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Pricing an optimal carbon credit for a competitive italian biochar supply chain as an alternative to carbon black

An optimization of wood-chip biochar plants

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Abstract

It has been well established that reaching net-zero is not enough to push back climate change into kinder scenarios. Carbon removal is becoming unavoidable as a tool to fight emissions. Biochar is a stable form of carbon storage produced by the pyrolytic conversion — heating in an environment poor in oxygen — of biomass, whose promising capabilities as a carbon sink are being studied and exploited at an increasing pace. The production of biochar, depending on the specific plant, is associated with a number of side products that can be exploited to generate revenues. This study focuses on the Italian biochar market, aiming to understand under which economic conditions biochar production can be sustainable enough to compete against carbon black demand from hard-to-abate sectors. A mixed-integer non-linear programming model has been applied to determine the optimal pricing of carbon credits, defined as the one that allows the whole supply chain to achieve the sale of biochar at a competitive price against carbon black. The model is applied to wood-chip conversion plants; the data have been collected by directly interviewing the producers. The results show that the fully centralized or decentralized expansion of existing plants does not constitute an optimal strategy; the optimised configuration is nevertheless weak, as sensitivity analysis showed, with the transport being the weakest parameter in determining the final credit for biochar. With highly conservative assumptions, it follows that a carbon credit, in the range of 240–1,110 €/t-CO_2 (economies of scale exploited - not exploited) is needed to allow biochar to be competitive at the volume required by the market.

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Chapter 1

The biochar solution

"The biochar solution" is a direct quote from the title of a famous book which, more than ten years ago, popularised to the vast public the possibility of using biochar as a front soldier against climate change. This chapter's scope is to introduce the reader to the promises and the complexity of the biochar world, how such complexity has been tamed to few precise research questions (why those and not others, on the basis of the available datasets), and how the journey to answer them has been structured.

Firstly, the numerous sources this chapter makes use of, lead to the definition of two stylised readings of biochar's promise — an *enthusiast* and a *cautious* one — that recur throughout the work. Neither denies biochar a role in carbon dioxide removal; they disagree on pace, on scale, and on the confidence with which large-scale deployment is urged. The chapter then turns to the figures of the global and European markets, asking of each one not only what it says but how it was produced and by whom, and on that basis the question is narrowed twice: to Italy, and to the substitution of carbon black. The closing section confronts the Italian numbers — the environmental and economic performance of domestic production, and the role that a recent national assessment assigns to biochar — and ends on the difficulty that runs beneath all of them: the scarcity, and at times the internal inconsistency, of the data describing what Italian plants actually process today. That difficulty is the subject of Chapter 2 in full.

1.1 To Biochar or not to biochar?

The starting point for this section is a pair of works that, ten years and a considerably different institutional background apart, both make a full-length case for biochar as a central tool against climate change: Albert Bates's *The Biochar Solution: Carbon Farming and Climate Change* [1], and *Biochar, Carbon R-evolution*, co-authored

by Bates and Kathleen Draper and cited here from its 2024 Italian translation of the original *Burn: Using Fire to Cool the Earth* (2018) [2]. Neither is an academic monograph in the narrow sense: both are long-form, narrative works and their register is one aimed at the general public rather than a community of peers. Opening a literature review with two popular books may look like an odd choice, and thus deserves a direct answer. Both authors are not commentators but practitioners with extensive hands-on and institutional experience in the field — Bates through decades of direct pyrolysis experimentation and long involvement with the International Biochar Initiative, Draper through her own presidency of that same initiative and her work at Carbon Standards International — and it is precisely this vantage point that lets them condense, in accessible language, a landscape otherwise scattered across chemistry, soil science, climate policy, carbon markets and engineering regulation. Starting from their own words is, for this reason, the most direct way to give the reader the context needed before the chapter turns to the more specialised literature.

Both books describe biochar as charcoal obtained by pyrolysis: biomass fired in a low-oxygen environment, which converts its labile, biologically active carbon into a recalcitrant, chemically stabilised, highly porous carbon structure — one gram can reach a surface area of 1000 to 2500 square metres — that resists microbial decomposition for centuries rather than years, sequestering 25 to 50 percent of the original feedstock's carbon for decades, in some cases even centuries, against less than 10 to 20 percent over five to ten years for ordinary decomposition or stubble-burning. A more technical treatment of this terminology and of the underlying chemistry is given in the reference volume the authors themselves point to on this specific point [3]. On this basis, both books converge on the same broad thesis: carbon should be treated as a resource to be redirected, to be made an ally of the climate, rather than a mere emission to be avoided; and biochar is one of the very few tools able to act at the pace and the scale that climate mitigation now requires thanks to the pool of advantages it brings on the table, with the outstanding ones being: a large theoretical sequestration potential, and most importantly, a range of possible uses beyond the soil, from filtration to a substitute for fossil-derived materials such as carbon black (more on this below).

Table 1.1 organises this divergence, for the rest of this thesis, around two stylised positions, *enthusiast* and *cautious*; associating *Carbon R-evolution* with the former and *The Biochar Solution* with the latter. This labelling, as already noted, is a classification proposed by the author of this thesis for expository purposes only, and does not correspond to an established distinction in the biochar literature. Both positions agree that biochar deserves serious consideration as a climate tool; they disagree on how far, how fast, and under which safeguards: the following table can be used as compendium of the whole "clash" in the field accessible even for readers not belonging to the field.

Table 1.1: Enthusiast and cautious positions on biochar, as they emerge from *Biochar, Carbon R-evolution* [2] and *The Biochar Solution* [1]. The enthusiast/cautious labelling is proposed by the author of this thesis for expository purposes and is not an established distinction in the literature.

Aspect	Position	Claim	Source
Fit with today's constraints	Enthusiast	Biochar is presented as the only carbon-removal technology that already meets, simultaneously, the cost, scalability and technological-maturity constraints required for rapid deployment.	[2, p. 38]
Fit with today's constraints	Cautious	Biochar is not a cure for the addiction to industrial growth at any cost; changes in agricultural practice alone cannot, by themselves, reverse the present trajectory.	[1, p. 22]
Sequestration potential	Enthusiast	Theoretical global storage capacity is estimated at 224 GtC in cropland soils and 175 GtC in temperate grasslands, enough to offset up to 12% of annual fossil-fuel emissions if slash-and-char replaced slash-and-burn.	Lehmann, Gaunt & Rondon (2006) [4], cited in [1, pp. 101–102]
Sequestration potential	Cautious	Large, engineered carbon-removal strategies — biochar included — carry systemic uncertainty and should be judged against the same governance standards as other geoengineering options.	The Royal Society (2009) [5], cited in [1]

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Aspect	Position	Claim	Source
Scale-up risk	Cautious	An unmanaged, market-driven scale-up of biochar could push the soil-atmosphere carbon balance into overcorrection; good soil-building practice alone, without biochar, is argued to already be sufficient.	E. Ingham, personal communication, in [1, p. 23]
Feedstock and land use	Cautious	Without strict rules, biochar's entry into carbon markets could make biomass cultivation more profitable than food production, incentivising monoculture plantations, land grabbing and deforestation.	Ernsting & Smolker / Biofuelwatch (2009) [6], cited in [1]
Institutional culture	Enthusiast	The prospect of large carbon-credit revenues has drawn entrepreneurs, patents, brand trademarks and venture capital into the sector at gold-rush pace.	[1, p. 22]
Institutional culture	Cautious	Within the International Biochar Initiative itself, the cautious approach of soil scientists — personified by Johannes Lehmann — prevails over the industry's promotional hyperbole.	[1, p. 219]
Economic viability today	Cautious	At current market prices, adding even one tonne of biochar per hectare turns the ordinary profit margins of maize and soybean cultivation into losses.	[2, pp. 84–85]

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Aspect	Position	Claim	Source
Scope of application	Enthusiast	Framing biochar purely as a soil amendment undersells it: the same recalcitrant carbon can serve as a filtration medium, a construction additive, or a substitute for fossil-derived materials such as carbon black.	[2, pp. 85–88]

Testing which of the two readings is closer to reality is only possible against actual data: the next section turns to the numbers and the trends of the global and European biochar markets, to see how far either position currently holds up.

1.2 Reading the market data

In this section, the numbers about biochar are going to be crunched, starting from a preview of the European market, followed by few comments on the rest of the world and finally focusing on the Italian case. In this way a complete perspective is depicted. How is the European biochar market actually moving, and which of its declared trends are genuinely measurable? The figures quoted in what follows are only as trustworthy as the answer to three further questions that deserve to be answered: how an observable is actually measured, or on what underlying data is it built, and — naming the institution, survey, or model responsible — where did that data originate? These questions are necessary since measuring the market turns out to be harder than quoting a single growth figure, because "the market" changes definition depending on who is counting, over what geography, and against what benchmark. At the global level, the market-analysis literature puts the value of the biochar market at USD 541.8 million in 2023 and projects a compound annual growth rate of 13.9% between 2024 and 2030, and reports that agriculture already accounts for more than 77% of global revenue while North America hosts over 80% of the world's large- and medium-scale producers, ahead of Europe and Asia-Pacific [7].

However, these data come from market research reports, often private, and whose methodology is not disclosed or publicly available. Additionally they don't refer to any academic literature and on prices the situation is worse: systematically compiled databases of biochar prices do not exist, so any attempt to study market dynamics has to start from assembling scattered, heterogeneous sources. Nevertheless, tracking the price across that sea of reports shows that it fell from

around $2740 per tonne in 2013 to roughly $1300 per tonne by 2021 [8].

An unaudited market-size estimate and the absence of a reference price series point to the same underlying problem this chapter returns to in its final paragraph: at global scale, biochar market data is compiled by market-research firms or reconstructed piecemeal by individual research groups, not measured by any standard statistical apparatus.

At the European level the situation is different in kind: the main source is not a market-research firm but Biochar Europe, the industry association representing around 130 member companies, which has published an annual European Biochar Market Report since 2021 and has now reached its fifth edition [9]. Its methodology is at least transparent about what it measures and how: the report surveys production plants installed or planned for commissioning by its members and partner networks, classifies installations by production-volume category, and separates capacity explicitly dedicated to Biochar Carbon Removal (BCR, i.e. credited on carbon-removal registries) from capacity feeding other markets such as barbecue charcoal and metallurgical biocarbon [9, p. 20]. Actual output, moreover, is not measured directly but estimated from installed capacity through assumed utilisation rates — 50% uptime over six months in a plant's commissioning year, 70% uptime thereafter [9, p. 41] — an explicit modelling choice rather than a measurement, worth keeping in mind whenever a "tonnes produced" figure from this source is used later in this thesis. Figure 1.1 sets out this distinction explicitly for the three sources used in this section, comparing what each one reports against how transparently it explains getting there.

On this basis, the market has grown more slowly than the industry itself had expected. Figure 1.2 sets the two most recent editions of the report side by side: gross new installations came in at 33 against a forecast of 54 for 2024, and at 28 against 52 for 2025 (panel A); the cumulative installed base reached 205 plants by the end of 2025, with a further rise to roughly 235 expected by the end of 2026 (panel B) [10, p. 48][9, pp. 29–31]. BCR-dedicated production capacity followed the same pattern, growing to 91,000 t in 2025 against a forecast of 114,000–115,000 t made a year earlier [10, p. 53][9, pp. 38–39], and the report's own growth-rate chart shows this expansion slowing further, to an expected 9% for 2026 [9, p. 40] — a deceleration the report attributes explicitly to project postponements and cancellations rather than to any technical bottleneck. Actual BCR biochar production is estimated at 60,000 t for 2025, corresponding to roughly 170,000 tCO_2e removed, against 55,000 t and about 150,000 tCO_2e the year before [9, p. 42][10, p. 57]. Two further facts qualify this growth. First, as panel C of the figure makes clear, BCR is only a fraction of the sector: total European biochar production capacity across all applications reached 270,000 t in 2025, so carbon-removal-dedicated capacity still accounts for a third of what is actually produced, the usage of the rest is expected to grow as a clean alternative to charcoal and, increasingly, metallurgy [9, p. 47]

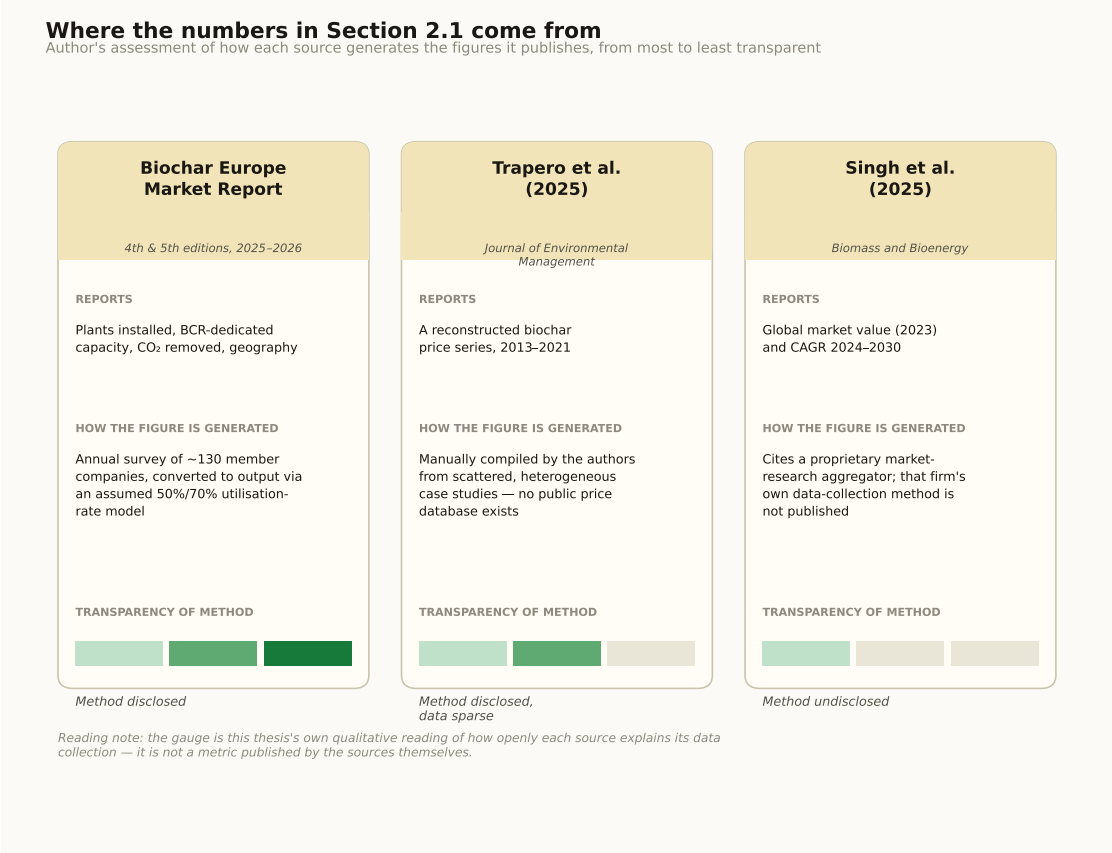

Figure 1.1: Provenance of the three market-data sources cited in this section: what each one reports, how the underlying figure is actually generated, and the author's own qualitative assessment of how transparently that method is disclosed.

against its major, more polluting, opponents. Second, where building materials are still described as a niche of "modest volumes", metallurgy is presented as a use case with "sharply rising interest" and "immense market potential", driven by ETS carbon prices and defossilisation targets in that industry [9, p. 7]. This assesses both the capacity of biochar to treat more emitting competitors in really far away sectors and the rising interest despite absolute values of usage still relatively modest and concentrated in few applications. Geographically, too, the market remains concentrated (panel D): about 70% of European BCR capacity sits in just three areas — Germany, the Nordic countries, and Austria/Switzerland — with Spain, France, the United Kingdom and, implicitly, Italy grouped under a growing but still undifferentiated "other countries" residual [9, p. 48].

What, then, can honestly be concluded from these numbers, and why? The market is real and growing at every geographical scale, which supports the basic premise shared by both *The Biochar Solution* and *Carbon R-evolution* that biochar deserves serious consideration. But growth has consistently undershot the industry's own forecasts, the sector's centre of gravity is visibly moving from carbon removal toward the industrial substitution of fossil carbon, and, as Figure 1.1 summarises, a non-trivial share of what gets reported as "market data" is either self-surveyed by an industry association or extrapolated by market-research firms rather than independently measured. So: in light of this evidence, what spirit should animate the remainder of this thesis? First of all: it must be concluded that the times to attempt a financial model of biochar are yet to come: the data necessary to study correlations, price oscillations and other financial properties as in [11], a milestone for the study of biofuels in global commodity and financial markets, simply don't exist. In the future those methodologies might be applied to biochar as well.

A second conclusion is that no rejection of the enthusiast reading nor naive confirmation of it can be deduced from those data only: the market is too vast to be discussed about without further focusing. The latter will be the scope of the following sections, both "geographically" and from the point of view of biochar's applications.

