralized at remote sites worldwide. Slow pyrolysis has innumerous simplifications as compared with the more sophisticated fast and flash pyrolysis reactors. The reactor may have simple configuration in terms of form, volume, and constituting materials (bricks, metallic, etc.) and can be operated batch-wise or continuously e.g. screw-drive, moving bed (downdraft), or rotating cylinder. Larger plants can be built just by adding parallel processing reactors, exchanging heat when operating synchronously. They can process heterogeneous and variable substrates (composition, moisture content and size distribution) allowing for sufficient time-temperature patterns to make the conversion to completion irrespective of the initial charge. Small reactors for temporary operations at places where the harvested biomass will be available for short periods (e.g. in event of agricultural losses, or for collecting plastic wastes), can be used in transportable platforms. The gaseous and liquid products don’t need to be recovered, may be used for thermal energy generation to supply the reactor itself. For example, the following figure shows the “Pyrolix” process developed at UFMG and tested for urban, health care, and industrial wastes, using this post-combustion of released gases and vapors.

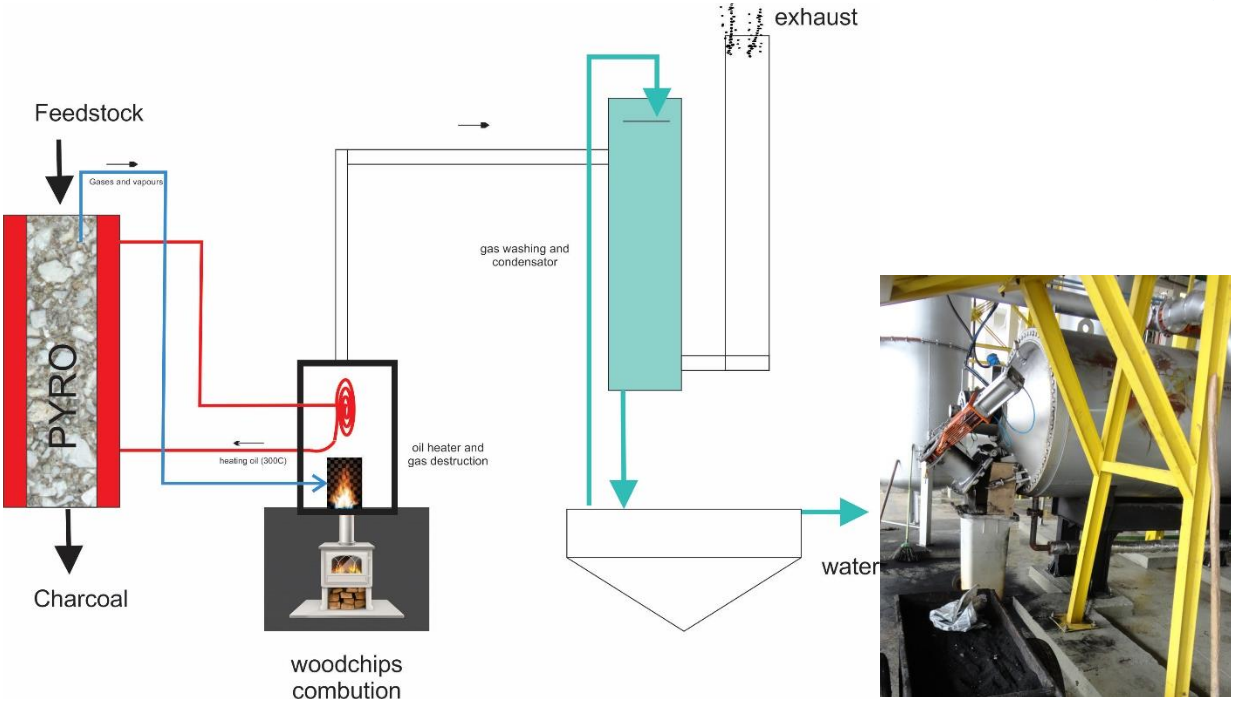

Figure 6: Pyrolix process (UFMG – E9 project). At the left the flowchart is shown. Feedstock is processed at 300°c in a reactor that is heated from outside by a circulating thermal oil in closed loop. The oil is heated by an auxiliary woodchips combustor. Gases and vapors released are burnt for thermal destruction with energy generation combustible gases (methane, carbon monoxide) and organic odors are destroyed. A washing tower serves as gas cleaning and water condensation, the excess water is removed and may be used for controlled application on soil irrigation. At the right a picture of the pilot plant tested for wastes and biomass treatments.

The only two main products of the plant are therefore the biocarbon/pyrocarbon and the condensed water, this water may be used under controlled conditions for soil irrigation. Exhaust gases contain only wood combustion products (from the auxiliary fuel used), and combustion products from the gases and vapors released from the pyrolysis reactor, thus, no harmful pollutants.

For the larger scale application, using lignocellulosic woody or from AFOLU generated renewable biomass, there are several developments of carbonization reactors, with the collection and treatment of gases and liquors. In a recent report prepared for the UNDP, the charcoal-based iron & steel and metallurgical industry in Minas Gerais was described for their achievements in the development of carbonization reactors[3]. Among them, the following figure describes one of the technologies evaluated and reported.

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[3] Waycarbon Report: "Diagnóstico de Emissões Indiretas de Gases de Efeito Estufa (GEE) das Propostas Apoiadas pelo Programa das Nações Unidas Para o Desenvolvimento (PNUD) através do Projeto Siderurgia Sustentável", 2021.