1.3 Scoping the question: Italy and carbon black

Testing the two perspectives against the Italian case first requires scoping a question, (the n-th one about biochar's necessary focusing strategy), that could otherwise sprawl indefinitely, because biochar is not a single material but a family of them: different feedstocks yield biochars with different chemical compositions and physical properties, and biomass production, consumption, and import patterns vary not only from country to country but from region to region within the same country. Faced with this complexity, the approach adopted here is to anchor the analysis

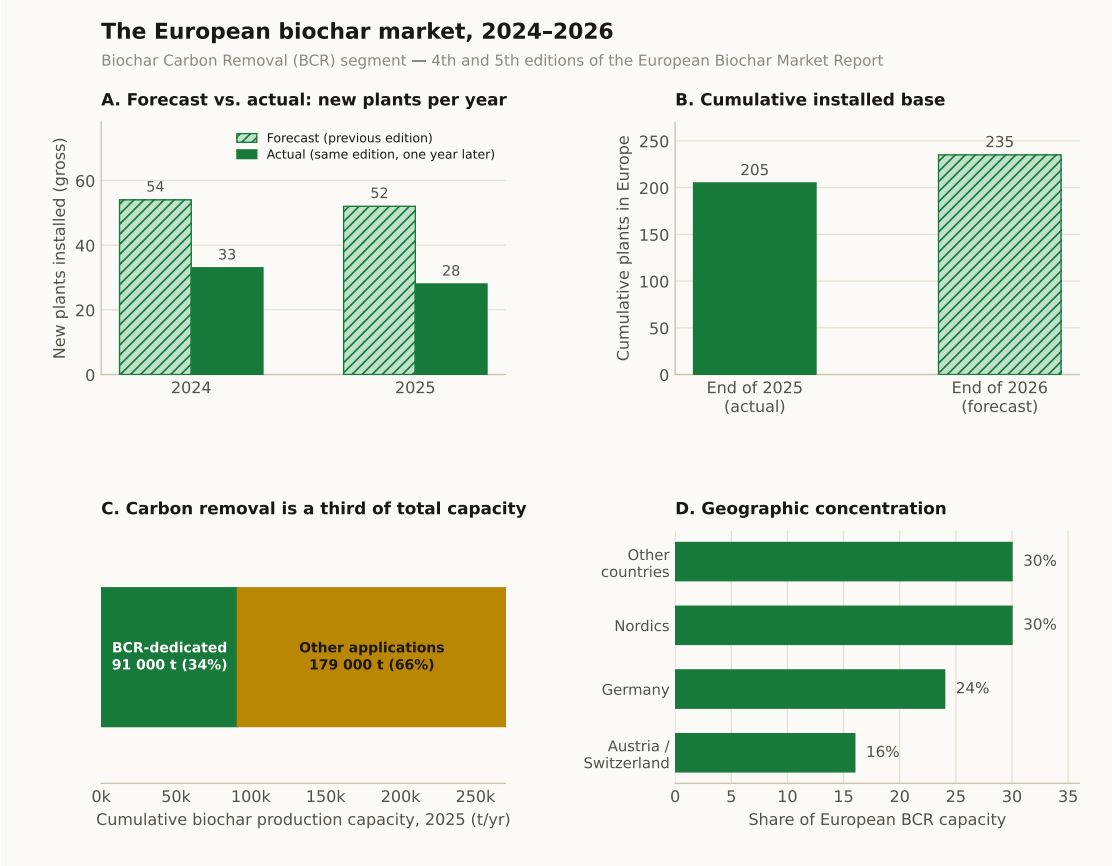

Figure 1.2: The European biochar market, 2024–2026, as reported by the two most recent editions of the European Biochar Market Report [10, 9]. Panel A compares each edition's own forecast against the installations actually realised one year later; panel B shows the cumulative installed base; panel C shows how much of total European production capacity is dedicated to Biochar Carbon Removal (BCR) rather than other applications; panel D shows the geographic concentration of BCR capacity at the end of 2025.

to the Italian case as it stands today: the biomass volumes used throughout this work are those actually processed, right now, by real companies producing biochar in Italy, and even the hypothetical scenarios explored later are built around real projects currently under discussion in the Italian biochar debate, rather than around abstract possibilities.

Nevertheless, fixing the geography does not remove the second dimension of the same problem: biochar's possible uses span agriculture, construction, water filtration, and industrial materials, each with its own market dynamics, competing technologies, and barriers to entry. Narrowing this thesis to a single application is therefore essential. The obvious rivals are the two outlets that Section 1.2 found the European industry itself watching — construction materials and metallurgy — so the choice of carbon black has to be argued against them rather than simply announced.

Construction is the easier of the two to set aside, and the market report cited above does it on its own: building materials remain a niche of "modest volumes" [9, p. 7], which is to say a market at which a supply-chain optimisation would have little to optimise. Metallurgy is the harder case, and the honest answer is not that it is less promising. The same source calls it a use with "sharply rising interest" and "immense market potential", pulled by ETS carbon prices and by that industry's own defossilisation targets [9, p. 7]. The difficulty is that this momentum is documented precisely where the European capacity already sits: some 70% of Europe's BCR capacity, and with it the metallurgical demand drawing on it, is concentrated in Germany, the Nordic countries and the Austrian–Swiss area, with Italy appearing only inside the undifferentiated residual [9, p. 48]. Choosing metallurgy would mean optimising an Italian supply chain against a demand signal observed somewhere else. The use of carbon black in rubber industry, by contrast, offers a demand signal that is Italian, current, and quantified.

Three considerations before continuing, with the first being scale. Carbon black is consumed in large volumes by the Italian tyre and rubber industries [12, 13, 14, 15], and the substitution problem is correspondingly large: replacing even 20% by weight of the carbon black used in tyre manufacturing would require on the order of 100 kt/year of biochar, while, for comparison with the most well-established application, replacing traditional soil amendments with biochar on a comparable scale would require closer to 1 Mt/year [16, slide 21] — both figures orders of magnitude above Italy's current biochar output, a gap quantified in Section 1.4 below.

The second is methodological, and it is what makes the question of this thesis answerable at all. Carbon black is a commodity with a quoted market price, and that price supplies a single exogenous benchmark against which the entire supply chain can be optimised. Agriculture offers no comparable anchor — what a farmer will pay for a soil amendment varies with crop, soil, and subsidy regime — and

construction offers none at all. It is this benchmark that converts a vague question about competitiveness into the well-posed one this work actually attempts to answer: how large must a carbon credit be for an optimised Italian chain to break even while selling at that price? The general case for biochar as a substitute for fossil-derived carbon, already sketched in Section 1.1 [2, pp. 214–217], is taken up against the specific techno-economic literature in the modelling of Chapter 4.

The third, and most concrete, is that the substitution is not only discussed in the abstract but is already being tested commercially: interviews conducted for this thesis with Italian biochar producers (Chapter 3) reveal that contacts with major tyre manufacturers already exist, including a request from Pirelli's Italian operations asking a leading domestic producer about the feasibility of supplying 50 big-bags of biochar per day — a volume the sector cannot currently meet at a competitive price. It is this concrete, if still unmet, demand that the rest of this chapter uses as a benchmark against which to read the current numbers of the Italian biochar sector.

A further consideration on the choice of exploring carbon black over agricultural amendment is based on the results of direct interviews with active biochar-producing companies in Italy: the main buyers of produced biochar

consist of micro or small agricultural activities or private citizens; most of the agricultural world is declared to be unable to invest in "new" technologies as biochar and even not-informed on the possibilities that this material offers. On the other hand, as previously stated, contacts between biochar producing plants and the well-aware rubber industry have already been established.

1.4 The biochar solution for Italy in numbers

Where, then, do the numbers behind that resolve actually come from for the Italian case? A first, technical answer is offered by a 2026 presentation by Mattia Bartoli [16], built around a life-cycle assessment (LCA) of biochar production run specifically on an Italian scenario — a kiln-type reactor converting olive-waste or corn-derived feedstock, sourced and processed on the same site, energy drawn from the medium-voltage grid, and product distributed by Euro-6 truck [16, slides 9–11]. Before reporting what it measures, it is worth being explicit about what it asks: is biochar production even emission-neutral in Italy, given a biomass supply that is unevenly distributed across the country, a production base still scarce and small in scale, regulation that remains unclear, and a transport system that relies on trucks rather than rail [16, slide 8]?

The LCA answers with numbers, run across ten standard environmental impact categories — from the depletion of abiotic resources and acidification to the global warming potential (GWP100) that matters most here [16, slide 12].

GWP100, (Global warming potential), is a standard measure in LCA calculation; this parameter answers the question about how much heat is a certain greenhouse gas able to trap in the atmosphere, in a century, with respect to carbon dioxide. It is measured in kg of equivalent carbon dioxide: if it is greater than zero it indicates a net emission, vice versa when less than zero.

The central statement of the former source is at once encouraging and fragile: converting waste biomass on site, with no transport involved, yields a genuinely carbon-negative process, at -1.08 kg CO_2 eq. per functional unit [16, slide 13]; but that balance flips to a net emission of $+0.11$ kg CO_2 eq. once the product is trucked 100 km, and profoundly worsens to $+0.86$ kg at 200 km [16, slides 14–15]. The numbers are computed by considering the production of 1 kg of biochar. Transport is not the only fragile link. Keeping the same waste feedstock and merely switching the process energy carrier away from natural gas — to petrol, or to LPG — drives the balance to roughly $+1.00$ kg CO_2 eq. in either case [16, slides 16–17].

Read together, the presentation's conclusions are direct: on-site processing of waste is the only configuration that keeps the balance negative; truck transport, the one available in Italy, is the single most damaging variable in the whole chain; and energy usage is to be taken into careful and serious consideration when the willingness to scale up supply develops [16, slide 18].

Even in its best configuration, moreover, the process is not carbon-negative for free: 1 kg of biochar derives from roughly more than three times of dry biomass whose unit of mass is roughly one third carbon by weight each, (a yield of 18 to 60 wt.% biochar at a carbon content of 60 to 90 wt.%), which leaves between 0.16 and 0.30 kg of that carbon inside the finished biochar, per kilogram of dry feedstock [16, slide 20]. Set against the 0.33 kg that entered the reactor, this means that somewhere between roughly one tenth and one half of the original carbon does not end up sequestered in the solid: a carbon loss that remains volatile and counts as an emission (up to 200g).

What about the economic performance? The resulting figures are the ones this thesis returns to repeatedly: it prices biochar produced in Italy at around 2–2.5 EUR/kg and biochar imported from China at roughly 0.2 EUR/kg [16, slide 19]. Virgin carbon black — the fossil-derived product biochar would substitute, manufactured mostly by the furnace process, as distinct from the recovered carbon black obtained from end-of-life-tyre pyrolysis — trades on the international market at roughly 1.2–1.7 EUR/kg [12, 13, 14, 15].[1]

[1]The reference is *virgin* carbon black, i.e. carbon black produced from fossil feedstock, predominantly by the furnace process, as opposed to recovered carbon black (rCB) obtained from the pyrolysis of end-of-life tyres. Its price is far from settled. The presentation of Bartoli [16, slide 19] reports it at 0.02 EUR/kg; this value is not adopted here, as it is implausibly low — it would make carbon black about two orders of magnitude cheaper than the wood biomass feedstock

Its own question, posed immediately after these figures, is the one this chapter has been building toward: can carbon sequestration save biochar from a price war it is not otherwise positioned to win [16, slide 19]?

Every source consulted for this chapter that speaks to cost — the literature reviewed above and, independently, every interview conducted with Italian biochar producers for this thesis (Chapter 3) — converges on the same diagnosis: what limits biochar's industrial uptake in Italy is not its technical performance but the price of its feedstock, and the remedy these sources propose, with equal consistency, is not to lower that cost directly, which none of them treats as realistic in the short term, but to offset it through a carbon credit sold alongside the biochar itself. However, as just shown by simple calculations, the carbon credit too is far from being a definitive solution, given the delicate balance on which the net capture of carbon dioxide is staged.

This is precisely the mechanism this thesis sets out to size. These results sharpen the test proposed at the end of Section 1.2 into the following, specific, answerable question: at what price would the carbon credit need to be set for the Italian biochar supply chain, in its optimised configuration, to cover its own costs while selling biochar at a carbon-black-competitive price and at the volumes the Italian rubber industry actually requires? The obstacle seems to be, precisely, price: carbon black comes from an established, low-cost supply chain, while biochar's own raw material, woody biomass, is expensive to procure. The carbon credit — a tradeable instrument that a company purchases to offset its own emissions, more on that in the next chapters — enters here as an additional revenue stream: it does not lower production costs, but it allows the product to be sold below cost without a loss, so the question this thesis asks is precisely how much that stream would need to be worth.

A first step into a concrete answer to the feasibility of the "biochar solution" for carbon capture in the Italian context comes from the country's own carbon-removal-potential assessment, taken up next.

What, concretely, does this more realistic proposal consist of? The Carbon Removal Readiness Assessment (CRRA) report considers the whole Italian potential of carbon capture, including biochar, not as a pillar though, but rather as one of the many tools the country can line up in the years to come and it represents the

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itself — and does not reconcile with any market source. The commodity price indices consulted place virgin carbon black in Europe at about 1.2–1.7 EUR/kg in 2026 (some 1300–1800 USD/t, converted to euro) [12, 13, 14, 15]. A third, intermediate value of 0.12 EUR/kg, drawn from the Biodea interviews, is the reference price actually adopted in the optimisation model of Chapter 4. These three figures span two orders of magnitude: as for biochar, clear and readily available price data for carbon black simply do not exist, which is why the price enters the model as a swept parameter rather than a fixed input.

most up-to-date work on this kind of matter. It offers three projections for Italy: a Conservative, a Reference, and an Ambitious scenario, each modelling how far the country's CDR capacity could plausibly reach by 2030, 2040 and 2050 under different assumptions about policy support, social acceptance, and institutional capacity [17, pp. 4–5]. The report is explicit that these are "illustrative pathways", not forecasts [17, p. 5] — a methodological caution this thesis shares and has already applied to every market figure examined so far in this chapter. Only the Reference and Ambitious scenarios reach a combined removal capacity, natural sinks included, sufficient for net-zero by 2050.

Its specific role, in numbers, is this. The report sets a theoretical ceiling for Italian biochar — 8.33 $MtCO_2$/year, obtained by allocating 10.08 Mt/year of residual biomass to pyrolysis on the assumption that reactors are dedicated to biochar alone [17, p. 39] — against today's actual output, equivalent to roughly 1.9 $ktCO_2e$/year of removal [17, p. 28]. The realistic scenarios sit, deliberately, between those two figures rather than at the theoretical ceiling: biochar removals reach 0.8 $MtCO_2$/year by 2050 in the Conservative scenario, held back by "limited long-term evidence on benefits, low public support, and the absence of clear incentives"; 5 $MtCO_2$/year in the Reference scenario, "supported by a strengthened CAP focused on soil restoration"; and just over 6.7 $MtCO_2$/year in the Ambitious scenario, still short of the theoretical maximum [17, pp. 67–71]. Put differently: even the most optimistic of the three realistic pathways credits biochar with only about 80% of what full dedication of the available residual biomass would theoretically allow, and even the most conservative of them still represents somewhere on the order of four hundred times today's actual removals — a scale-up that is downsized relative to the theoretical ceiling, certainly, but still enormous relative to where the Italian sector stands now.

For comparison, the European Biochar Industry, cited in the same context, estimates Italy's removals will reach 46 $ktCO_2$ by 2030 and 1.6 $MtCO_2$ by 2040 [17, p. 28]. By 2040, this is putting Italy somewhere between our Conservative and Reference scenarios for 2050. Despite not being a direct validation, this industry projection confirms both independent estimates are on the same track.

But how were these numbers actually built, and on what data? The theoretical ceiling traces back to a national biomass mass balance: starting from an estimated 120.53 Mt/year of dry biomass produced in Italy across forestry, agricultural residues, municipal waste, manure, and agri-food co-products, the report subtracts biomass already committed to bioenergy (around 33.9 Mt/year) and to existing bioproducts and soil amendments (nearly 43.83 Mt/year), and further excludes roughly 14.7 Mt/year considered physically or regulatorily uncollectable, arriving at some 28 Mt/year of biomass "potentially available" for any CDR method, biochar included [17, p. 27].

This is a top-down residual — what is left over, nationally, once every other

claim on Italy's biomass has been subtracted — not a bottom-up account of what specific biochar producers are actually sourcing today.

The realistic scenarios, in turn, draw their resource-requirement assumptions from a purpose-built database assembled by Carbon Gap and the Rocky Mountain Institute, combining 442 data points from 129 peer-reviewed articles, 200 from applications to the Frontier carbon-removal fund, and 330 from direct surveys of active CDR operators [17, p. 15]. The report is candid about the limits of each component: peer-reviewed studies mostly reflect laboratory-scale or modelled conditions of uncertain real-world applicability, and Frontier fund filings, while closer to actual deployments, are self-reported and not peer-reviewed — "declarative", in the report's own word [17, p. 15].