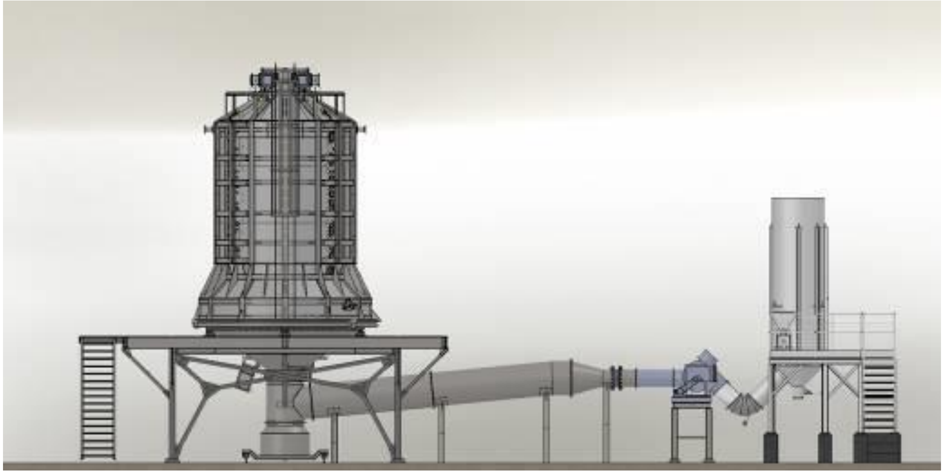

Figure 7: RIMA Container Furnace. Industrial wood carbonization furnace developed by RIMA Industrial Ltd in Bocaiuva – Minas Gerais. (Source: Doctoral Thesis Adriana de Oliveira Vilela – UFMG – 2014)

F. Carbon Dioxide Removals or Emissions Reversals: the necessary action for reaching Paris Agreement global commitments

The use of slow pyrolysis for negative carbon emissions has been realized years ago at UFMG. In 2007 the proposal was submitted to the UNFCCC Executive Board for Clean Development Mechanism (CDM-EB) as a baseline and monitoring methodology based on controlled pyrolysis, including the carbon storage as a quantifiable negative emissions component for the calculation of Certified Emissions Reductions – CERs. However, the proposed methodology was not accepted by CDM-EB with this negative emissions component, for not being compatible with the 'Marrakech Accords', where the CDM has been created under exclusion of avoided deforestation and carbon removals, except for the afforestation and reforestation (UNFCCC 2005).

Now, where the Paris Agreement has formally accepted the removals by sinks as technologies for climate mitigation, and the IPCC AR6 WGIII is recommending the large scale adoption of CCS and CDR technology for achieving the Paris goal of 1.5°C overall warming, the carbon-recycling become not only institutional acceptable, but, more than this, it is financially attractive option to be added to the portfolio of the much more complex and expensive technologies preconized by IPCC, namely the Bioenergy with Carbon Capture and Storage - BECCS.

The following table makes a comparison between the main features of the approach based on carbon capture and storage (CCS) based on Bioenergy with Carbon Dioxide Capture and Storage (BECCS), as preconized by the IPCC, and the here proposed approaches based on carbon recycling (Biocarbon and/or Pyrocarbon harvesting and storage). It is easily concluded what are the advantages and enhanced economic attractivities of the carbon-recycling, as compared to the BECCS. It is worth to note, however, that the two approaches BECCS and Carbon Recycling are not necessarily competing to each other: the Biocarbon, as a biobased energy carrier, is also a possible feedstock for BECCS plants, in sites where its use for energy generation and storing the CO_2 from its combustion are demonstrated as more attractive by a financial analysis.

Table 1: Technical and economical comparison between two possible negative emissions technologies: Bioenergy with carbon dioxide capture and storage (BECCS) and the here proposed carbon recycling.

Criteria for comparison	Bioenergy with Carbon Dioxide Capture and Storage (BECCS)	Carbon Recycling
Source of feedstock	Renewable biomass or biofuels originated sufficiently close to final energy (electricity) grid and to secure CO_2 geological storage site. Long distance transportation of crude biomass/biofuel, electricity output, and gaseous CO_2 may impose exponentially increasing costs.	Renewable biomass and or urban solid wastes. The feedstock may be processed locally, and stored locally above ground or underground at any close favorable site, until it is processed. Tangible assets of carbon are generated and may be tracked for permanence.
Carbon sequestrating substance	Gaseous CO_2 (44 g.mol^{-1})	Biocarbon, mainly solid elemental carbon (12 g.mol^{-1}), less dense than water (floatable).
Energy balance at the processing	Strong exothermic combustion, bioenergy is released and can be used; most part is dissipated to the environment. High energy penalty for the necessary separation of CO_2 from other gaseous combustion products.	The pyrolysis process is slightly exothermic, very limited potential of energy generation on site, most part of the bioenergy is preserved at the elemental carbon that is a product of the process. No relevant energy penalty.
Side products	Inert gases and vapors (N_2, H_2O), ashes, no hazard atmospheric or water pollutants.	Water liquors able to be used, small amounts of ash from auxiliary biomass fuel also able to be used. No hazard atmospheric pollutants.
Stage of development	Experimental pilot plants under testing conditions.	Ancient technology widely used, but at very low stage of development. Technological gaps may be subject to quick developments.
Complexity for installation, operation and maintenance	Very high, requires high specialized labor and equipment.	Very low, can be operated by intermediate education level workers, even household devices are able to be developed and made commercially available.
Size scale of the plants	Large scales are required (biomass sources from a relatively large catchment area to be transported to the plant).	Any size from nano-, micro-, small- to very large-scale plants are conceivable.
Consumables	Depending on technology, demand of consumables for gas separations, e.g. CO_2 absorbents or membranes.	No purchased consumables required, low power electricity, that is able to be generated by the plant itself (e.g. organic Rankine cycle – ORC), or by auxiliary biomass based generation.
Transportability of the plant	Not feasible	Possible. Mobile processing plants transportable over water or ground are conceivable.
Size limitation of the carbon storage space	Limited by the geological formation where the gaseous CO_2 is stored. Once exhausted this space, the plant shall be decommissioned or the gaseous CO_2 transported to long distant storage sites using high cost gas transportation modes.	Unlimited, possibility of long distance transport at low cost one directional and relatively safe mode floating on river waters, and able to be transported or longer-time kept overseas.
Accountability of negative carbon emissions	Amount of gaseous CO_2 produced and sent to geological storage can be measured, but the permanence of the stored gas is a matter of discussion and difficult or impossible to monitor.	Simple metrics based on weight and fix carbon content. All amounts transferred can be easily measured and the stored amount can be monitored at any point in space or time. Losses are mainly by risk of fires, easily to be identified and quantified for discounting in case of accidental fires.
Reversibility	Irreversible. The CO_2 stored cannot be retrieved back to the atmosphere for any human or biogeochemical service.	Reversible. The CO_2 is stored in the form of solid elemental carbon until it becomes able to be used in a climate friendly way. A circular recycling route for carbon is created.