Summing up the latter considerations: even a report as recent and as methodologically careful as this one runs, within its own text, into the same difficulty: a national, top-down estimate of how much biomass is theoretically available is not the same thing as a measured account of which biomass is actually being collected, transported, and processed by the handful of biochar plants operating in Italy today. Excellent, well-documented studies of this kind exist in some numbers; what remains genuinely scarce is data on the feedstock actually running through real plants, on real sites, right now.

The point generalises beyond this one report, and it is where this chapter ends. What decides how far biochar can grow in Italy is how much woody biomass real producers can actually secure — yet not one source examined here measures that quantity directly. Biochar Europe surveys installed capacity, not feedstock [9, p. 41]; the CRRA report allocates a national residual by top-down subtraction, not a plant-level census [17, p. 27]; the Italian LCA figures are self-reported slide data [16]. The answer adopted in this work is to interview Italy's biochar producers directly and to cross-check their declared feedstock against the officially registered producers of that same biomass, treated — under the enthusiast hypothesis this chapter set out to test — as if their output were destined for pyrolysis. The merits and the limits of that assumption, and the reasons for adopting it at all, are the subject of Chapter 2; the complementary question of which economic studies exist has been addressed at the end of the market analysis; the ones concerning what biomass, and with what models, is taken up in the data and modelling of Chapters 2 and 4.

Chapter 2

The Data Problem

for the Italian case

The previous chapter established the context for this thesis and its analysis of biochar. Its aim was to convey the reality of biochar as a complex but powerful climate-mitigation tool; two perspectives have been delineated, an optimistic (the enthusiasts) and a cautious one, and their claims have been made explicit and compared with the available market data.

This comparison showed that market growth has repeatedly fallen short of industry forecasts, while much of the available data is based on self-reported surveys, reconstructed estimates or private, not-disclosed market reports. In the light of those data, the kind of research questions that rely on unavailable data, (the financial ones) have been excluded. After narrowing the focus to Italy and to the potential substitution of carbon black, the following specific research questions can now be stated for this work:

Supposing the exploitability of a carbon credit for biochar destinated to carbon black industry: how should a spatially optimised Italian biochar supply chain price a carbon credit in order to break even? How in the context of selling biochar at a price competitive with carbon black, given the volumes required by the domestic rubber industry? Can the spatial optimisation of the supply chain consistently decrease the resulting carbon credit?

However, answering this question is complicated by a fundamental data gap: there is no reliable source that directly measures the amount of woody biomass currently processed by biochar plants in Italy. This chapter explains and addresses this gap.

Answering that question means building an optimisation model, and a model is only as good as the quantities it is fed.The framework adopted here — a two-stage adaptation of the supply-chain model of Grimm et al. [18], whose full formulation

is deferred to Chapter 4 — needs only a description of what those quantities must be. Its first stage is a cost-minimising facility-location problem, deciding over a set of candidate sites which biochar plants to build, at what size, and how to route the available biomass to them; its second stage turns the resulting costs and revenues, through a life-cycle and financial calculation, into the net CO_2 removed per tonne of product and the break-even carbon-credit price this thesis is after. Table 2.1 lists the inputs this structure requires: for each, what it is and why the model cannot do without it.

Table 2.1: The data required by a two-stage optimisation model of the Italian wood-chip biochar chain: for each input, its definition and its role in the model.

Datum	Definition	Role in the model
Biomass nodes		
Location and availability	Coordinates of each chip source and the dry tonnes per year it can supply	Fix the candidate sites and the biomass each plant may draw, hence the spatial structure of the first stage
Delivered price	Purchase price of chips at the plant gate, transport included	Dominant feedstock-cost term in the objective
Quality	Moisture, ash, carbon content and calorific value, by ISO class	Convert wet to dry tonnes and feed the mass, energy and carbon balances
Conversion		
Biochar yield	Mass of biochar per unit mass of dry feedstock	Turns processed biomass into product; one of the five that decide the result
By-product yields	Mass fractions and calorific values of syngas and any bio-oil	Set the energy the plant can self-consume or sell
Carbon content and H/C ratio	Carbon fraction of the biochar and its hydrogen-to-carbon ratio	Feed the sequestered-carbon and permanence terms
Plant		

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Table 2.1 continued from previous page

Datum	Definition	Role in the model
Capital expenditure	Installed cost of a reference-size plant	Annualised through the capital-recovery factor into the fixed-cost term
Operating expenditure	Annual running cost	Variable cost term
Scale rule and size bounds	Exponent of the cost-versus-size law and the minimum and maximum plant size	Govern how the first stage trades aggregation against decentralisation
Useful life and availability	Plant lifetime in years and operating hours per year	Set the capital-recovery factor and the capacity constraint
Specific electricity use	Electricity consumed per unit of feedstock	Enters the plant's electricity balance, here netted against self-production
Energy and by-products		
Electricity price	Italian wholesale electricity price (PUN)	Prices the electricity sold to the grid, treated here as a revenue
By-product value	Economic value assigned to retained syngas or heat	By-product revenue subtracted in the break-even
Carbon		
Permanence coefficients	Fraction of the biochar carbon still stored after one hundred years	Scale sequestered carbon into credited removals
Grid emission factor	CO_2 emitted per kWh of Italian grid electricity	Emissions charged against, or credited to, the process
Demand and financial scalars		
Required volume	Big-bags per day and days per year demanded by the rubber industry, hence annual production	The scale the optimised chain must reach

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Table 2.1 continued from previous page

Datum	Definition	Role in the model
Competitive price P^*	Carbon-black price scaled by a biochar-for-carbon-black substitution factor	Exogenous price the biochar must meet; decisive for the result
Discount rate and horizon	Financial discount rate and project time horizon	Annualise the capital cost and discount cash flows
Reference credit price	Market benchmark price of biochar carbon credits	Yardstick against which the computed break-even price is judged
Scenario ranges	Low, central and high values of the uncertain inputs	Drive the sensitivity analysis

An anticipation: two features of this list matter more than its length. A small number of quantities carry the result almost entirely — the competitive price P^*, the biochar yield, the capital cost, the electricity price, and the net CO_2 removed per tonne — so the credibility of the final figure rests on those five and on remarkably little else. And not one of them is a universal constant to be looked up in a handbook: each is a property of the Italian chain as it operates today — which plants exist, what they cost, which biomass they buy, and from whom. A model of this kind does not ask the literature for its parameters; it asks the territory for measurements. Whether those measurements exist, and in what state, is the question the rest of this chapter takes up — beginning with the official Italian sources one would consult first, and the reasons they do not suffice.

If the model needs territory-level measurements, the natural first move is to ask which official Italian sources already report figures on woody biomass, and to hold each to the same five questions: what it provides, how it was built, what choices went into it, how it is reported, and where it fails. Three are the obvious candidates, and are the evergreen cited "sources" — the ENEA biomass atlas, the EU biomass-flow data of the Joint Research Centre (JRC), and the modelled national potential of the S2Biom project, in the form in which the CRRA assessment already used in Chapter 1 most recently aggregates it. Table 2.2 sets them side by side; none survives the test intact.

Table 2.2: The main official sources of Italian biomass figures, and why none can feed a plant-level supply-chain model of wood-chip biochar.

Source	What it provides, and how	Why it cannot be used here
ENEA — *Atlante delle Biomasse* (RT/2021/4) [19]	Potential availability of agro-industrial residues — cereal straw, fruit-tree, olive and vine prunings, nut shells, citrus pulp, olive pomace, grape marc — assessed at national scale for 2018 and published through the WebGIS *Atlante delle Biomasse* portal. The portal does include forest layers (*Incremento forestale*, *Legno forestale*), but only as map strata with data frozen at 2005, the date of the last national forestry inventory; no tonnage figure for them appears in the report text.	The atlas was never completed for its forest component: the agro-industrial residues carry provincial time series updated to 2019, while the forest and energy-crop layers remain at a single 2005 snapshot that was never refreshed, and the report itself omits any quantitative estimate for them. Even that 2005 datum is reported only at a level of aggregation that cannot be resolved to the specific wood-chip fraction that Italian biochar plants actually process today.
JRC — *EU Biomass Flows* [20]	EU-harmonised statistics on wood, animal, agricultural and biomass production and trade, compiled by the JRC from national reporting into standardised aggregate categories and flux (Sankey) diagrams.	The categories cannot be resolved to the specific wood-chip fraction usable for biochar, nor can domestic production be separated from imports; a harmonised national aggregate says nothing about what a given territory actually produces and can mobilise, and there is no specification (not at the needed level) of the fate of the single sources or what composes them.

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Table 2.2 continued from previous page

Source	What it provides, and how	Why it cannot be used here
S2Biom Italy roadmap (Panoutsou et al. 2016) [21]	A modelled estimate of Italy's sustainable technical potential of lignocellulosic biomass to 2030: 34.4 Mt/yr of dry matter from residues, dedicated crops, biowaste and post-consumer wood, primary forestry excluded — the output of the project's spatial-modelling exercise, not of a field survey.	A top-down projection to 2030, not a record of what is mobilised today; the 34.4 Mt is a national, multi-sector aggregate whose forest-residue share is only about 3.75 Mt (primary forestry, a further 11.81 Mt, is excluded from it), and it resolves to neither plant nor territory.

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Table 2.2 continued from previous page

Source	What it provides, and how	Why it cannot be used here
CRRA assessment (2026), Annex A [17]	The most recent and careful national study; aggregates the sources above in Tables A.1–A.3 to derive the biomass "available" for carbon removal.	A close comparison between the figures in Annex A and the cited S2Biom (2016) source raises a few hesitant doubts, which might well stem from my own misunderstanding. Primarily, the 34.4 Mt assigned to *Forest harvesting residues* in Table A.1 seems to correspond, in the S2Biom data, to the total national lignocellulosic potential (the sum of forest residues, agricultural biomass, waste, and dedicated crops), rather than to forest residues alone. Similarly, the 11.81 Mt for *Hedgerows & agroforestry* appears to match S2Biom's primary forestry production. Assuming I am not simply misinterpreting the fields due to a lack of explicit definitions, this leads to a second concern: if the 34.4 Mt already includes dedicated crops, the presence of an autonomous 9.1 Mt row for dedicated crops respectfully begs the question of whether the same biomass fraction is being double-counted. Lastly, a minor point of disorientation arises from the mismatched labels between tables, with the 34.4 Mt row becoming *Expanded forest residues (stumps, branches)* in Table A.3. I have reached out to the authors in the hope they might kindly clarify these points.

What these four share is more telling than their separate faults. Each is either a national top-down aggregate or a modelled potential; not one is a bottom-up record of the woody biomass that identifiable Italian plants actually buy and process. It is worth asking, then, on what data the model this thesis adapts was itself built, and why Italy cannot simply reproduce it.

The supply-chain model this thesis adapts, that of Grimm et al. [18], produced clean results for the European case. It is worth asking what data let it do so, because the answer is precisely what Italy lacks. Grimm's model runs on two industrial feedstocks — paper-mill and sewage sludge — across thirty-two European countries; Table 2.3 sets its data environment against the one faced here.

Table 2.3: The data environment of the base model [18] against the one this thesis faces. The difference is not one of care but of subject: an industrial feedstock is registered, a woody residue is not.

What the model needs	**Grimm et al. (EU sludge)**	**This thesis (Italian wood chip)**
Feedstock	Two industrial sludges, paper-mill and sewage: concentrated point sources	Woody chip: a diffuse residue of many small forestry and agricultural producers
Location and quantity	Taken from open, official databases — the European Environment Agency, HydroWASTE, Eurostat — since every sludge source is a permitted, geolocated facility that reports its throughput	No register of usable quantities exists; the data had to be built by direct survey (this chapter)
Techno-economic parameters	Measured mass and energy balances from a TCR pilot plant (Fraunhofer)	Assembled from a single, extensively interviewed plant (Biodea), less complete survey reports of other companies, and scattered literature; several values assumed through conservative choices

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Table 2.3 continued from previous page

What the model needs	Grimm et al. (EU sludge)	This thesis (Italian wood chip)
Scope	Thirty-two countries under harmonised European datasets	One country, one feedstock, reconstructed from the bottom up

Grimm could lift feedstock locations and quantities from official registers because the feedstock is industrial: a paper mill or a sewage works is a permitted, geolocated plant that reports what it treats. The former sector is profoundly different from the woody-chip one: the latter is produced by many small, largely unregistered operators, and counted, if counted, only in the national aggregates — which have been shown not to be usable. A model that would run, for example, in Germany on an open and complete dataset, in Italy requires the dataset to be built from scratch. Building it is the task the rest of this chapter takes on.

No official register measures what a given plant processes; the alternative adopted here is to put the question to the biochar producers themselves, asking two things of each — what biomass it converts, and who supplies it. Two surveys bound what that yields. A 2023 CREA survey of the producers authorised by the Ministry (MASAF) took the sector's own census [22]; the interviews conducted for this thesis (Chapter 3), of which the site meeting with Biodea is the fullest [23], took its measure at first hand. Table 2.4 sets out what the two together establish, and where each finding stops being usable.

Table 2.4: What asking Italy's biochar producers actually yields, from the 2023 CREA survey [22] and the interviews conducted for this thesis [23], and how far each finding can be used.

Aspect	What the producer surveys show	Consequence for the model
Size of the sector	The 2023 CREA survey finds only six companies actually producing biochar in Italy, out of nine respondents — five of them a single group operating one plant.	The population to interview is tiny: a full census is feasible, but it returns very few demand-side nodes.

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Table 2.4 continued from previous page

Aspect	What the producer surveys show	Consequence for the model
Response	Even that small population does not answer in full, and participation is self-selected.	The resulting picture is partial and cannot be assumed representative.
Declared biomass availability	Where producers estimate the biomass "available" to them, the figures are large and unsourced: Biodea puts the Italian wood biomass mobilisable from forest thinnings at the order of 40–45 Mt/yr, a number its own meeting notes flag as unverified.	Such availability claims cannot enter the model as inputs; they are advocacy, not measurement.
Declared feedstock and suppliers	The same interviews do reliably report what each plant processes — virgin wood chip, mostly branch wood, of mixed, traceable, locally collected essences [22] — and who supplies it: Biodea names three to four local suppliers within about 120 km [23].	The usable output: not a quantity, but a set of named, real biomass producers to verify against.

Asking the producers may, nevertheless, yield new problems that the official reports did not include: their own estimates might be inflated or understated. However, it makes it possible to show what the official sources never did: the identity of the feedstock actually used, and of the firms that supply it. Now, to obtain verifiable, local data, the next, spontaneous, step is to survey these suppliers directly, as detailed in the following paragraph.

The suppliers the producers named are not scattered or anonymous: the woodchip trade in Italy has its own register. AIEL, the Italian agroforestry-energy association, maintains a public list of certified woody-biofuel producers [24] — firms that sell chip and pellet, none of which makes biochar, but each of which is a real, locatable, verifiable producer of exactly the feedstock a biochar plant would buy. That register is the sampling frame this thesis uses: its producers were contacted directly and asked, in their own terms, what they produce, in what quantity, at what quality and price, and where (Chapter 3). Table 2.5 reports the outcome [25].

Table 2.5: Outcome of the direct survey of the AIEL-registered wood-chip producers conducted for this thesis [24, 25].

Metric	Value	What it is
Producers contacted	131	The set contacted, drawn from the AIEL register of chip producers.
Respondents	32 (about one in four), all localised in northern Italy	A low response rate, but every reply is first-hand.
Usable, quantified nodes	20	Real, local, precise, non-theoretical supply nodes, each with declared feedstock, quantity, quality and price.
Declared output	about 219,000 t/yr (wet)	Aggregate wood-chip production of the responding nodes, as received (wet); after the class-wise moisture correction this is $\approx$ 138,400 t/yr of dry biomass, the quantity B the model processes (Chapter 4). A few cells are estimates; see below.
Producing biochar	0	None is a biochar producer; under the enthusiast hypothesis this thesis tests, their output is treated as if it were destined for pyrolysis.

These figures differ from the sources reported in Table 2.2 in two main respects. First, they are based on direct information provided by individual firms rather than estimates derived from national aggregates. Second, they provide information at a more local and specific level. The main limitation is the coverage of the survey: 32 producers responded out of 131 contacted, and only 20 provided sufficiently complete information to be included in the analysis. The survey therefore does not provide a representative picture of the entire Italian wood-chip supply. However, the information collected from these producers provides a set of real supply nodes that can be used directly in the model. The analysis therefore starts from these producer-to-plant links and uses the broader, theoretical potentials reported by official sources where the survey does not provide sufficient coverage. The aggregated results of the survey, for both the biochar and wood-chip sides of the analysis, are presented in the following sections. The information provided by respondents on the current

state of the supply chain is discussed separately in Chapter 3.

The two surveys can now be read for what they measured, with names and coordinates withheld: the figures below are aggregates of the dataset, not a directory of firms. On the biochar side the picture is thin by nature — six active producers leave little to aggregate — so their results are given as headline numbers in Table 2.6. The chip side, twenty supply nodes, is richer, and Figure 2.1 summarises it in four views.

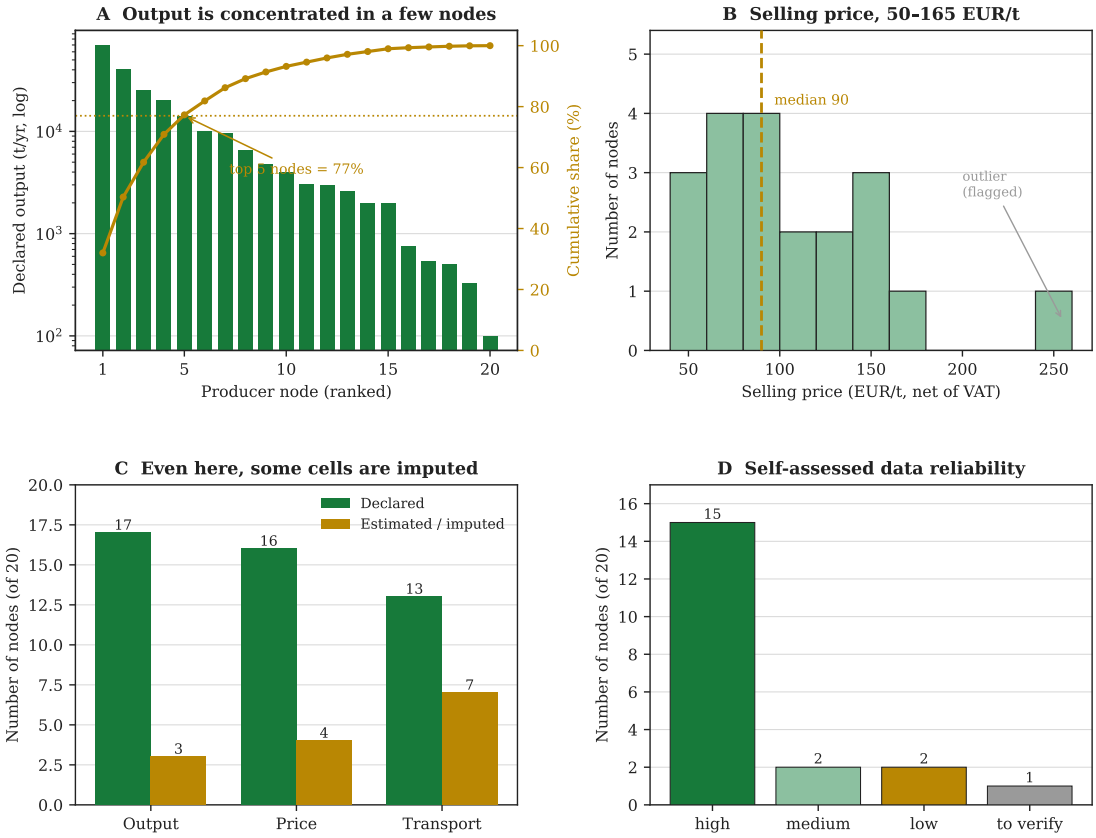

Figure 2.1: The surveyed wood-chip supply nodes ($N = 20$), in aggregate and anonymised. Panel A: declared annual output per node, ranked, on a log scale (bars) with the cumulative share (line) — the five largest nodes hold 77% of the volume. Panel B: distribution of the net selling price, median 90 EUR/t, with a single flagged outlier. Panel C: for output, price and transport cost, how many of the twenty nodes carry a declared figure rather than an estimated or imputed one. Panel D: the nodes' self-assessed data reliability.

Table 2.6: Headline results of the two surveys, aggregated. The biochar-producer figures come from the 2023 CREA survey [22] and the Biodea interview [23]; the chip-producer figures from the direct survey conducted for this thesis [25].

Quantity	**Value**	**Note**
Biochar producers (CREA 2023 survey; Biodea interview)		
Active producers in Italy	6	Of nine respondents, five a single group [22]
Feedstock	Virgin wood chip, mostly branch wood, mixed local essences	[22]
Prevalent technology	Downdraft gasification, 480–1000 °C	[22]
Biochar moisture at sale	about 18%	[22]
Carbon content; ash	88.3%; 5%	Single plant [23]
Sequestration	about 3 t CO_2 per t biochar	Declared [23]
Biochar in storage (unsold)	57 m^3	Single plant [23]
Chip producers (direct survey for this thesis)		
Supply nodes	20	Producers only; demand and marginal nodes excluded [25]
Total declared output	about 219,000 t/yr (wet; ≈ 138,400 dry)	Sum over the twenty nodes
Output per node	median 3,530 t/yr (100–70,000)	Strongly skewed; top five = 77%
Selling price	median 90 EUR/t (50–165)	One flagged outlier at 260
Transport cost	median 19.46 EUR/t	Where separately quantified

Two features carry over into the model. The supply side is dominated by a handful of industrial nodes — five firms account for more than three quarters of

the surveyed volume — so where the model chooses to build depends heavily on a few large, verifiable producers rather than on the long tail of small ones. It is from exactly these numbers, and with these caveats attached, that the model's input parameters are assembled.

Paragraph (1) listed which data the model needs; this one gives the values that currently fill each slot, with the source and the standing of every number. Table 2.7 collects them.

Table 2.7: The parameters that currently feed the model, with value, source and standing. *Measured* = from an external source or firm datum; *decided* = an explicit modelling choice; *assumed* = a value adopted from the prototype and therefore swept across an interesting interval.

Parameter	Value	Source	Status
Conversion and carbon			
Biochar yield	0.20 t/t dry	Sawdust at 800 °C, Sci. Rep. 2024 [26]	measured (external)
Carbon content	0.80 kg/kg	Prototype LCA dataset	assumed (Biodea: 0.883)
H/C ratio	0.40	Typical biochar value	assumed
Permanence β_1; β_2	0.8; 0	Grimm et al. / EBC [18]	assumed
Energy and by-products			
Syngas self-consumption	0.17	Biodea [23]	measured
Specific electricity use	0 MWh/t	Biodea: self-sufficient, energy sold	decided
Electricity price	125 EUR/MWh	La Scalia et al. 2022; PUN 2026 [27]	measured (market)
Plant and scale			

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Table 2.7 continued from previous page

Parameter	Value	Source	Status
Reference capex (theoretical)	20–60 M EUR (theoretical scenario)	Prototype	assumed and swept (Biodea ≈ 1.6 M EUR, processed through the scaling law)
Reference size y_{ref}	5 t/h	Prototype	assumed (Biodea ≈ 0.05 t/h)
Scale exponent	0.60	The 0.6 rule	assumed (used by Grimm)
Opex fraction	0.02/yr	Prototype	assumed as an interesting interval to explore (Biodea ≈ 0.028)
Size bounds	0.5–30 t/h	Prototype — to recalibrate	assumed
Availability	7,884 h/yr	0.9×8760	assumed
Useful life	20 yr	Grimm et al. [18]; Biodea survey	adopted
Life-cycle emission factors			
Process emissions	0 kg CO_2e/t	Arbitrary (no per-kWh gasification LCA in the nine papers)	assumption
Transport factor	0.1008 kg CO_2e/(t km)	Ilari et al. 2022, load 51–80% [28]	measured
Grid factor	300 kg CO_2e/MWh	ISPRA, indicative	assumed
Capital factor	0 kg CO_2e/EUR	To estimate	assumed
Logistics and finance			

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Table 2.7 continued from previous page

Parameter	Value	Source	Status
Transport cost	0.077 EUR/(t km)	Empirical, nodes id 1 and 13 [25]	measured
Discount rate	0.06	Grimm / prototype [18]	assumed
Piecewise-linear segments	15	Numerical setting	numerical

Two numbers are missing on purpose: the biochar selling price and the carbon-black price P^* it must meet, the pair that decides the whole result, are left open here and fixed only in the modelling chapter, during the sensitivity analysis (Chapter 4).

None of this makes the data better than it is: several numbers remain uncertain and assumed, and one remains an admitted guess. This is to be understood as a first step in collecting true and honest data about the Italian biochar supply chain; the official Italian sources dissected earlier were not transparent about how their figures were made, and this work begins by making that transparency explicit.

This chapter began from a question of data and ends with one honestly answered. A supply-chain model of Italian wood-chip biochar needs feedstock quantities, qualities and prices resolved to real producers, together with the plant, energy, carbon and financial parameters that turn them into a break-even carbon-credit price; and the official Italian sources — ENEA, the JRC *EU Biomass Flows* data, the S2Biom potential, and the CRRA assessment that aggregates it — cannot supply the first of these: the reason is that they offer national (incomplete) top-down aggregates, modelled potentials, and they may present internal inconsistencies as well. The answer adopted here was to build the missing data from the bottom up: to ask Italy's few biochar producers what they process and who supplies it, and then to survey the AIEL-registered chip producers directly, obtaining twenty real, local, verifiable supply nodes — a thin sample, still carrying some imputed cells, but a bottom-up one. From these, with a handful of external sources, the model's parameters were assembled and each was labelled by provenance and status: a minority measured, many still assumed and therefore swept across interesting intervals, one an admitted assumption, and the two decisive prices left deliberately open. The data problem, in other words, has firstly been made honest, then a way of facing the challenge has been proposed and carried out.

Chapter 3

State of the Italian Biochar Supply Chain

This chapter leaves the questions of data and method behind and looks at the object itself: the Italian wood-chip biochar chain as it stands in 2026. Chapter 2 described its figures and argued why they are so hard to measure; here the aim is plainer description — what exists on the ground, who operates it, and under which rules — and what carbon credits are, so that the objective of the model of Chapter 4 has been defined, discussed and linked to some real world documented cases.

Three movements organise the account. The first surveys the chain as it is today: how Italian law classifies biochar and the waste biomass it is made from, how that framing has shifted over time and where it appears to be heading; the firms now active and the chip producers already counted in Chapter 2, recalled here only in their essential figures and joined by the producers' own views on what the chain needs; and the alternatives to the prevailing "all-pyrolysis" model, in which a plant lives off energy and by-products rather than off the char itself. The second consists in the exploration of one of the main obstacles reported from every player in the sector: bureaucracy and legislation. Drawing on reports and official publications, the evolution of the legislation will be tracked and reported up to the state of the art. The third turns to the mechanism on which the whole economic case rests, the carbon-credit market: what it is, who its actors are and what each of them does, how a credit is generated and how it enters a balance sheet, and — through a documented case study — evidence that this market is already operating and not merely theoretical.

3.1 The Supply Chain Today - 2026

Read across the responses, and reported in aggregate without names, the producers converge on one obstacle before any other: bureaucracy. The recurring complaint is common to both biochar and its feedstock: pruning and maintenance residues classified as waste rather than as raw material, and the cost and paperwork of certification. Those are the items every respondent marks.

The structural difficulties that have been identified are, thus: the cost of bureaucracy and its slowness; weak local demand, and a scarcity of biomass plants to sell to (even if their main outlet, heating, has rising demand); low margins, squeezed further by uncertified imported product (particularly from China, as they state - this was reported even by biochar companies); and, for the smaller firms, the cost of renting of storage spaces. The picture appears consistent with the quantitative one of a short-radius chain with most supply drawn from within fifty kilometres.

Suggestions on how to strengthen the chain were asked for too, the answers can be summarised in three recurrent suggestions: aggregation into producer organisations (*organizzazioni di produttori*) to give scattered firms the scale and bargaining weight they now lack; keeping the chain short-radius, so that it stays sustainable and can become a genuine source of income for the marginal and inland areas where the biomass grows — a plan whose own limit, the finite size of the national wood resource, is documented in the state-of-the-forests report [29]; and, above all, building demand where it is missing by spreading wood-chip district heating.

Biochar does not figure in it at all: asked directly, not one of the responding chip producers counts a biochar-linked client among its buyers [25], and none puts it forward as a prospect. The producers are, in short, a trade world well informed about its own market but neither informed about biochar nor hopeful of it, even though they sell the same feedstock needed for it; the outlet they actually pin their hopes on is thermal, namely chip-fired district heating, which they treat as the natural and almost only market for their product. That bet rests on a real strength but points at a narrowing target. The strength is cost: wood chip stays markedly cheaper than fossil heating, with reported savings on the order of 70% against heating oil — a figure that comes from the wood-energy sector itself and should be read as a positioning claim [30] — and the public incentive framework still favours the switch [31]. But biomass thermal energy is at the same time one of the leading sources of atmospheric particulate, a point conceded even in the sector's own statistics [32] and quantified independently in the national emissions inventory [33]; and it is on exactly this ground that the thermal sector, district heating included, is now under pressure to decarbonise toward other vectors, its networks still largely fossil-fed today [34, 35]. The producers, then, read district

heating as their market at the very moment that outlet is being reconsidered, while the alternative this thesis is concerned with sits outside their field of view altogether.

3.2 Up-to-date state of bureaucracy - 2026

For the Italian administration, biochar has almost no free-standing legal existence. The governing text is Legislative Decree 75/2010, which orders the whole discipline of fertilisers [36]; biochar was written into its Annex 2, among the soil improvers (*ammendanti*), by the ministerial decree of 22 June 2015 [37], following a petition the Italian Biochar Association (Ichar) had filed in 2012. With that single administrative act Italy became one of the first countries to give biochar a formal identity as an agricultural product — a fact this chapter takes as its starting point, and one reconstructed here mainly from the CREA account of the supply chain [38].

However, the legal definition is deliberately a process definition. Biochar is the carbonaceous material obtained by pyrolysis — and, the decree adds, by gasification — of vegetable products and residues from agriculture and forestry and from the activities connected to them: olive pomace, grape marc, bran, fruit shells, untreated offcuts of wood processing. What makes a given char a lawful *ammendante* is then a table of thresholds such as: a molar $H:C_{org}$ ratio of at most 0.7, which is the standard proxy for the stability of the fixed carbon, an organic-carbon content of at least 20%, polycyclic aromatic hydrocarbons below 6 mg/kg, PCBs below 0.5, dioxins below 9, and a ceiling on heavy metals common to many other rule tables of this kind. Whether a batch of char is a product, a by-product or a waste, however, is not decided by that table at all. It is decided upstream, by the legal status of the biomass it was made from, under the environmental code, Legislative Decree 152/2006 [39]. Its Article 184-bis defines a by-product through four joint conditions — that the material is not the primary aim of the process, that its later use is certain, that it needs no treatment beyond normal industrial practice, and that it causes no overall harm to health or the environment — while Article 184-ter governs when a waste ceases to be one. If the feedstock is a waste, so is the char made from it, unless it passes through a recovery operation and satisfies end-of-waste criteria; there is no master list, and the judgement is made case by case, guided by the criteria of the by-product decree 264/2016 [40] and, in the European frame, by the Waste Framework Directive [41]. This distinction and the impossibility of registering biochar, legally, as a product on its own constitute the main legal obstacles for biochar potential's exploitation, however, it is true that the legal frontier is being pushed forward.

How the framing moved over time is summarised in Figure 3.1. The national line runs from the 2010 fertiliser decree to the 2015 entry as a soil improver, to

a 2018 petition for Annex 4 (a component of growing media), to the opening to organic agriculture in 2020, and finally to the decree of 10 October 2022, which placed biochar in Annex 13, among the fertilisers admitted in organic farming [42]. The registry follows the same curve: at the end of 2022 the ministerial register counted thirty producers of "ammendante biochar" and sixty-five distinct registered products, against essentially none in 2016.