G. Additionality, Tangibility, Permanence, International Transferability, Granularity: climate mitigation in participative and cooperative approach.

The conventional methods to demonstrate and measure the effects of climate mitigation project activities (UNFCCC CDM and other market-based mechanisms based on the “cap and trade” principle) are based on monitoring of the **“baseline”, “project” and “leakage”** level of emissions. The effect of the project is estimated ex-ante and monitored ex-post during the crediting period, during which it is assumed that the action (the project scenario) is causing a net environmental effect of reducing the emissions levels below the baseline scenario. The baseline is either the pre-existing, historical levels of the emissions, or the emissions expected by the extrapolation into the future of the “business as usual – BaU” continuation of the economic activity, without having implemented the project. If any increased emissions are expected to occur at the neighborhood of project, and are attributable to its implementation, this effect is considered as leakage and needs to be monitored and discounted. At the end, the monitoring will allow to calculate the **Certified Emissions Reductions – CERs**, which are able to be commercialized in the market as emissions allowances for offsetting the non-mitigated emissions for the other businesses or players in the regulated market, for which there is an overall limit of GHG allowed by the agreed cap required to achieve the climate mitigation goals. The following figure describes the market mechanisms approaches as designed for the Paris Agreement, in order to arrive at the stabilization of the mean global temperature increase at the limiting level of well below 2°C, pursuing the limitation of 1.5°C temperature increase above the pre-industrial levels. The carbon mitigation outcomes achieved in the countries will be used to fulfill their own National Determined Contributions (NDCs), which will be tightened up to the net zero global emissions levels at the middle of the centuries. The market mechanisms set by the Paragraphs 6.2 and 6.4 of the Agreement, however, following the Glasgow Accords, allow for International Transfers of Mitigation Outcomes (ITMOs) among the countries, or to the voluntary market for carbon offsets. The first market exchange window will last up to the year of 2030. Every 5 years the NDCs achievements will be demonstrated, and further adjusted. A next time window for ITMOs negotiations is thus opened.

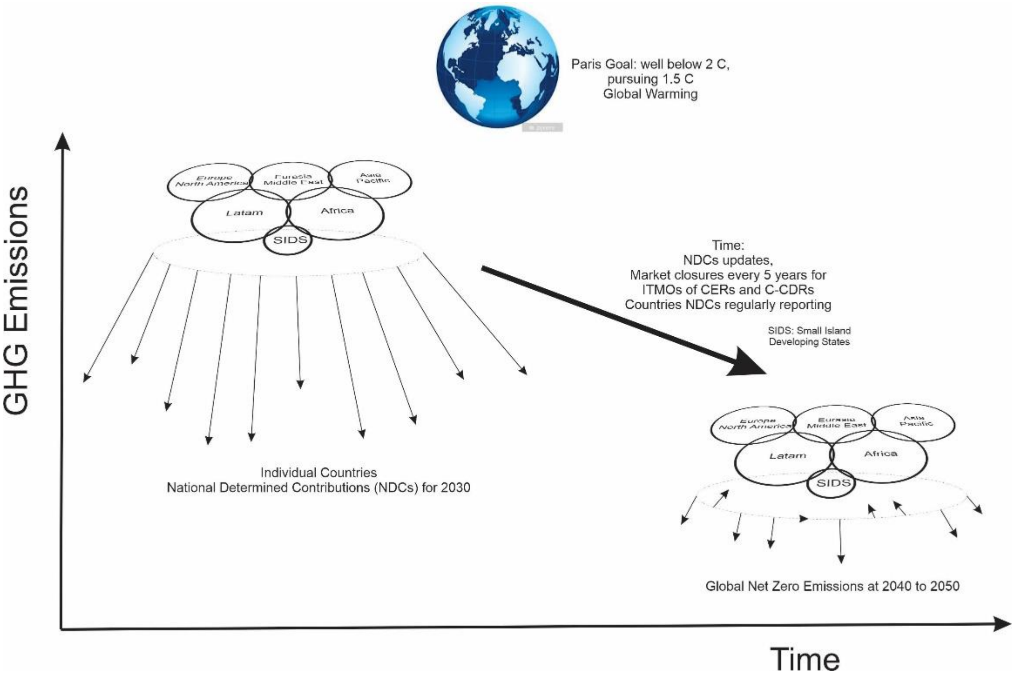

Figure 8: The Paris Agreement approach for the National Determined Contributions (NDCs) convergence to the overall cap on global mean temperature increase above pre-industrial levels. The NDCs shall achieve

the net zero global emissions level in the time between 2040 and 2050, the International Transfer of Mitigation Outcomes (ITMOs) based on the Glasgow Accords (Market mechanisms of Paragraph 6.2 and 6.4) will assist NDCs to arrive at their targets, the market for ITMOs transfer has closures at each 5 years intervals, starting 2030.