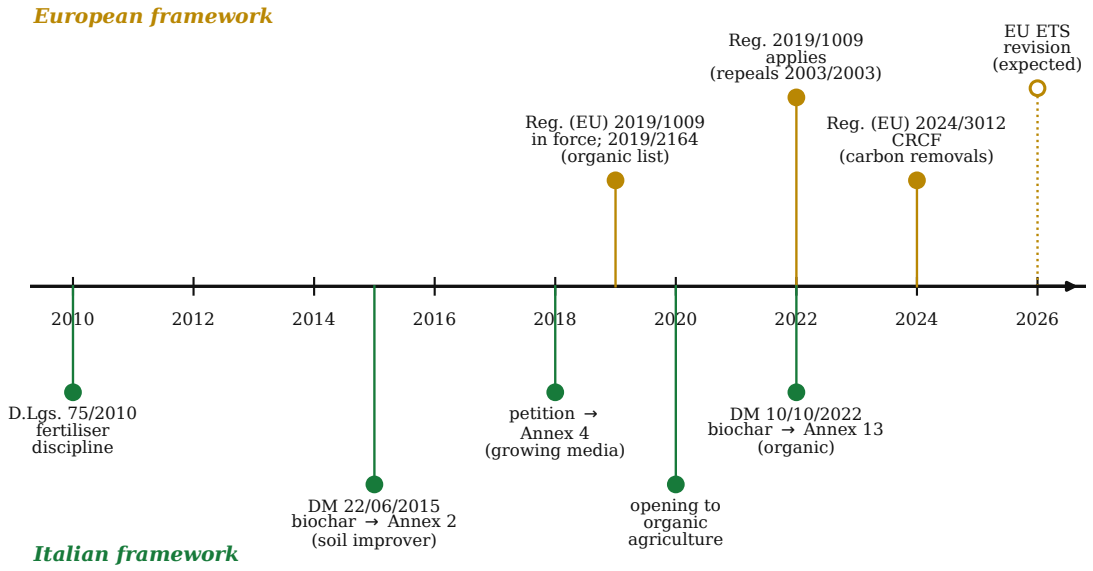

Figure 3.1: The Italian and European regulatory framing of biochar over time, each marker with its source. *Italian line (below):* 2010, Legislative Decree 75/2010, the fertiliser discipline [36]; 2015, ministerial decree of 22 June 2015, biochar entered as a soil improver in Annex 2 [37]; 2018, petition to add it to Annex 4 (growing media) [38]; 2020, opening to organic agriculture [38, 43]; 2022, decree of 10 October 2022, biochar into Annex 13, organic farming [42]. *European line (above):* 2019, Regulation (EU) 2019/1009 enters into force, with implementing Regulation 2019/2164 [44, 43]; 2022, Regulation 2019/1009 becomes applicable, repealing Regulation 2003/2003 [44]; 2024, Regulation (EU) 2024/3012, the carbon-removal certification framework [45]; 2026 (hollow marker, prospective), the expected review linking certified removals to European climate policy, including the ETS [45, 46].

An additional source of complication lies in the European rules, above the Italian ones, which rely on a different logic. Regulation (EU) 2019/1009 [44], in force since 16 July 2019 and applied from 16 July 2022, opened a single-market route for fertilising products, organised into seven product function categories and a set of component material categories, of which CMC 14, "pyrolysis and gasification

materials", is the slot that holds biochar — a slot shaped by the STRUBIAS working group of the Joint Research Centre [47], which fixed criteria such as the same $H:C_{org} < 0.7$ stability limit, a minimum process temperature, an input list that excludes municipal, sewage and industrial sludge, and registration under the chemicals regulation REACH [48]. Crucially, the two regimes coexist rather than one replacing the other: a CE-marked fertiliser may circulate across the whole single market, but a member state can still restrict *use* to products meeting its own rules, so the national decree is not abolished by the European one. Which of the two applies in a concrete case is still unclear, and this is one of the open questions also mentioned in the CREA account.

A related European act, the implementing regulation 2019/2164 [43], added biochar to the list of products allowed in organic farming. The 2022 national decree later followed the same approach.

The direction of travel looks like that: the frontier is a shift of frame, from biochar as an agricultural input to biochar as a "aimable" product, a carbon-removal medium. At European level the Carbon Removal Certification Framework, Regulation (EU) 2024/3012 [45], builds the legal base for certifying removals, feeding the voluntary market and, prospectively, the emissions trading system whose revision is expected in 2026. Domestically the live front is the end-of-waste question for biochar made from the organic fraction of municipal waste: until a plant obtains formal end-of-waste recognition for such a char, producing it from organic waste for any purpose is effectively blocked, and the Tuscan ALIA/Selvapiana project — known locally as "I Cipressi" — is reported as the first in Italy to pursue that recognition [46, 49, 50, 51]. As of 2024 the project was still completing its authorisation process, delayed by environmental objections on the site location and the consequent loss of PNRR funding [51]. The bureaucratic trajectory therefore points at the same two unresolved questions that will condition the economics of the whole chain: which regime governs a given product, and how much commercial room opens once biochar is recognised not merely as something to spread on soil, but as a certified way of keeping carbon out of the air.

A last feature of the chain as it stands concerns not who is in it but how it earns. Most active Italian units are run for energy, not for char. Many are gasifiers — loosely called pyro-gasifiers — operated at high temperature to turn the wood almost entirely into gas; in such a plant the biochar is, quite literally, the carbon the process failed to gasify, a minor by-product rather than the aim [52]. The revenue rests on the energy sold, often supported by incentives, and on the liquid and solid by-products — the pyroligneous extract that a producer such as Biodea markets, for instance [23]. Selling by-products and energy, in short, is the present business model; the char rides along with it.

The alternative that has been proposed is to run the plant "all-pyrolysis", that is, product-oriented, with biochar as the primary output. What this means is fixed

by thermochemistry rather than by choice: the mode of the process sets the split between solid, liquid and gas. Push temperature up and residence time down, toward gasification (roughly 800–900 °C), and almost everything leaves as gas, with char below five per cent; tune toward fast pyrolysis and the yield swings to bio-oil; run slow pyrolysis instead (400–650 °C, long residence time) and the char fraction rises to about a third of the feed. Table 3.1 sets out the routes. An all-pyrolysis plant is a slow-pyrolysis unit deliberately held in this last regime, with the pyrogas and the little biocrude burned to supply the process its own heat rather than sold as the main product; the carbon is kept in the solid as stable, recalcitrant char, tunable to its intended use and available for return to the soil or — in the terms this thesis cares about — for durable storage [52]. The hardware is mature and comes in several families — kilns, retorts, rotary drums, screw (auger) reactors, fluidised beds — at capacities of the order of 900 to 6000 t/yr.

Table 3.1: Thermochemical routes for woody biomass and their typical product split, after Chiaramonti [52]. The mode of the process, not the feedstock, decides how much of the carbon leaves as solid char, liquid or gas: gasification is an energy route in which char is a residue, whereas slow pyrolysis — the "all-pyrolysis" configuration — is the product route that maximises it.

Route	**Temp. (°C)**	**Char**	**Liquid**	**Gas**
Fast pyrolysis	~ 500	12%	75%	13%
Intermediate pyrolysis	~ 500	25%	50%	25%
Slow pyrolysis	400–500	35%	35%	30%
Gasification	800–900	$< 5\%$	$< 5\%$	95–99%

The difference is one of business model, not only of temperature. Gasification is an energy-oriented process, its economics leaning on energy incentives and its char a by-product; slow pyrolysis is product-oriented, its economics resting on the value of the char itself [52]. The all-pyrolysis route is therefore the one a carbon-black-substitution chain would need, since it is what turns biochar from a residue into the product; but it carries its own costs — emission control, complex handling of the solids, and a penalty in size and cost when a single plant must accept many feedstocks. A further solid-product route, hydrothermal carbonisation, exists but yields a lower-quality, more labile char that needs downstream processing for most uses [52].

The model developed later assumes a plant of this product-oriented, slow-pyrolysis kind; its yields and costs are taken up in Chapter 4.

3.3 The Carbon Credit Market

Now it is time to delve into the carbon credit market: the financial tool that lies under the core assumption that it is possible to make biochar competitive by monetizing the "trapped" carbon dioxide. As will be shown, there are rigorous procedures and specific certificates a product made by/with biochar - let it be even only the original amendment purpose - must get. In this thesis and in the following chapter it will be assumed that the biochar involved in carbon black application may respect such boundaries. Evidence and limitations of such assumption will be made explicit in the brief case study at the end of this chapter.

A carbon credit is a certificate that one tonne of carbon dioxide has been removed from the atmosphere, or kept out of it, and that this can be proved. One credit usually stands for one tonne of CO_2-equivalent — "equivalent" because the other greenhouse gases are converted into the amount of CO_2 that would cause the same warming — and it takes the form of a digital certificate, issued by an independent body recognised for the purpose [53]. The reason for turning a removal into a certificate is that the claim can then be moved: whoever runs the removal generates the credit, and whoever buys it may "retire" it, cancelling the credit so as to count that tonne against its own emissions. Because the whole value rests on a claim about something that did not happen, a tonne removed and kept removed, or simply never emitted, the quality of credits varies widely, and the system has drawn steady criticism over weak projects and the risk of abuse [54].

The market has two aspects that do not really mix. The first is the compliance, or regulated, market, where firms are obliged by law to account for their emissions. It works by cap and trade: the state fixes a ceiling on total emissions and divides it into permits, each worth about one tonne of CO_2; a firm that emits more than its share must buy permits, and one that emits less may sell what it has not used. The European Emissions Trading System is the example that matters here. The second is the voluntary market, which took shape from about 2005, where non-governmental programmes issue credits that firms or individuals buy by choice rather than by obligation. The two are largely separate: a voluntary credit cannot normally be used to discharge a compliance duty, and the bridges between them have been built only in isolated cases, by particular countries [53].

Several kinds of actor make the market work. At its centre are the credit programmes, the bodies that issue credits. A programme does three things: it sets the standard a project must meet; it evaluates each project against that standard, and, if the project passes, issues the credit; and it keeps a registry, the platform on which credits are issued, transferred and finally retired. Some programmes are governmental, others independent, and it is the independent ones that matter for biochar: Verra and Gold Standard among the general registries, and, specific to this material, Puro.earth, whose biochar credits are the subject of the case study

below. Around the programmes sit the other roles. Project developers run the removal itself, here a biochar plant, and apply for the credits. Independent verifiers, third parties, check that the project really meets the standard; the credibility of a credit rests on them. Buyers are of two sorts: compliance buyers, the capped firms that must cover their emissions, and voluntary buyers, firms or people offsetting for a net-zero pledge or for their reputation. Between sellers and buyers, finally, work the intermediaries: traders, who deal in credits for financial gain on price differences; brokers and exchanges, who match buyers with sellers, the brokers handling the smaller and non-standard volumes at retail; and credit providers, who aggregate many projects and resell them, giving a firm a convenient way into the market [53].

For biochar, then, the relevant door is the voluntary market through independent programmes, (such as, as follows, the ones carried out by industrial production sites, as in the German case): this is one reason the activity has not taken shape yet in Italy.

What remains is to see how one such credit is actually generated, step by step, and how those steps constrain the life-cycle assumptions on which the model will later rest.

Generating a biochar carbon credit is a defined procedure, standardised under the Puro.earth framework a credit is a CO_2 Removal Certificate (CORC), certifying one net tonne of CO_2e removed and computed as

$$\text{CORCs} = C_{stored} - C_{baseline} - C_{loss} - E_{project} - E_{leakage}. \tag{3.1}$$

Table 3.2 sets out the steps that produce one, what each is for, and where each rule comes from; the rules are those of the approved methodology [55].

Table 3.2: How a biochar carbon credit (a CORC) is generated under the Puro.earth biochar methodology [55]: for each step, what must be done, what it is for, and the rule it follows. Section numbers (§) refer to that methodology.

What to do	What it is for	Source
Register as CO_2 Removal Supplier, enrol the production facility, set the crediting period.	Fixes who removes the carbon, at which plant, and over what period credits may be claimed.	Puro §2.1–2.2

continued on next page

Table 3.2 continued from previous page

What to do	What it is for	Source
Show the activity is eligible: biochar as defined, from eligible biomass, in a durable-storage use.	Ensures the project falls under the methodology and the carbon is kept, not diverted.	Puro §3, §3.6
Measure stored carbon $C_{stored} = Q_{biochar} \times C_{org} \times \frac{44}{12}$ (dry mass, organic carbon by accredited lab).	Quantifies the gross CO_2e locked in the biochar.	Puro §6.1 (Eq. 6.1)
Deduct storage losses C_{loss} (decay of the labile fraction over the permanence horizon).	Counts only carbon that stays durably stored.	Puro §6.2
Deduct the baseline $C_{baseline}$ (what would have been stored anyway).	Credits only removal additional to the baseline.	Puro §6.3
Quantify project emissions $E_{project}$ by LCA (operational and embodied; co-product allocation; cut-off).	Subtracts the supply-chain emissions the activity causes.	Puro §7
Quantify leakage $E_{leakage}$ (indirect, market- and activity-shifting effects).	Subtracts indirect emissions displaced elsewhere.	Puro §8
Compute the net result (Eq. 3.1); one CORC = one net tonne of CO_2e.	Fixes how many credits the activity earns.	Puro §5

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Table 3.2 continued from previous page

What to do	What it is for	Source
Monitor and report per the monitoring plan (batch mass, moisture, carbon content).	Gives the verifiable, time-stamped record the claim rests on.	Puro §9, §5.2–5.3
Submit to independent audit (production-facility and periodic output audits, third-party auditor).	Validates conformity and volumes; without it no credit is issued.	Puro; case study §3.3
Issue the CORCs into a registry, then sell and finally retire them.	Makes the credit exist and transferable, and on retirement consumes it.	Puro §2.3; registry [56]

Only the link to the model needs spelling out. Equation (3.1) is itself a life-cycle assessment: net removal is the carbon durably stored in the biochar, less every emission the chain causes to put it there. The model of Chapter 4 computes exactly this, the net CO_2 removed per tonne of biochar, and its life-cycle assumptions must answer to the rules above. It keeps the backbone — boundary, stored carbon, operational and embodied emissions, permanence — and sets aside, and flags as conservative assumptions, the parts a plant-level optimisation cannot yet resolve on Italian data: a detailed baseline, leakage, the finer allocation to co-products. The price this thesis seeks is the price of one CORC, one net tonne; the full accounting is deferred to that chapter.

To show that this market is real and current, not only theoretical, one case is examined at first hand from its published sources. Table 3.3 answers the natural questions about it; only the reading of those sources is left to prose, below.

Table 3.3: A documented biochar carbon-credit case, read from its public records: the Novocarbo listing on the Puro.earth registry [57].

Question	Answer	Source
Which credit?	CO_2 Removal Certificates (CORCs), issued on the Puro.earth registry, listing #100056.	[57]
By whom?	Novocarbo GmbH (Dörth, Germany), an operator of industrial pyrolysis plants (and owner of Swiss Biochar).	[57]
For what?	Carbon removal by pyrolysis of biogenic residues into biochar; among the uses the supplier declares is "biochar as additive/filler for industrial composite materials such as concrete and high-performance polymers".	[57]
Where published?	On the public Puro.earth registry and marketplace (`puro.earth/100056`).	[57]
At what value?	Listed at 220 EUR per CORC; first issuance 2021; declared permanence over 1000 years; embodied carbon 2.94 tCO_2e per unit. Total volume not stated on the listing.	[57]
Who assessed it?	Puro.earth issues the CORCs; the facility was independently verified by bio.inspecta AG (audit statement FAS-0007; status "Audited").	[57]
Is the buyer known?	No. The credits were issued and traded, but the registry does not disclose the buyer.	[57]
How many such cases?	Several: each certified facility is fully documented in the registry (public project description plus output audit). Carbo Culture's R3 facility in Finland, for instance, has 4.82 CORCs verified by 350Solutions. Novocarbo was chosen for its declared industrial-composite use.	[58]

The information directly stated by the source is taken as a true fact. This

includes:

- Novocarbo is a certified supplier on Puro.earth;
- its facility was independently audited by bio.inspecta AG;
- CORCs have been issued since 2021;
- the supplier declares industrial composites, including concrete and high-performance polymers, as possible uses. These are the types of applications where a carbon-black substitute could be used.

Information that is not directly stated in this list is labelled as an inference. The buyer is not disclosed, so no claim is made about who owns the credits.

More importantly, this is regulatory and commercial evidence that biochar carbon credits can be generated and sold in practice. It is not direct scientific evidence that the carbon remains stored permanently.

This case was selected because it is similar to a possible carbon-black application. The fact that Puro.earth and its third-party auditors accepted a supplier whose declared uses include industrial composites shows that a recognised certification system considers these applications compatible with its permanence requirements. However, this does not prove that carbon remains permanently stored in a specific polymer product, whose lifetime is generally shorter than that of concrete or soil.

The listing also presents these uses only as examples. CORCs are issued at production, when the carbon is measured, while the permanence of the carbon is evaluated based on the eligible final use. Therefore, the listing alone cannot show whether the specific credits sold are linked to the industrial-composite use or to the soil-amendment use.

With these limitations, the case shows what it can reliably support: a market for biochar carbon credits exists, it is independently audited, and industrial uses are already recognised within this market.

Three points close the chapter. The state of the Italian chain is first of all a matter of law lacking a recognition of biomass needed for biochar as feedstock on its own to allow the production of biochar as a product on its own; secondly, it is a reality of a few sparse producers whose biochar is not their core revenue; and of a credit market that is real but that Italian biochar has barely begun to enter. The carbon credit, whose rules Section 3.3 set out and whose reality this case attests, is the mechanism on which the whole economic question turns. What its price would have to be, for an optimised Italian chain to break even while selling biochar at a carbon-black-competitive price, is the question the model of Chapter 4 now takes up.