Automatic Additionality. In the climate mitigation market mechanisms, however, any project activity, before registration, needs to pass the additionality test: the demonstration that the project is achieving an emission reduction below the cap that has been set for this activity under the enforcement of the agreed commitments. The additionality test is a challenging tool to be set by the regulatory bodies, and to be demonstrated by the project activities. However, whenever a technology is adopted where the only and solely effect is the climate mitigation, and this effect does not generate any economic revenue, the project is deemed as automatic additional. Classical example for that is the methane flaring from biogas or fugitive methane emissions, which are automatic additional under CDM. The Carbon Recycling as a technology able to achieve Certified Emissions Reductions (CERs) and Certified Carbon Dioxide Removals (C-CDRs, negative emissions) is also automatic additional: pyrolysis of renewable biomass or solid wastes and secure storage of the biocarbon or pyrocarbon for the future does not generate any financial revenues, only costs. Therefore, the only income carbon-recycling projects are able to receive are for climate mitigation effect, and for the achieved CERs and CDRs certificates, at the carbon pricing set by the demand and offer of these certificates. Being climate mitigation the only driving force to promote and implement carbon recycling, the Supervisory Body of the Paris Agreement Paragraph 6.4 mechanism will be able to declare publicly and transparently that any Carbon Recycling project is exempted from demonstrating additionality.

Tangibility and Permanence. The conventional market-based climate mitigation projects also need to be monitored for their net effect in reducing emissions by monitoring the baseline, project, and leakage effects as described above, and the results of the measurements need to be verified by independent auditors, based on the evidence provided by measuring instruments, e.g. the recorded energy generation and/or use, the flows and composition of gaseous streams consumed in methane flaring systems, etc. In the case of carbon recycling, the net outcome of the mitigation activity is the tangible physical quantity of mass of biocarbon and pyrocarbon produced by the pyrolysis plant and stored at the disposal site (reverse mining). This amount is available for any materiality check during the entire existence of the site. It means, at any time in the future, the quantity and quality of the stored material may be easily checked by tangible measurements of mass/volumes, and by sampling to demonstrate the quality of the stored recycled carbon. This makes the quantitative determination of the emissions reductions and carbon dioxide removals straightforward and quantitatively measurable, during its produce or at any time in the future. Besides, in the case of AFOLU based biocarbon route, the measurement of the carbon pools in the land used to produce the renewable biomass are also checkable and monitored quantitatively by straightforward methods (biomass above and below ground, soil organic carbon) thus allowing for an undisputed proof of the achieved outcomes. Each ton of CO_2 removed from the atmosphere corresponds to a precise amount of 272.72 kg of carbon. Each cubic meter of biocarbon and pyrocarbon produced and stored will be measured for its carbon content (based on bulk density and fixed carbon content, which are easily measured at the process), and the precise amount of CO_2 removed from the atmosphere is thus exactly known. At the storage site, this amount may be checked any time by the measurement of the stored volumes and taking samples as necessary to determine the quality of the stored reserves, tangible, thus being stored as a physical asset of “carbon-coins” in the reverse banking approach. It is like the creation of a physical treasured amounts of negative emissions (removals or reversals) registered at the global climate governance by the UNFCCC as the regulatory body for measuring and recording the achieved outcomes. This tangibility is a unique and singular characteristic of the carbon-recycling mitigation methods, under the global governance of the Paris Agreement market-based mechanisms. Any losses of biocarbon or pyrocarbon stocks, e.g., eventually in case of accidental fires during the transportation and or disposal can be quantitatively measured and reported, and the effects on the accounted Certified CDRs and CERs are able to be removed from the registry. Conventional insurance or liability coverages can be used to cover accidental losses, based on the risk analysis of safety preventive measures at the producing, transportation, and storage of the coins.

International Transferability. The Paris Agreement market mechanisms for climate mitigation (Paragraphs 6.2 and 6.4) are based on the National Determined Contributions – NDCs of all the 194 countries that are part of the Agreement. Any international use of mitigation outcomes for the use at another country or in the voluntary markets requires the first transfers of **"International Transferred Mitigation Outcomes – ITMOs"**: the mitigation achieved in any host country, in order to be used outside the country, need to be excluded as achievements by the host NDC and thus made tradable for inclusion at a purchasing foreign NDC or at any business/entity interested in their acquisition for carbon offsets purposes. Carbon recycling, however, has not yet been part of any country NDC commitment, because the technological approach has not been in any approved method under Kyoto CDM, or even in the recently released IPCC mitigation technology portfolios (WGIII AR6 Report). We may state without any doubt that the carbon recycling is totally new and first ever announced technology up to this moment, where this .G initiative is released, in the 22 September 2022[4].

Granularity. The pyrolysis processing plants for renewable biomass and for solid wastes treatment within the cooperative approaches may be implemented territorially segregated into individual "captive carbon capture catching regions", i.e., split as single registered facilities designed and operated to collect the contribution from nano-scale communities (which feedstock generation is in the scale of kg/week, e.g. few households or group of farms), micro-scale (tons/week communities or sources), or small-scale (tons per day) or large-scale (tons per hour). The regional segregation of the carbon-recycling network is a feature that allows it to be classified as a "grassroots innovation" or a "granular technology" (see IPCC WGIII AR6 section 5.5.3), with the following advantages for its dissemination: *"smaller scale, more 'granular' technologies are empirically associated with faster diffusion, lower investment risk, faster learning, more opportunities to escape lock-in, more equitable access, more job creation, and higher social returns on innovation investment. These advantages of more granular technologies are consistent with accelerated low-carbon transformation"*. The carbon-recycling has thus this capability of an exponential disruptive increase of its utilization, once it is accepted formally accepted by the Paris Agreement Paragraph 6.2 and 6.4 mechanisms and being able to receive the labeling as a "nature-based solution" for climate mitigation.