Chapter 4

An Optimization Framework for the Italian Biochar Supply Chain

4.1 Model definition

In the previous chapters the vastness of the possible questions and their broadness have been narrowed to few sharp and precise ones. This chapter builds an optimisation model to test them, in the following they are re-stated for the reader: whether the geography of the Italian chip supply can be arranged to lower the cost of removal; what carbon-credit price would be needed to make the chain break even; and, above all, *which* parameter that price is really governed by.

The model adapts the two-stage framework of Grimm, Niazmand and Runge [18] to the twenty real producer nodes discussed and reconstructed in the previous chapters. The two stages answer two different questions and are solved in sequence. *Stage A* is a location–allocation problem: given where the biomass is, decide where to build the conversion plants, how large to make them, and how to route each node's chips, so as to minimise the cost of building and feeding the network. *Stage B* takes the layout fixed by Stage A and computes its full economic and carbon balance, from which a single figure of merit is extracted — the *break-even carbon credit* $p^\star$, the credit price that exactly cancels the chain's deficit:

$$p^\star \;=\; \frac{\text{full annual cost} \;-\; \text{annual revenues}}{\text{net } CO_2 \text{ removed per year}}. \tag{4.1}$$

Equation (4.1) is the model's output: a high $p^\star$ means the chain needs an expensive credit to survive, a negative $p^\star$ means it is already profitable without one. Everything that follows exists to compute the three ingredients of this ratio and to trace

how each responds to the choices made along the way.

The engine of Stage A is a single tension. Concentrating the biomass into a few large plants makes each plant cheaper per unit of capacity, because the fixed cost of a conversion plant grows less than proportionally with its size; but concentration also forces the chips to travel farther, and transport is paid by the tonne-kilometre. The optimiser sits exactly between these two pressures, which can be written schematically as

$$\min_{\text{layout}} \ \underbrace{\text{fixed plant cost(scale)}}_{\text{falls with concentration}} \ + \ \underbrace{\text{transport cost(distance)}}_{\text{rises with concentration}} . \tag{4.2}$$

The qualitative behaviour to expect follows directly from Equation (4.2): when transport is cheap the fixed-cost term dominates and the optimum concentrates the supply into few large plants; when transport is expensive the balance tips towards many small plants sited close to the biomass; and the stronger the economies of scale, the more the optimum leans towards concentration.

The whole point of solving the model, rather than assuming an answer, is to locate this balance for the real Italian geography and to measure how far it actually shifts the cost of removal.

It is essential to be explicit about what this optimisation does *not* touch. Only the quantities that depend on the network topology enter Stage A: the opening decisions x_j, the allocations z_{ij}, the plant sizes, and therefore the fixed and transport costs. Every other ingredient that contributes to determining the break-even credit in Equation (4.1) — the purchase price of the biomass, the selling prices of biochar, energy and by-products, the process yields, and the life-cycle emission factors — is evaluated in Stage B *on the layout already chosen*. These "downstream" parameters re-scale $p^\star$ but leave the optimal layout unchanged, because they enter neither the objective nor the constraints of Stage A; only the "upstream" parameters (the transport tariff, the reference capital cost, the scale exponent, the discount rate, the capacity bounds and the nodal availabilities) can actually move the plants. This asymmetry is a choice for this model: its direct consequence lies on the fact that, as the sensitivity analysis of Section 4.2 will confirm, the spatial optimisation turns out to be weak, unfortunately, next to the price of the feedstock, which dominates the credit from outside the optimisation. The last section of this chapter discusses how a richer model could internalise some of these terms.

The decision variables and index sets of Stage A are collected in Table 4.1. The same formulation is instantiated in two scenarios that differ *only* in how the fixed cost C_j is built — a theoretical chain with genuine economies of scale and a realistic chain of replicated modular units — so that the two can be compared on equal terms; the two constructions are detailed in Section 4.1.1, and the scenarios themselves in Section 4.2.

Table 4.1: Decision variables and index sets of the location model (Stage A). The two plant-size variables are alternatives: y_j is used in the theoretical scenario (continuous capacity with economies of scale), n_j in the realistic scenario (an integer number of identical modules).

Symbol	**Type**	**Meaning**
$i \in \mathcal{I}$	index	producer node, i.e. a source of wood chips
$j \in \mathcal{J}$	index	candidate conversion site; here $\mathcal{J} = \mathcal{I}$, so every producer node is also a possible plant location
x_j	binary	1 if a plant is opened at site j, 0 otherwise
z_{ij}	[0,1]	fraction of node i's biomass routed to site j
y_j	≥ 0	installed capacity of plant j, in $\mathrm{t\,h^{-1}}$ (theoretical scenario)
n_j	integer	number of identical modules installed at site j (realistic scenario)
C_j	≥ 0	total annualised fixed cost of plant j, in $€\,\mathrm{yr^{-1}}$

4.1.1 The fixed-cost block: economies of scale and its linearisation

Of the cost and benefit blocks that make up the break-even credit of Equation (4.1), the fixed cost C_j is the only one that carries a nonlinearity, and the only one through which economies of scale — the mechanism the spatial optimisation exists to exploit — enter the model. It is therefore treated first and in the most detail. Two basic but instructive scenarios can be built on this consideration, differing *only* in how this block is constructed: the theoretical chain models genuine economies of scale, the realistic chain considers the impossibility of such exploitation. The names follow from which type of plant is currently operative in the Italian supply chain: as noted before, these are micro-plants, whose technologies have been developed or bought by each company, with unclear or evidence-lacking proof of the possibility of scaling up, so the "realistic case" is to be read in the sense of the *current* Italian reality, not of its future possibilities.

The theoretical construction and its linearisation are given first, the linear modular case at the end.

Some financial definitions are needed in what follows:

CAPEX (capital expenditure) without a plant yet in place, this is the initial, upfront investment required to build and equip it — the cost of purchasing and installing the equipment and infrastructure the facility needs in order to operate.

OPEX (operating expenditure) the costs incurred while the plant operates: energy, raw materials, labour, maintenance and other recurring operating costs.

Annualised fixed OPEX (FOPEX) the recurring annual costs that are relatively independent of the plant's production volume or operating level (they must be paid for the sole reason that the plant exists and must be maintained).

When no detailed cost data are available, the six-tenths rule provides a first-order estimate of capital cost based on the capacity of a reference plant: capital cost is assumed to scale with plant capacity according to a power law, with an exponent of 0.6 as a conventional approximation. The rule is widely used for early-stage capital-cost estimation of (bio)chemical and biorefinery processes [59, 60] and is documented as a scale-up power law in the process-engineering literature [61]. Grimm et al. [18] adopt it without citing an explicit source; my deep dive in the literature showed that the rule is usually traced back to Chilton [62], building on the earlier note of Williams [63], and it is presented in the same form by institutional sources [64].

For a plant of capacity y (in $\mathrm{t\,h^{-1}}$), the CAPEX follows this six-tenths rule, by which capital cost scales sub-linearly with plant capacity:

$$K(y) \;=\; K_{\mathrm{ref}} \left(\frac{y}{y_{\mathrm{ref}}} \right)^{R}, \qquad R = 0.6, \tag{4.3}$$

where K_{ref} is the CAPEX of a reference plant of capacity y_{ref}. Thus a plant k times larger requires only $k^{0.6}$ times the capital investment, which is precisely the economic incentive to concentrate. The one-off capital expenditure — therefore, the initial expenditure required to purchase and install the plant — is converted into an equivalent constant annual cost through the capital recovery factor (CRF),

$$\mathrm{CRF} \;=\; \frac{r\,(1+r)^{n}}{(1+r)^{n}-1}, \tag{4.4}$$

where r is the discount rate and n the plant lifetime in years, so that the annualised CAPEX is

$$K_{\mathrm{ann}}(y) \;=\; \mathrm{CRF} \cdot K(y). \tag{4.5}$$

The fixed operational and maintenance costs are taken to amount to a fraction f_{OPEX} of the CAPEX, so that the total annual fixed cost is $F(y) = K_{\mathrm{ann}}(y) + f_{\mathrm{OPEX}}\,K(y)$ or, equivalently,

$$\boxed{F(y) \;=\; \Big(\mathrm{CRF} + f_{\mathrm{OPEX}}\Big)\, K_{\mathrm{ref}} \left(\frac{y}{y_{\mathrm{ref}}} \right)^{R}} \tag{4.6}$$

which corresponds directly to the fixed cost C_j of an open plant ($x_j = 1$) used in the model. Capacity is tied to the biomass actually routed to the plant, which cannot exceed what the plant can process in a year:

$$\sum_{i \in \mathcal{I}} z_{ij}\, S_i \;\le\; y_j\, H \qquad \forall\, j \in \mathcal{J}, \tag{4.7}$$

with H the effective operating hours per year (a 90% availability is assumed) and S_i the biomass available at node i. Equation (4.7) is what forces a larger y_j, and hence a larger C_j, when biomass is concentrated on site j.

Equation (4.6) is concave and nonlinear, whereas the location problem is a mixed-integer *linear* program: the cost curve must be replaced by a linear surrogate.

In equation (4.6) two separate nonlinearities are present. However, the location model is a mixed-integer linear program, so both must be removed before it can be solved. The first is the curve just built: $F(y)$ is concave in the capacity y, growing as y^R with $R = 0.6$. The second comes from the fixed cost being charged only when the plant is open, indeed: what should be written in the cost function is $F(y_j)$ multiplied by the opening variable x_j, so that the cost disappears when $x_j = 0$.

Even after the concave curve is linearised, this second requirement would eventually leave the product $x_j y_j$, bilinear and thus inadmissible in a linear solver. The two nonlinearities are independent and must be managed separately.

Grimm et al. [18] approached the problem by approximating the curve with a single affine function valid between a minimum and a maximum capacity, and handled the product $x_j y_j$ with a McCormick envelope, a standard linear relaxation of a product over the bounds of its two variables. This construction was reproduced first, but it proved unsatisfactory. A single straight line follows the concave curve only near the capacity it was tuned to, and leads, outside the interval $[y_{\min}, y_{\max}]$, to wrong configurations. The plants whose required capacity falls outside that window, for example the smaller ones, which the optimisation should aggregate in case of low transportation cost, could even fail to do so.

A different solution was therefore studied and proposed: the concave curve is approximated by a piecewise-linear (PWL) function, accurate across the whole capacity domain rather than on a single interval; and the product $x_j y_j$ has been avoided with an escamotage: enforcing the open/closed switch of the fixed cost exactly and linearly through the PWL "new" boundary conditions. The two roles stay separate: the PWL replaces the curve, and the weight constraint introduced below replaces the product.

In detail, the capacity domain $[y_{\min}, y_{\max}]$ is sampled at $n_{\text{seg}} + 1$ breakpoints; each breakpoint k carries a capacity $\hat{y}_k$ and the exact concave cost evaluated there, $\hat{c}_k = F(\hat{y}_k)$:

$$\hat{y}_k \;=\; y_{\min} + k\,\frac{y_{\max} - y_{\min}}{n_{\text{seg}}}, \qquad \hat{c}_k \;=\; \Big(\text{CRF} + f_{\text{OPEX}}\Big)\, K_{\text{ref}} \left(\frac{\hat{y}_k}{y_{\text{ref}}}\right)^{R}, \qquad k = 0, \ldots, n_{\text{seg}}. \tag{4.8}$$

For each site j the capacity and its cost are written as a convex combination of the breakpoints, with weights $\lambda_{jk} \geq 0$, while the binaries b_{js} mark the active segment:

$$y_j = \sum_{k \in \mathcal{K}} \lambda_{jk}\, \hat{y}_k, \qquad C_j = \sum_{k \in \mathcal{K}} \lambda_{jk}\, \hat{c}_k, \qquad \sum_{k \in \mathcal{K}} \lambda_{jk} = x_j, \qquad \sum_{s \in \mathcal{S}} b_{js} = x_j,$$

$$\lambda_{jk} \leq \begin{cases} b_{j0} & k = 0, \\ b_{j,k-1} + b_{jk} & 0 < k < n_{\text{seg}}, \\ b_{j,\,n_{\text{seg}}-1} & k = n_{\text{seg}}, \end{cases} \qquad \lambda_{jk} \geq 0, \quad b_{js} \in \{0,1\}, \tag{4.9}$$

with $\mathcal{K} = \{0, \ldots, n_{\text{seg}}\}$ the breakpoints and $\mathcal{S} = \{0, \ldots, n_{\text{seg}} - 1\}$ the segments. The normalisation $\sum_k \lambda_{jk} = x_j$ carries the open/closed switch: when $x_j = 0$ every weight is forced to zero, so $y_j = 0$ and $C_j = 0$, and the product $x_j y_j$ is never written; when $x_j = 1$ the weights sum to one and (y_j, C_j) lands on the curve, while the adjacency inequalities enforce the SOS2 condition — at most two adjacent weights nonzero — so the interpolation always uses a single segment.

For the realistic chain the fixed cost is built instead as a linear function of an integer number of identical Biodea modules n_j, with no economies of scale; each module costs c_{mod} per year and processes q_{mod} tonnes of dry biomass:

$$c_{\text{mod}} = \left(\text{CRF}+f_{\text{OPEX}}\right) K_{\text{mod}}, \qquad C_j = c_{\text{mod}}\, n_j, \qquad \sum_{i\in\mathcal{I}} z_{ij}\, S_i \;\le\; n_j\, q_{\text{mod}}, \qquad x_j \;\le\; n_j \;\le\; N_{\max} \tag{4.10}$$

with n_j a non-negative integer and $N_{\max}$ a non-binding cap on the modules per site. Here the capacity constraint (4.7) is replaced by the module throughput $n_j\, q_{\text{mod}}$, and the linking $x_j \le n_j \le N_{\max}\, x_j$ forces $n_j = 0$, hence $C_j = 0$, at a closed site.

The symbols of the whole block are collected in Table 4.2.

Table 4.2: Symbols of the fixed-cost block, Equations (4.3)–(4.10). Decision variables are chosen by the optimiser; parameters are inputs. Base values marked *provisional* are placeholders pending the final choice of plant scale.

Symbol	**Meaning**	**Base value / unit**	**Type / source**
y_j	capacity of plant j	t h^{-1}	decision variable
C_j	total annualised fixed cost of j	€$\,\text{yr}^{-1}$	decision variable
λ_{jk}	weight on breakpoint k (PWL)	[0,1]	decision variable
b_{js}	active-segment indicator	binary	decision variable
n_j	number of modules at j (realistic)	integer ≥ 0	decision variable
R	scale exponent (six-tenths rule)	0.6	[18]
K_{ref}	reference capital cost	26.6 M€	provisional (theoretical)
y_{ref}	reference capacity	$5\,\text{t h}^{-1}$	provisional (theoretical)
$[y_{\min}, y_{\max}]$	PWL capacity domain	$[0.5,\ 30]\,\text{t h}^{-1}$	provisional
r	discount rate	0.06	[18]
n	plant lifetime	20 yr	assumption
f_{OPEX}	opex, fraction of capital	0.02 / 0.028	theoretical / modular (Biodea)

continued on next page

Table 4.2 continued from previous page

Symbol	Meaning	Base value / unit	Type / source
CRF	capital recovery factor	Eq. (4.4)	derived
H	effective operating hours	$0.90 \times 8760 \approx 7884\,\mathrm{h\,yr^{-1}}$	90% availability
n_{seg}	number of PWL segments	15	computational choice
$\hat{y}_k,\ \hat{c}_k$	breakpoint capacity, cost	Eq. (4.8)	derived
K_{mod}	capital cost of one module	1.6 M€	Biodea (realistic)
q_{mod}	annual throughput of a module	$401.5\,\mathrm{t\,yr^{-1}}$	Biodea (realistic)

This scenario must be considered as a basic baseline for comparison: what if the Italian companies, independently, tried to increase their production with the current plants and capacities? Or, again, it can model the following: if it happens that multiple production nodes exist near each other in the same location, too close to be considered separated nodes and thus aggregated, and, again, independently, they would invest and install their own plant to become player in this sector: this is what the outcome would look like in such cases. (The data justification is that: many did not answer to our data requests and the typical size of an Italian independent producer is less than 500 tons per year)

4.1.2 The material-cost block

The second addend of the full cost is the material cost: the biomass purchased from the producers, plus, eventually, the disposal of the solid residues (if any) generated in conversion. Unlike the fixed cost, this is a purely variable cost — it scales with the biomass throughput, not with the number or size of the plants — and, as shown below, it does not enter Stage A at all. It is written

$$K^{\mathrm{mat}} \;=\; \underbrace{\sum_{i\in\mathcal{I}}\sum_{j\in\mathcal{J}} z_{ij}\, S_i\, \pi_i}_{\text{biomass purchase}} \;+\; \underbrace{\rho_{\mathrm{res}}\, B\, g}_{\text{residue disposal}}\;, \qquad B \;=\; \sum_{i\in\mathcal{I}} S_i, \tag{4.11}$$

where π_i is the purchase price of the chips at producer node i, B is the total biomass processed, ρ_{res} the residue yield per tonne of feedstock, and g the gate fee paid to dispose of one tonne of residue. Two modelling choices in Equation (4.11) deserve to be made explicit, because both bear directly on the break-even credit.