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[4] The carbon-recycling has been submitted by the authors and founders of ".G Carbon-Recycling initiative" to peer reviews scientific journals in the past, but has not been yet published. Therefore, although not proprietary, for not being subject to requests for patents or exclusivity in their development and use, the carbon recycling is an innovative climate mitigation action. The Environmental Engineering Department of UFMG in Belo Horizonte, Brazil, has been the origin the pyrolysis research activities giving rise to the carbon-recycling as a negative emissions technology, several master and doctoral theses have dealt with the subject. We may consider the carbon-recycling approach as a "recombinant innovation" defined by IPCC WGIII AR6 Section 16.2.2.2. as follows: *"experimenting with existing knowledge and combining different technologies, knowledge spillovers can result in the emergence of novel technological solutions, which has been referred to as recombinant innovation. Recombinant innovations speed up technological change by combining different technological solutions, and make things happen that would be impossible with only incremental innovations"* (page 16.16). If necessary, the carbon-recycling may be evaluated within a Technology Readiness Assessment (TRA) as indicated by the same WGIII AR6 Section 16.2.1.4. Unfortunately, UFMG has not been supported locally to implement the technology to the commercial status. The only commercial plant designed by the developers to treat the solid wastes at the city of Ponte Nova was interrupted by the local justice authority and remains out of public support.

H. Co-benefits: biodiversity, oxygen, water, social inclusion, income generation, individual/local interconnection to the global climate governance, and a chance for a just transition

Climate mitigation is the motivation and, if carbon pricing is introduced for achieving the goals of the Paris Agreement, the payments for CERs and C-CDRs are the major source of finance for the carbon recycling. Nevertheless, several other co-benefits in the environmental, social, and economic aspects are achievable by carbon recycling, many of them may be quantified and subject to proper payments, if there are financial mechanisms in place. Some of these are shortly described below and may be further detailed in future blogs within the www.carbon-recycling.eco platform.

Biodiversity. The participant urban or rural areas taking part in the carbon-recycling may be either subject to cultivation of agriculture or forestry, or in water bodies, subject to sustainable management practices to keep or enhance the carbon stocks. Natural ecosystems being eligible among them, e.g. in projects based on the approaches of Reduced Deforestation and Forest Degradation (REDD+), Afforestation and Reforestation (A/R), Sustainable Forest Management (SFM), etc., will be directly monitored during the crediting period (which, as per the Paris Agreement Paragraph 6.2 mechanism may last from 15 to 45 years), ensuring the carbon stocks are kept constant or increased. Therefore, these areas will be protected both against the anthropogenic impact of depleting carbon stocks, as well as from natural or human and climate change induced negative events (e.g. wildfires, droughts, floods), thus improving the ecological quality of the land and water bodies/oceanic ecosystems. Further, when the reverse mining concept is adopted, the restoration of natural ecosystems in exhausted mining sites can promote the recovery and reintroduction of native ecological assets. Biodiversity is thus measurable outcomes of carbon-recycling.

Oxygen and water. Unlike the BECCS systems for negative emissions based on bioenergy generation (combustion) followed by storage of the gaseous CO_2, the carbon-recycling is based in the storage of carbon (bio- or pyrocarbon) and the atmospheric oxygen (O_2) is net generated by the photosynthesis and will not be consumed until the stored carbon in the reverse mining sites are allowed to be used for energy by the future generations. Therefore, a net O_2 generation is also an outcome of the carbon recycling approach. Further, water and the hydrological cycles are benefited in different manners. First, by the regreening of the land and protecting the blue infrastructure in continent and water bodies or oceans where the biomass is harvested (e.g. when seagrass or macrophyte renewable biomass used as feedstocks). The protection and improved carbon stocks in the forests and urban/rural green land will improve the hydrological cycles flows, avoiding or reducing the intensity of extreme weather events (droughts, floodings, fires). Moreover, as described in the technological conversion process, water or aqueous liquors are also net outputs of the biomass and solid wastes treatment by pyrolysis, and these water outputs (from the moisture of the biomass processed or chemically formed in the thermal carbohydrates decomposition) can be used for controlled irrigation or ferti-irrigation of cultivation plots.

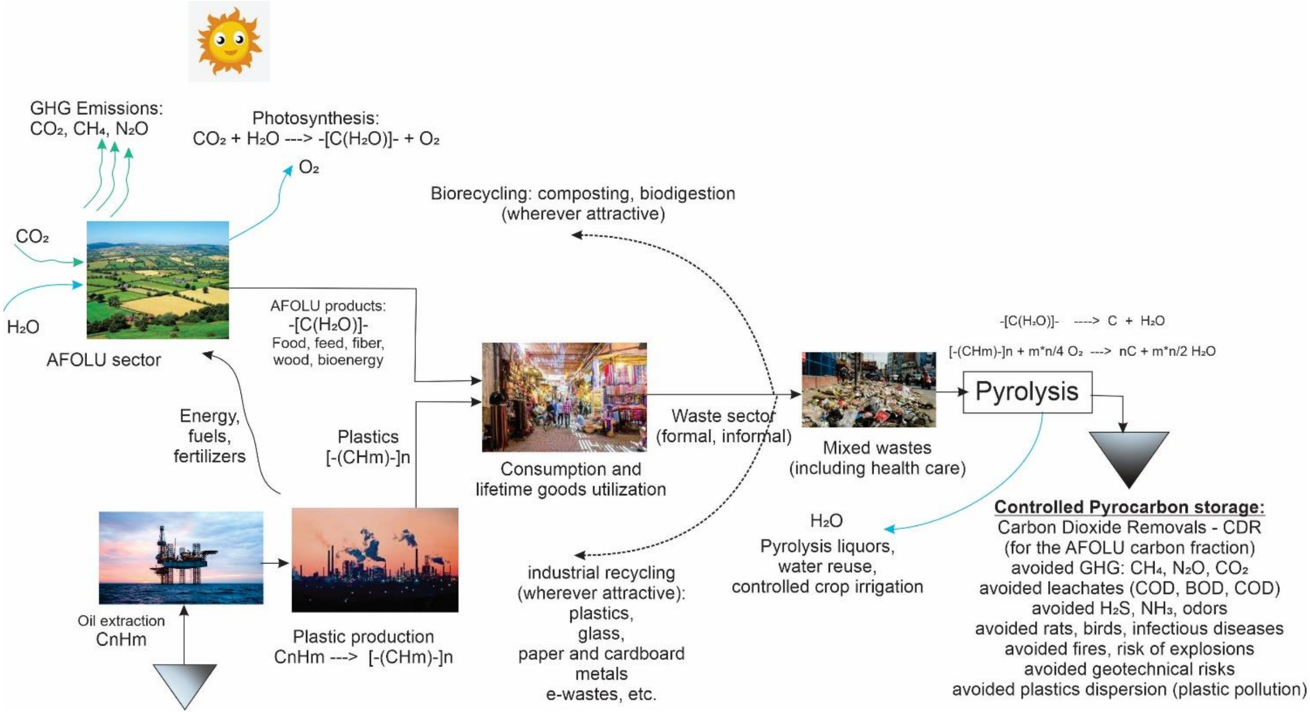

Figure 9: The many environmental and biophysical co-benefits of the carbon-recycling approach, for the wastes sector route. Some of these co-benefits can be quantified and subject to payments for environmental services. The co-benefits in the socio-economic aspects are not highlighted here, and are separately discussed below.