First, the biomass is bought at the price of the *producer* that supplies it, π_i, indexed by the source node i — not at any price attached to the site j that transforms it. The consequence is an invariance. Because every producer's biomass is fully allocated somewhere ($\sum_j z_{ij} = 1$ for all i), the purchase term collapses to

$$\sum_{i\in\mathcal{I}}\sum_{j\in\mathcal{J}} z_{ij}\, S_i\, \pi_i \;=\; \sum_{i\in\mathcal{I}} S_i\, \pi_i \Big(\sum_{j\in\mathcal{J}} z_{ij}\Big) \;=\; \sum_{i\in\mathcal{I}} S_i\, \pi_i, \tag{4.12}$$

a constant that does not depend on the layout $\{z_{ij}\}$.

At this stage, the production depends on the node but the cost of the feedstock, assumed for simplification to belong to the same quality type, has been set to the same value for every admissible configuration: it can be neither raised nor lowered by the spatial optimisation. Initially it is fixed at the medium cost computed on the collected data, then swept in the sensitivity analysis across the interval fixed by the same data.

This is why the material cost appears only in Stage B and never in the Stage A objective, and it is the concrete mechanism behind the "downstream parameter" asymmetry announced in Section 4.1: the feedstock price is both the single largest term in the balance and one the optimiser cannot touch. At the base data it amounts to about 15.5 M€ per year — larger, on its own, than the chain's total revenues at the base biochar price — which is the structural reason the break-even credit turns out high, as quantified in Section 4.2.

Second, a residue term is shown for completeness; it can be added to the model if needed. In the model of Grimm et al. [18] it was crucial to making the supply chain sustainable, because it eradicated the plants' dependence on the price of the feedstock: others pay to dispose of the residues, and the plants process them, converting them into product. This is not the case for the biomasses used in the Italian wood-chip chain, because its producers pay for the feedstock: in other biochar productions — such as those based on FORSU (the organic fraction of municipal solid waste) — the "feedstock" processed by the plant is instead a direct revenue, paid by whoever must dispose of it. The symbols of the block are listed in Table 4.3.

4.1.3 The transport block

The third cost block is transport, and it is the main downstream cost that enters the Stage A optimisation. Unlike the material cost, it depends on which plant each producer's chips are routed to, and it is precisely the counterweight to the economies of scale of Section 4.1.1: concentrating the supply lowers the fixed cost but raises this term, and the optimum of Stage A is the layout that balances the

Table 4.3: Symbols of the material-cost block, Equation (4.11). The producer prices π_i and the biomass S_i are measured (the survey of Chapter 3); the two residue parameters are inherited from Grimm et al. [18].

Symbol	Meaning	Base value / unit	Type / source
π_i	purchase price at producer i	node-specific, €$\,t^{-1}$	measured (Ch. 3)
S_i	dry biomass at node i	$t\,yr^{-1}$	measured (Ch. 3)
B	total biomass processed	$\approx$ 138,400 $t\,yr^{-1}$	$= \sum_i S_i$
ρ_{res}	residue yield	0.03	[18]
g	residue disposal gate fee	0 €$\,t^{-1}$	measured†
K^{mat}	total material cost	≈ 15.5 M€$\,yr^{-1}$	derived

†Only one producer reported being paid to dispose of usable biomass; since this is no longer the case, the parameter has been set to zero.

two. The cost of moving the biomass is

$$K^{\mathrm{tr}} \;=\; \sum_{i\in\mathcal{I}}\sum_{j\in\mathcal{J}} \tau\, d_{ij}\, S_i\, z_{ij}, \tag{4.13}$$

where τ is a flat tariff per tonne-kilometre, d_{ij} the distance from producer i to site j, and $S_i\, z_{ij}$ the (dry) tonnes routed along that link.[1] The distances are great-circle (haversine) distances [65],

$$d_{ij} \;=\; 2R_{\oplus}\, \arcsin\sqrt{\sin^2\frac{\phi_j-\phi_i}{2} + \cos\phi_i\, \cos\phi_j\, \sin^2\frac{\lambda_j-\lambda_i}{2}}\,, \tag{4.14}$$

with $R_{\oplus} = 6371$ km the Earth's radius and (ϕ_i, λ_i) the latitude and longitude of node i.

Several approximations survive in Equations (4.13)–(4.14), aiming to simplify the model where further additions would have only complicated the model without adding accuracy or insight to it.

First, the distance is the straight-line great-circle distance, not the real road distance: it underestimates the true haulage length by a roughly constant detour factor, which is absorbed into the tariff τ rather than modelled explicitly. Second, the tariff is a single linear constant per tonne-kilometre, independent of load, vehicle and direction; in reality the two directions of a link may cost differently — the volume moved from i to j need not equal that from j to i — and empty return trips are not separately priced, but for a national siting study a flat τ is the standard simplification [18]. Third, only the inbound transport of the feedstock to the plant is counted; the onward distribution of the biochar to its end user is not, for the same reason its use is excluded from the carbon balance (Section 4.1.5) — those costs and emissions belong to the sector that consumes the product, not to the removal. A richer model could relax both assumptions, making the biomass price and the transport cost specific to each node and each mass moved. In the light of the sensitivity analysis of Section 4.2, however, this refinement would change little: the spatial optimisation lowers the total cost of the chain only marginally, so a more granular treatment of these terms would not move the break-even credit appreciably.

[1] Both the tariff τ and the haulage emission factor e_{tr} of the life-cycle balance (Section 4.1.5) are referred to the tonne *as delivered*, i.e. the wet chip on the truck: τ is extrapolated from operators' quotes per delivered tonne and e_{tr} from [28]. Consistently, in the computation both the transport cost K^{tr} and the transport emissions are charged on the as-received (wet) mass $S_i/(1-M_i)$, not on the dry S_i that governs yields and capacity, where M_i is the moisture of node i (10–40%, quantity-weighted ≈ 0.37); this raises the effective tonne-kilometres by roughly a factor 1.6. The dry symbol S_i is kept in Equations (4.13) and (4.15) for readability, and the wet mass re-enters the Stage-A objective, so it also shapes the optimal siting.

The base tariff is $\tau = 0.077\,€\,\mathrm{t^{-1}\,km^{-1}}$, an empirical, survey-extrapolated value for wood-chip transport. Because transport is the hinge of the spatial tension, it is the parameter deliberately swept across the three values $\{0.077,\ 0.300,\ 1.000\}\,€\,\mathrm{t^{-1}\,km^{-1}}$ in the scenarios of Section 4.2, to see how far a more expensive logistics shifts the optimum. Finally, the same tonne-kilometre aggregate that Equation (4.13) costs,

$$\mathrm{TK} \;=\; \sum_{i\in\mathcal{I}}\sum_{j\in\mathcal{J}} d_{ij}\,S_i\,z_{ij}, \qquad K^{\mathrm{tr}} = \tau\,\mathrm{TK}, \tag{4.15}$$

is reused in the life-cycle balance to charge the transport emissions (Section 4.1.5): a layout that ships biomass far is penalised twice, once in euros here and once in CO_2 there. The symbols are collected in Table 4.4.

These considerations are reorganised and extended in a table at the end of the chapter.

Table 4.4: Symbols of the transport block, Equations (4.13)–(4.15). The coordinates (ϕ_i, λ_i) are measured (Chapter 3); the tariff τ is an empirical base value, also swept in the scenarios.

Symbol	Meaning	Base value / unit	Type / source
τ	flat transport tariff	0.077 (swept 0.077–1.0), $€\,\mathrm{t^{-1}\,km^{-1}}$	empirical / swept
d_{ij}	great-circle distance $i \to j$	km, Eq. (4.14)	derived (coords)
$R_\oplus$	Earth radius	6371 km	constant
ϕ_i, λ_i	latitude, longitude of node i	degrees	measured (Ch. 3)
TK	total tonne-kilometres	$\mathrm{t\,km\,yr^{-1}}$	derived
K^{tr}	total transport cost	$€\,\mathrm{yr^{-1}}$	derived, $= \tau\,\mathrm{TK}$

4.1.4 The revenue block

The revenues that offset the costs in the break-even credit of Equation (4.1) come from three streams: the sale of the biochar itself, of the by-products, and of the electricity generated from the syngas. They are

$$Rv \;=\; \underbrace{\rho_{\mathrm{bc}}\,B\,p_{\mathrm{bc}}}_{\text{biochar}} \;+\; \underbrace{\rho_{\mathrm{sp}}\,B\,p_{\mathrm{sp}}}_{\text{by-products}} \;+\; \underbrace{E\,p_{\mathrm{el}}}_{\text{electricity}}\ , \tag{4.16}$$

where the sellable electricity E (in MWh per year) is obtained from the biomass through the syngas chain,

$$E \;=\; \rho_{\mathrm{en}}\, B\, \mathrm{LHV}_{\mathrm{sg}}\, \eta_{\mathrm{el}}\, f_{\mathrm{sell}}. \tag{4.17}$$

From left to right, Equation (4.17) multiplies the fraction ρ_{en} of each tonne of feedstock that leaves as syngas, the lower heating value $\mathrm{LHV}_{\mathrm{sg}}$ of that syngas, the electrical efficiency η_{el} of the engine, and the fraction f_{sell} of the electricity actually sold rather than self-consumed by the plant.

Three points on this block deserve further exposition. First, the energy is counted as a *revenue*, not as an avoided cost: the plant is taken to be energy self-sufficient, and only the surplus fraction $f_{\mathrm{sell}} = 0.83$ — the complement of the 17% self-consumption reported by Biodea — is sold to the grid at the price p_{el}; this proportion, measured on the Biodea micro-plant, is assumed to hold for larger plants as well. Second, the by-product term is set to zero as a conservative choice for two reasons ($p_{\mathrm{sp}} = 0$): firstly, defensible data about prices, rate of production, type of sub-product have not been provided; secondly, their absence has only the effect of raising the break-even credit, so the conservative choice can lead to more cautious estimates.

Third, the biochar price p_{bc} is left at a base of 100 € t^{-1} and is the decisive parameter of the whole study: it is swept from 0 to 3000 € t^{-1} — the band spanned by the agronomic and the (supposed) carbon-black-competitive uses of biochar — in the results, precisely to locate the price at which the chain breaks even without any credit.

At the base values the three streams are markedly unequal. The electricity, at about 4.8 M€ per year, actually exceeds the biochar revenue of about 2.8 M€, for a total of roughly 7.5 M€ per year — which is to be expected, since, as emerged from the interviews, energy is the core business of those companies. That total is less than half the material cost of Section 4.1.2: at the base biochar price the chain therefore runs at a deficit and needs a carbon credit to break even. The symbols are collected in Table 4.5.

Table 4.5: Symbols of the revenue block, Equations (4.16)–(4.17). The by-product price is set to zero as a conservative choice; the biochar price is a base value later swept over the nerofumo band.

Symbol	Meaning	Base value / unit	Type / source
ρ_{bc}	biochar yield	0.20 t t^{-1}	[26]

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Table 4.5 continued from previous page

Symbol	Meaning	Base value / unit	Type / source
p_{bc}	biochar selling price	100 (swept 0–3000) €$\,\mathrm{t}^{-1}$	base / swept (decisive)
ρ_{sp}	by-product yield	$0.40\,\mathrm{t\,t}^{-1}$	inactive ($p_{\mathrm{sp}} = 0$)
p_{sp}	by-product price	0 €$\,\mathrm{t}^{-1}$	prudent choice
ρ_{en}	syngas fraction	$0.27\,\mathrm{t\,t}^{-1}$	Survey
$\mathrm{LHV}_{\mathrm{sg}}$	syngas lower heating value	$3.5\,\mathrm{MWh\,t}^{-1}$	[18]
η_{el}	electrical efficiency	0.35	Survey
f_{sell}	sellable energy fraction	0.83	Survey (Biodea, $1 - 0.17$)
p_{el}	electricity price	125 €$\,\mathrm{MWh}^{-1}$	[27]
E	sellable electricity	$\mathrm{MWh\,yr}^{-1}$	derived
Rv	total revenue	€$\,\mathrm{yr}^{-1}$	derived

4.1.5 Life-cycle balance and the break-even carbon credit

The three cost blocks and the revenue block fix the euro side of the balance; the carbon side — the denominator of the break-even credit — is the net carbon dioxide actually removed from the atmosphere by the chain. This is where the life-cycle boundary of the study must be drawn explicitly, because the credit is only as meaningful as the emissions it does, and does not, count against the removal.

The removal proper is the carbon locked into the biochar and expected to stay there. Of each tonne of biochar a fraction χ_C is carbon, and of that carbon a fraction χ_{stab} is stable over the hundred-year horizon used for carbon-removal accounting; the stable carbon is converted to its carbon-dioxide equivalent by the molar mass ratio 44/12. With B tonnes of feedstock and a biochar yield ρ_{bc}, the sequestration is

$$\mathrm{CO}_2^{\mathrm{seq}} \;=\; \rho_{\mathrm{bc}}\, B\, \chi_C\, \chi_{\mathrm{stab}}\, \frac{44}{12}. \tag{4.18}$$

The permanence fraction $\chi_{\mathrm{stab}} = 0.80$ follows the conservative end of the European Biochar Certificate range rather than the higher value reported by the Italian char producers, so as not to over-credit the removal.

Against this sequestration the emissions that the removal itself causes are set. Following the framework set by Puro.earth and proposed also by Grimm et al. [18], these are grouped into three terms — the emissions of biomass supply, of biochar production and of biochar end-use — so that

$$\mathrm{CO}_2^{\mathrm{em}} \;=\; \underbrace{\mathrm{TK}\, e_{\mathrm{tr}}}_{\text{biomass supply}} \;+\; \underbrace{B\, e_{\mathrm{pr}} + E\, e_{\mathrm{grid}} + K^{\mathrm{fix}}\, e_{\mathrm{cap}}}_{\text{biochar production}} \;+\; \underbrace{\rho_{\mathrm{bc}}\, B \left(e_{\mathrm{use}} + \bar{d}\, e_{\mathrm{tr}}\right)}_{\text{biochar end-use}}, \quad (4.19)$$

and the net removal is the stored carbon minus all three,

$$\mathrm{CO}_2^{\mathrm{net}} \;=\; \mathrm{CO}_2^{\mathrm{seq}} - \mathrm{CO}_2^{\mathrm{em}}. \quad (4.20)$$

Each term has a clear meaning. The *biomass-supply* term is only the transport of the wood chips to the plant, charged on the same tonne-kilometres TK as the transport cost, through the wood-chip haulage factor e_{tr} [28]. The *production* term collects the emissions of making the biochar: the conversion step (e_{pr} per tonne of feedstock), the electricity possibly drawn from the grid (e_{grid}), zero in this case, and the emissions embodied in the plant's capital (e_{cap}). The *end-use* term collects the emissions of carrying the biochar over a mean distance $\bar{d}$ to its point of use and of using it there (e_{use}).

About the counterfactual: Grimm et al. [18] sidestep the problem with a zero-burden assumption on their feedstock, legitimate because industrial sludge is a waste that others pay to dispose of; that assumption may not hold here, because wood chip is not a zero-burden waste but a product with its own market and its own supply-chain footprint. For an Italian residual-forest-biomass chain, it is estimated to be about 0.027 kg CO_2 per kilogram of chips [66].

At the base data the sequestration is about 64,900 t CO_2 per year and the biomass-supply emissions about 2,300 t, the other terms being zero, so the net removal is roughly 62,600 t CO_2 per year: the emissions charged to the chain shave about 3.5% off the gross removal. A further consideration: the combustion of the syngas-derived electricity is left to the grid that buys it, which accounts for its own generation mix.

With both sides of the balance specified, the figure of merit announced in Section 4.1 can be written in full. The full annual cost is the sum of the three cost blocks — the fixed cost of Section 4.1.1, the transport of Section 4.1.3 and the material cost of Section 4.1.2 — and the break-even carbon credit is the deficit left after revenues, divided by the net removal, following Equation 9 of Grimm et al. [18]:

$$p^{\star} \;=\; \frac{\Big(\underbrace{\textstyle\sum_j C_j}_{K^{\mathrm{fix}}} + K^{\mathrm{tr}} + K^{\mathrm{mat}}\Big) \;-\; Rv}{\mathrm{CO}_2^{\mathrm{net}}}. \quad (4.21)$$

Equation (4.21) is the fully specified form of the schematic Equation (4.1), after all the model's assumptions and simplifications (at this stage): every term traces back to one of the blocks above, and only the fixed and transport costs depend on the layout chosen by Stage A. It is the single number the model reports for each scenario and each set of parameters in Section 4.2. The complete notation of the chapter is gathered in Table 4.6.