Social inclusion, income generation. The carbon recycling based on carbon pricing remuneration will be an extra and additional source of income for the local populations, everywhere the activity is introduced, that will be added to the remunerated or non-remunerated subsistence activities already practiced in all places where it is introduced. As described earlier, it is a possible source for generating a minimum universal income to the participant populations, connected to the network of pyrolysis plants that will be installed to process the raw materials from the forest keepers and waste pickers (belonging to formal and informal sectors). It doesn't impose any change or displacement of existing AFOLU or wastes collection and recycling activities and does not involve any shift in the pre-existing activities and populations, on the contrary: the carbon recycling is an additional source of income worldwide, sourcing its feedstocks from the existing or improved AFOLU and Wastes management systems. The result is the addition of income to the already established local production chains based on agriculture and recycling, at the rural and at the urban areas. The pyrolysis plants may be implemented as community-based equipment, operated locally, using local workforce, and serving to the collection and processing of the not yet valuated materials in urban and rural communities, and from indigenous native populations.

Individual/local interconnection with the global climate governance. Climate mitigation is an action towards the atmosphere as part of the "global commons", and the Paris Agreement, being ratified by 194 countries, is creating the basis for cooperative approaches under its Paragraph 6.2 and 6.4. This means, the global climate governance under UNFCCC may interconnect not only countries NDCs, but also their disaggregation into subnational (e.g. provinces and cities) levels, and, ultimately, to individual persons or households. The possibility that the negative emissions promoted by carbon recycling are stored by the reverse banking of "carbon-coins", e.g. the reverse mining of physical assets, allow to create an interconnection between the providers of feedstocks (the forest keepers and waste pickers) with the individual or institutional market players demanding emissions allowances, e.g. citizens and businesses in the developed or in developing countries, according to the NDCs. The common governance of PA6.2 and PA6.4 mechanisms will create the interconnection to bring all individual suppliers and demanders of carbon-coins in a network where each ton of CO_2 recycled and kept under the reverse banking is validated and verified independently by the common global governance of the UNFCCC, using the services of independent Designated Operational Entities – DOEs in similar manner as the conventional carbon offset mechanisms. In other words, the carbon recycling may allow to create under the UNFCCC a central registry (like a Carbon Central Bank) for each achieved carbon-coin, and their physical banking may be connected to the a of an asset of amounts of negative emissions negotiated to achieve individual, local, regional, national and global mitigation outcomes, excluding any possibility of **double counting** the achieved outcomes, thus ensuring environmental integrity to the bank accounting system for the negative emissions.

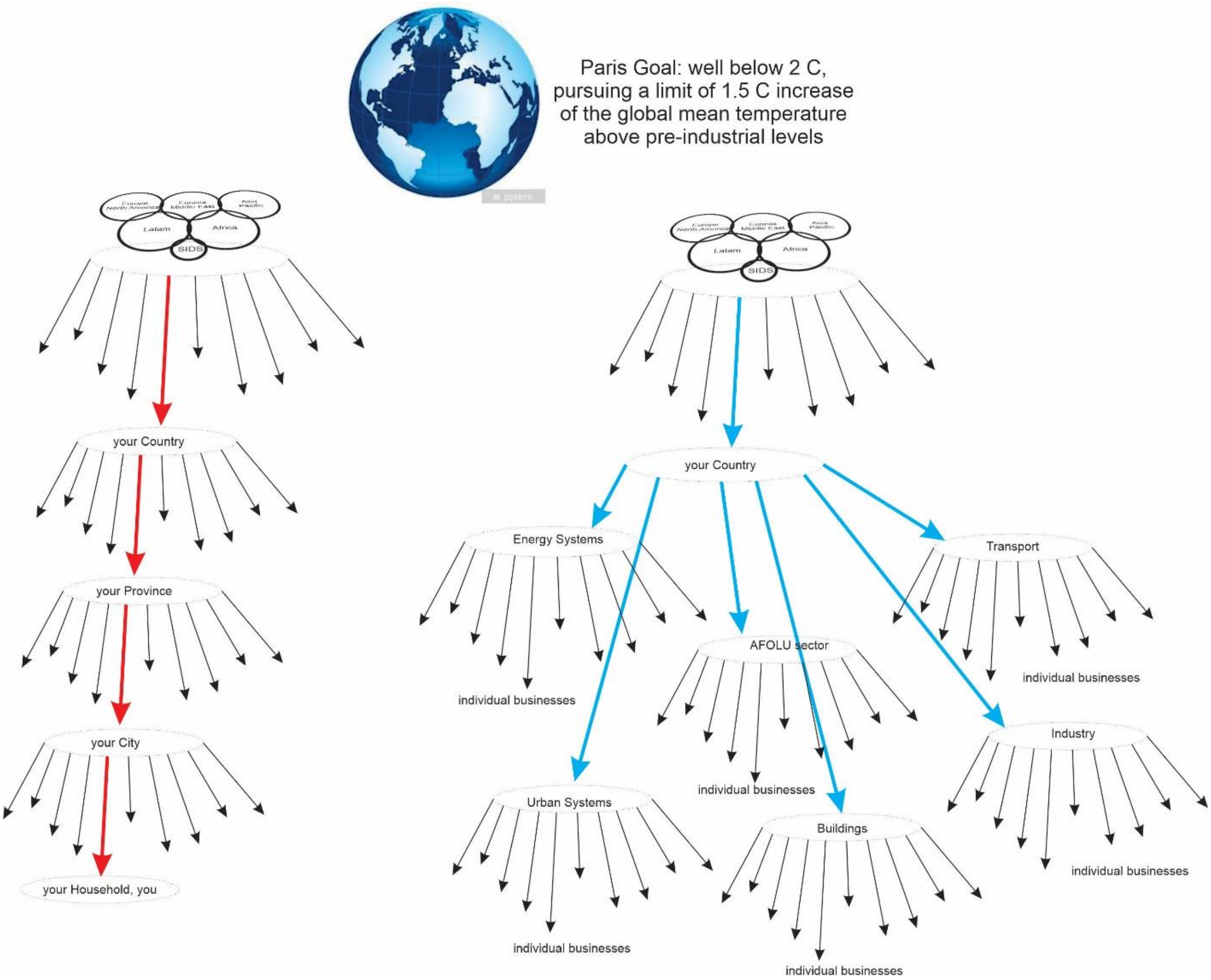

Figure 10: The potential disaggregation of NDCs regionally (left) up to the individual households or citizens (demand side), and for sectorial contributions (right) for the individual businesses (supply side). The countries may split their NDCs to attribute internally commitments (e.g. in a national market based mechanism) for implementation of the mitigation effort. When setting targets or "caps", the principle of a common but differentiated responsibility may be used to impose the expected contributions for each individual person or enterprise.

A chance for the just transition. The IPCC WGIII has highlighted the concept just transition as the most desired pathway for the "race to zero", that is, the shift from the present high emissions levels of the human economic activities into the net zero emissions scenario required by the middle of the century. The just transition requires a fair distribution of gains and costs for the winners and losers at the transition, thus, taking into account the interests of the incumbent sectors (and their investors and workforces), that will need to transit to the net zero by means of the reduced emissions (CERs) and for the negative emissions (C-CDRs). Carbon recycling is an approach that bridges the incumbents responsible for the large emissions levels presently, e.g. the fossil fuel based energy generation, transportation, industry, etc. to the reverse recyclers (waste pickers and forest keepers), as well as the bridge between the larger emitters countries and companies with the developing world with the adequate flows of values and of mitigation outcomes based on a common and unambiguous metrics of the carbon-coins. This bridging can be based in the concept of financial flows that matches the material flows, with the sectoral or geographic disaggregation of the NDCs to create a global market of emissions and removals (see figure).

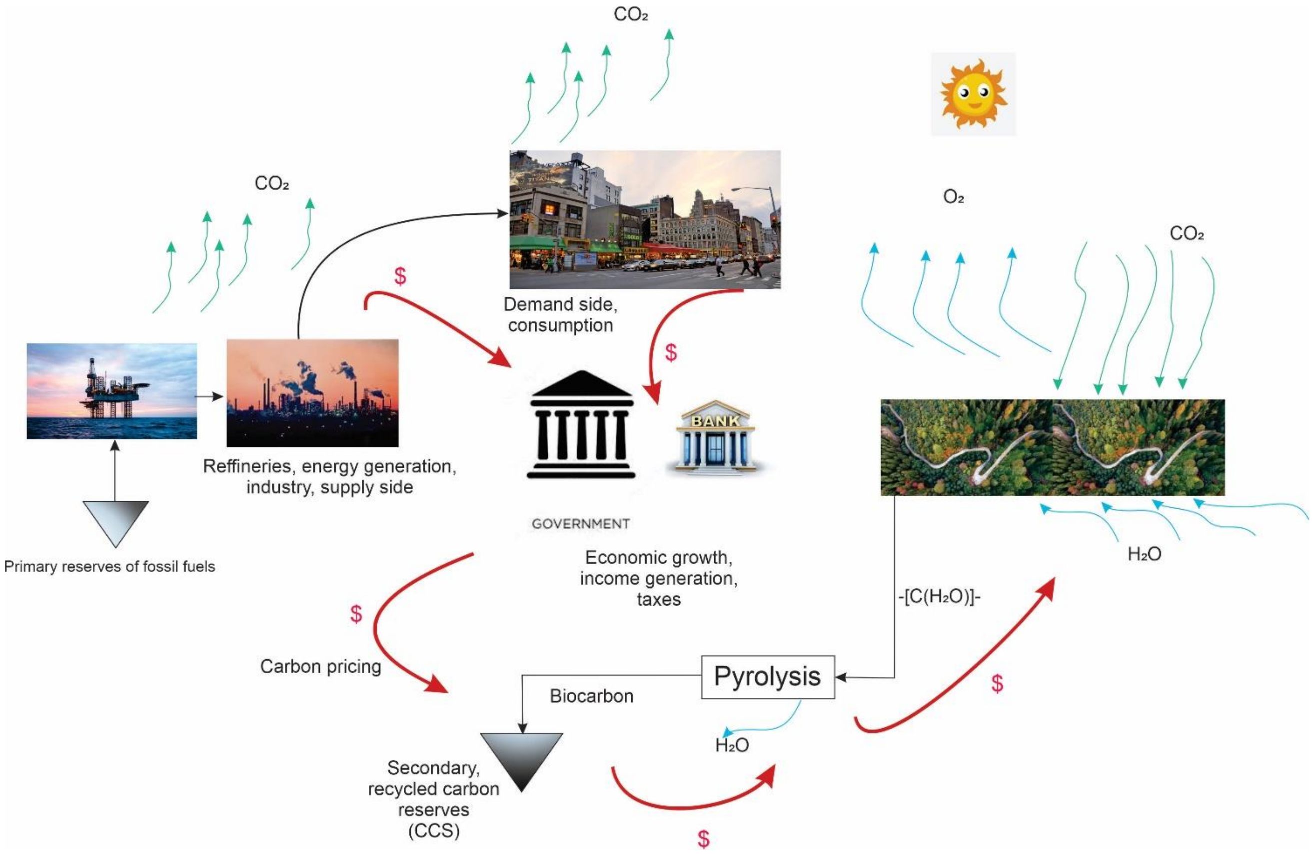

Figure 11: The interconnection of material flows for direct emissions and carbon dioxide removals, here taking the AFOLU route as the example, and the financial flows for using market mechanisms as the driving force for the carbon-recycling.

I. Circular economy and carbon pricing: the two milestones

Carbon-recycling may be seen as a collective global “geoengineering” project, aimed to revert and stabilize as much and as quick as possible the GHG flows, reducing the radiative forcing caused by the enhanced CO_2 levels in the atmosphere, as the climate emergency is now requiring. Figure below describes the insertion of carbon-recycling into the economic flows. It is evident from the figure that two principial and fundamental changes in the market economy are indispensable to make the carbon-recycling approach as a nature-based solution and, same time, a market based solution for climate change mitigation:

1. The circular economy, where the material flows of minerals (not only carbon) are made reversible, either by their industrial recycling or by their reverse mining in stable mineralized forms, stopping the accumulation of gases and waste materials in the atmosphere, land and oceans.
2. The carbon-pricing as remuneration for the reverse flows (based on quantified amounts), as a tool to internalize climate and environmental externalities, the payments for environmental and climate services being thus the driving force for reversing the linearity of traditional economic flows.

Circular economy and carbon pricing are thus milestones for the shift. Individual and collective actions, from the local throughout the regional and national, up to the global levels, will result in the governance of the earth commons (the atmosphere, the oceans, the natural ecosystems, and the human economic/ecological ecospheres) in sustainable and cooperative manner.

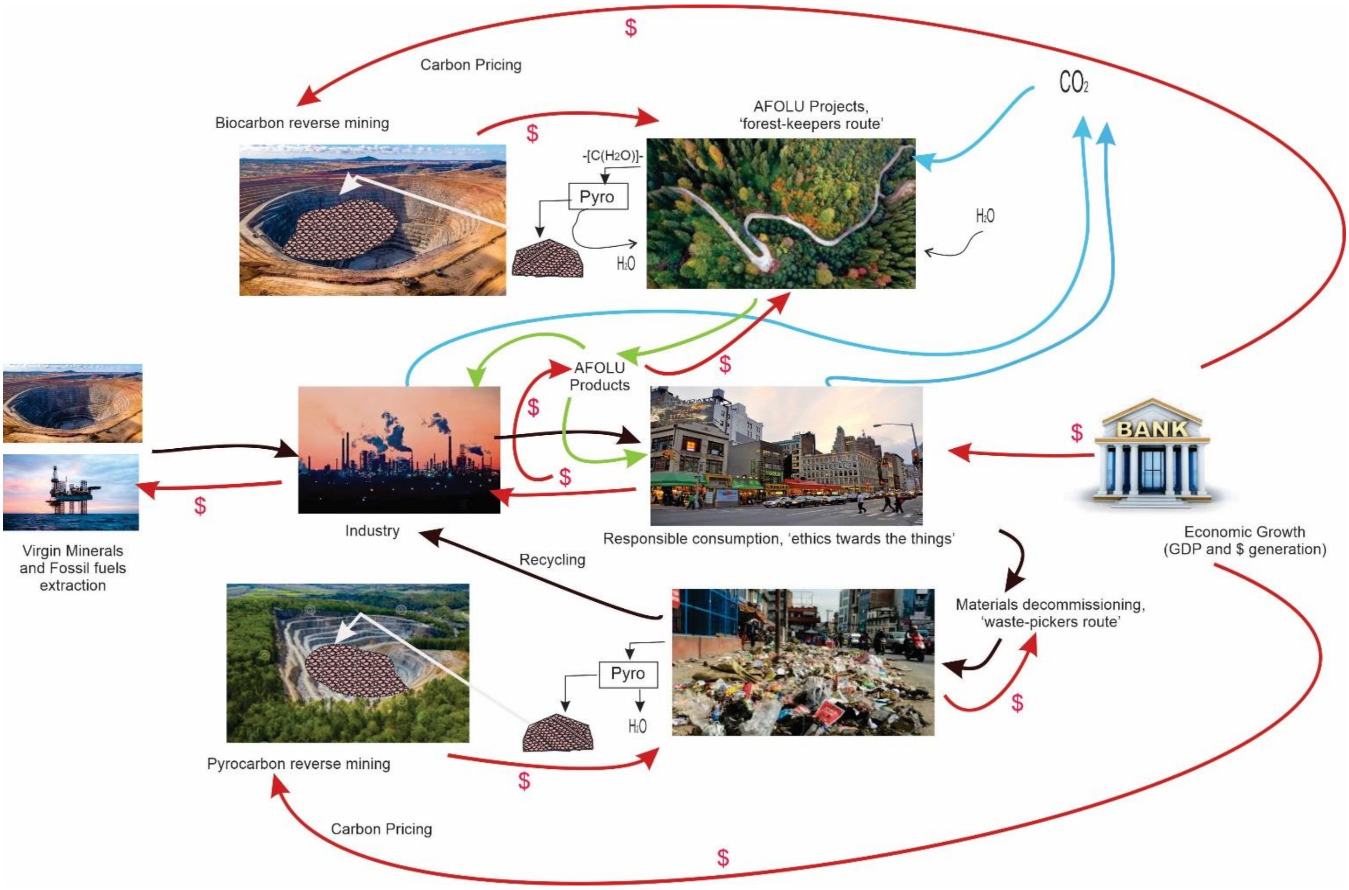

Figure 12: The materials and financials flows, remuneration of formal businesses, and income generation at the market chain connected with the "carbon-coins" and their storage or utilization as needed by the geoengineering management of the GHG climate forcers.

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