Table 4.6: Nomenclature of the optimisation model: all symbols of Equations (4.1)–(4.21), with their meaning and unit.

Symbol	Meaning	Unit
Sets and sizes		
$\mathcal{I}, \mathcal{J}$	producer nodes / candidate sites ($\mathcal{I} = \mathcal{J}$)	—
$\mathcal{K}, \mathcal{S}$	PWL breakpoints / segments	—
B	total biomass processed, $\sum_i S_i$	$\mathrm{t\,yr^{-1}}$
Decision variables		
x_j	open a plant at site j	binary
z_{ij}	fraction of node i's biomass routed to j	—
y_j	installed capacity of plant j (theoretical)	$\mathrm{t\,h^{-1}}$
n_j	number of modules at j (realistic)	integer
C_j	total annualised fixed cost of plant j	$€\,\mathrm{yr^{-1}}$
λ_{jk}, b_{js}	PWL weight / active-segment indicator	—, binary
Fixed-cost block		
R	scale exponent (six-tenths rule)	—
$K_{\mathrm{ref}}, y_{\mathrm{ref}}$	reference capital cost / capacity	€, $\mathrm{t\,h^{-1}}$
r, n, f_{OPEX}	discount rate / lifetime / opex fraction	—, yr, —
CRF	capital recovery factor	$\mathrm{yr^{-1}}$
H	effective operating hours	$\mathrm{h\,yr^{-1}}$
n_{seg}	number of PWL segments	—
$\hat{y}_k, \hat{c}_k$	breakpoint capacity / cost	$\mathrm{t\,h^{-1}}$, $€\,\mathrm{yr^{-1}}$
K_{mod}, q_{mod}, c_{mod}	module capital / throughput / annual cost	€, $\mathrm{t\,yr^{-1}}$, $€\,\mathrm{yr^{-1}}$
Material-cost block		
π_i	purchase price at producer i	$€\,\mathrm{t^{-1}}$
S_i	dry biomass at node i	$\mathrm{t\,yr^{-1}}$

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Table 4.6 continued from previous page

Symbol	Meaning	Unit
ρ_{res}, g	residue yield / disposal gate fee	—, €$\,\mathrm{t}^{-1}$
K^{mat}	total material cost	€$\,\mathrm{yr}^{-1}$
Transport block		
τ	flat transport tariff	€$\,\mathrm{t}^{-1}\,\mathrm{km}^{-1}$
d_{ij}	great-circle distance $i \to j$	km
$R_{\oplus}$	Earth radius	km
ϕ_i, λ_i	latitude, longitude of node i	degrees
TK	total tonne-kilometres	$\mathrm{t\,km\,yr}^{-1}$
K^{tr}	total transport cost	€$\,\mathrm{yr}^{-1}$
Revenue block		
$\rho_{\mathrm{bc}}, p_{\mathrm{bc}}$	biochar yield / selling price	—, €$\,\mathrm{t}^{-1}$
$\rho_{\mathrm{sp}}, p_{\mathrm{sp}}$	by-product yield / price	—, €$\,\mathrm{t}^{-1}$
$\rho_{\mathrm{en}}, \mathrm{LHV}_{\mathrm{sg}}$	syngas fraction / lower heating value	—, $\mathrm{MWh\,t}^{-1}$
$\eta_{\mathrm{el}}, f_{\mathrm{sell}}$	electrical efficiency / sellable fraction	—, —
p_{el}, E	electricity price / sellable electricity	€$\,\mathrm{MWh}^{-1}$, $\mathrm{MWh\,yr}^{-1}$
Rv	total revenue	€$\,\mathrm{yr}^{-1}$
Life-cycle balance and output		
$\chi_C, \chi_{\mathrm{stab}}$	carbon content / stable-carbon fraction	—, —
$e_{\mathrm{tr}}, e_{\mathrm{pr}}$	transport / process emission factor	$\mathrm{t\,CO_2\,(t\,km)}^{-1}$, $\mathrm{t\,CO_2\,t}^{-1}$
$e_{\mathrm{grid}}, e_{\mathrm{cap}}, e_{\mathrm{use}}$	grid / capital / end-use emission factor	$\mathrm{t\,CO_2\,MWh}^{-1}$, $\mathrm{t\,CO_2}$€$^{-1}$, $\mathrm{t\,CO_2\,t}^{-1}$
$\bar{d}$	mean biochar distribution distance	km
$\mathrm{CO}_2^{\mathrm{seq}}$, $\mathrm{CO}_2^{\mathrm{em}}$, $\mathrm{CO}_2^{\mathrm{net}}$	sequestered / emitted / net $\mathrm{CO_2}$	$\mathrm{t\,CO_2\,yr}^{-1}$
$p^{\star}$	break-even carbon credit	€$\,(\mathrm{t\,CO_2})^{-1}$

4.2 Model results

The model is solved in the two scenarios introduced in Section 4.1.1, which are identical in every block except the fixed cost. Both run on the same twenty producer nodes of Chapter 3 and share the same Stage B — the same prices, yields and life-cycle factors; the only difference is whether the plants enjoy economies of

scale. The *theoretical* scenario builds the fixed cost with the concave 0.6 rule (reference capital 26.6 M€ at 5 $\mathrm{t\,h^{-1}}$, continuous capacity); the *realistic* scenario replaces it with replicated Biodea modules (1.6 M€ and 401.5 $\mathrm{t\,yr^{-1}}$ each, an integer number per site, linear cost). Each scenario is solved at the three transport tariffs $\tau \in \{0.077, 0.3, 1.0\}$ € $\mathrm{t^{-1}\,km^{-1}}$.

One quantity is the same everywhere. Because all the biomass is processed, both scenarios produce 27,676 t of biochar per year, or 75.8 t per day — about ten times the reference threshold of 7.6 t per day set by the tyre-maker's enquiry (Chapter 1), a threshold we can read as the bare minimum needed to initiate the market's boom. The demand-side constraint is therefore never binding: the question the model answers is one of cost, not of quantity. In other words, the biomass needed to satisfy Pirelli's informal request is present, even under the conditions of the only existing active (micro)plants. The cost of the biochar is the problem.

The optimal layouts are shown in Figure 4.1. In the theoretical scenario, when transport costs are low, the optimum concentrates all twenty nodes into a *single* large plant (Figure 4.1a).

With strong economies of scale, it is cheaper to transport the biomass across the whole country and build one large facility.

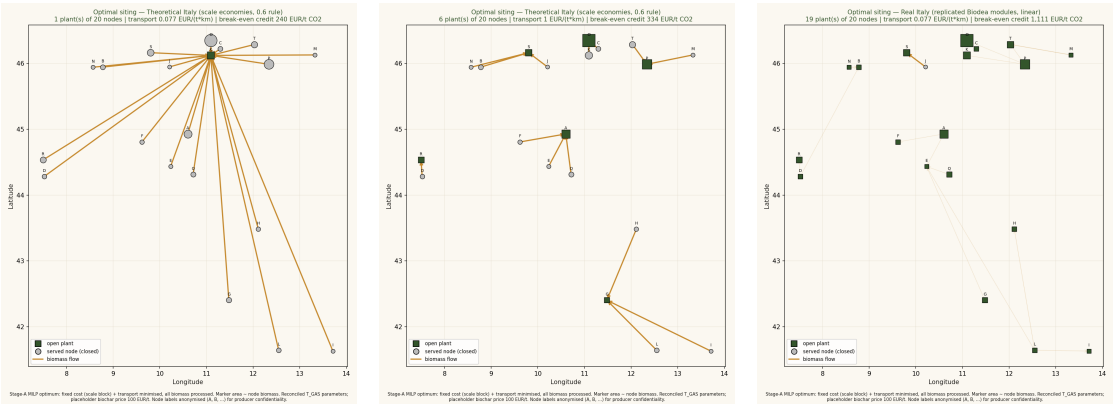
As transport costs increase, the optimum splits into four plants at $\tau = 0.3$ and six plants at $\tau = 1.0$ (Figure 4.1b).

The realistic scenario is very different: at every transport level, the optimum has nineteen plants, with essentially one Biodea module at each node (Figure 4.1c).

Without economies of scale, there is no benefit in moving biomass to larger plants. Transport is therefore only an additional cost, even when it is cheap, and the optimum keeps each producer's chips at the nearest plant.

A closer look at the realistic layout (Figure 4.1c) shows the optimiser doing something less obvious than "one module per node". It opens plants at 19 of the 20 nodes, not 20: the smallest node, Pizzo Camino (90 $\mathrm{t\,yr^{-1}}$), is left closed and its chips are shipped to a neighbour whose modules still have spare room, because paying a short haul is cheaper than switching on a whole new module for so little biomass. The same logic acts more finely inside the open sites: rather than round every node up to its own integer number of modules, seven sites hand the small overflow — the little that would trip one extra, nearly-empty module — to a nearby site with spare capacity. The fleet therefore settles at 346 modules — close to the packing minimum of 345 the total biomass would need — instead of the 355 a strict node-by-node build would require: nine modules, about 1.7 M€ per year, saved by transferring biomass rather than installing capacity. It is a small effect on the credit, but it is the clearest sign that the model is genuinely optimising, and not merely placing a plant on every node.

In the theoretical scenario, the break-even credit increases from 252 to 346 € per tonne of CO_2 as transport costs increase.



(a) Theoretical, $\tau = 0.077$: one plant **(b)** Theoretical, $\tau = 1.0$: six plants **(c)** Real, $\tau = 0.077$: nineteen plants

Figure 4.1: Optimal Stage-A layouts. Green squares are open plants, grey circles are closed nodes served by a plant, ochre lines are biomass flows, and marker area is proportional to node biomass. With economies of scale (a, b) the optimum concentrates when transport is cheap and disperses when it is expensive; without them (c) it disperses unless there happen to be micro-nodes. Node labels are illustrative at this size.

In the realistic scenario, the break-even credit is four to five times higher, at around 1,110 € per tonne. This value is almost constant across the transport range and is clearly too high to be accepted as realistic.

In the theoretical scenario, the fixed cost increases from 6.1 to 11.7 M€ as the plants become more dispersed and economies of scale are lost. Transport costs remain between about 1.8 and 2.7 M€.

In the realistic scenario again, the fixed cost is almost constant at 64 M€, corresponding to about 346 modules across nineteen open sites, with no economies of scale. Transport costs are negligible, at only a few tens of thousands of euros (compared to the cost of the system as a whole).

Therefore, the first question about the role of geography can, unfortunately, be answered:

the geography can be optimised, but its effect on the carbon credit is small (the sensitivity analysis will sharpen this claim).

The main difference between a credit of 252 and one of 1,110 is obviously the presence or absence of economies of scale, rather than the location of the plants.

The following subsections quantify this.

Table 4.7: Optimal Stage-A layout and break-even credit, by scenario and transport tariff. Production (27,676 t biochar per year) and, in Stage B, the material cost (15.5 M€ per year) and revenues (7.5 M€ per year) are identical in every row. In the realistic chain a *plant* is a single Biodea module, so the figure in the **Plants** column is the total number of modules; these are installed over 19 open sites (of the 20 nodes), the optimiser leaving one node closed and transferring its chips to a neighbour (discussed below Figure 4.1). In the theoretical chain each plant is instead one continuous-capacity facility.

Scenario	τ [€/(t km)]	**Plants**	**Fixed cost** [M€/yr]	**Transport** [M€/yr]	**Credit** [€/t CO_2]
Theoretical	0.077	1	6.06	1.76	252.2
Theoretical	0.3	4	9.18	2.74	310.9
Theoretical	1.0	6	11.66	2.71	345.8
Real	0.077	346	63.77	0.01	1105.2
Real	0.3	346	63.77	0.04	1105.6
Real	1.0	348	64.13	0.12	1112.7

4.2.1 What governs the break-even credit

The layout is only one of the ingredients of the credit, and Table 4.7 already hinted that it is not the decisive one. To see which parameter actually drives $p^\star$, Figure 4.2 varies each in turn between a low and a high value, holding the others at their base and re-solving the whole model (Stage A included) whenever a structural parameter changes. Each bar spans the resulting range of the break-even credit; the longer the bar, the more that parameter matters. The parameters are sorted by influence, most influential at the top.

The two panels tell the same story from opposite ends. In the theoretical scenario (Figure 4.2a) the credit is governed, above everything else, by the *biomass purchase cost*: moving it from 80 to 180 € per tonne swings the credit from 158 to 347 € per tonne of CO_2, a range of 189 that dwarfs every other bar. The biochar price comes second (208–296), and only then the parameters the supply-chain optimisation can actually influence — the transport tariff (a range of 59) and the reference capital cost (48) — followed by the electricity price and the interest rate. In the realistic scenario (Figure 4.2b) the ranking changes but the moral does not: now the *module capital cost* dominates (a range of 491 € per tonne), then the interest rate (241) and the biomass cost (182), while the transport tariff is dead last, moving the credit by barely 0.4 € per tonne of CO_2 across its whole range.

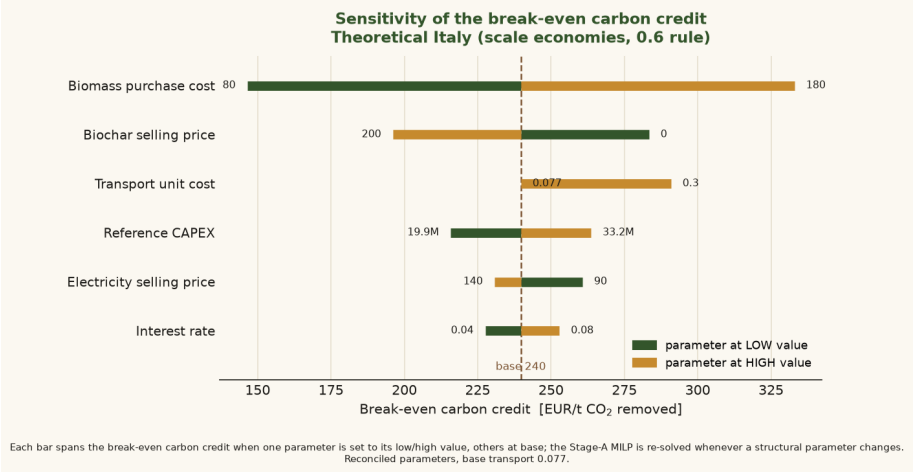
This provides a quantitative confirmation of the claim made in Section 4.1: transport cost is among the weakest parameters in both scenarios.

The credit itself is determined outside the optimisation, by the feedstock price in the theoretical chain and by the plant capital cost and cost of capital in the realistic one. This limited role of transport costs is also confirmed by a second, complementary test, in which the optimal layout is compared with layouts imposed by hand or generated at random.

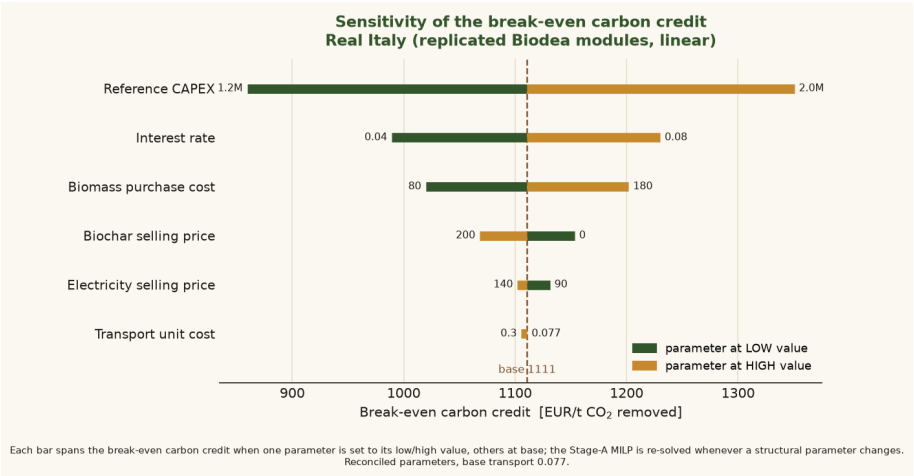
In the theoretical scenario, when transport is cheap, the optimum (252) essentially coincides with total centralization (253), since with one plant the two layouts are the same (the tiny gap is rounding). It performs better than total decentralization (376) and the random-layout average (401). When transport becomes more expensive, the optimum (346) moves further away from centralization (593), showing that transport costs have a larger effect on the optimal layout.

The realistic scenario shows a much smaller difference between layouts. The optimum (1,105) is only marginally lower than total centralization (1,171), total decentralization (1,130), and the random-layout average (1,276). Overall, the non-random layouts remain within a modest interval of about 1,105–1,510 € per tonne.

Solving the location problem, in other words, changes little; what moves the credit by a factor is the scale regime and the feedstock price, not the geography. This answers the thesis's question directly: optimising the logistics cannot, on its



(a) Theoretical Italy (economies of scale)

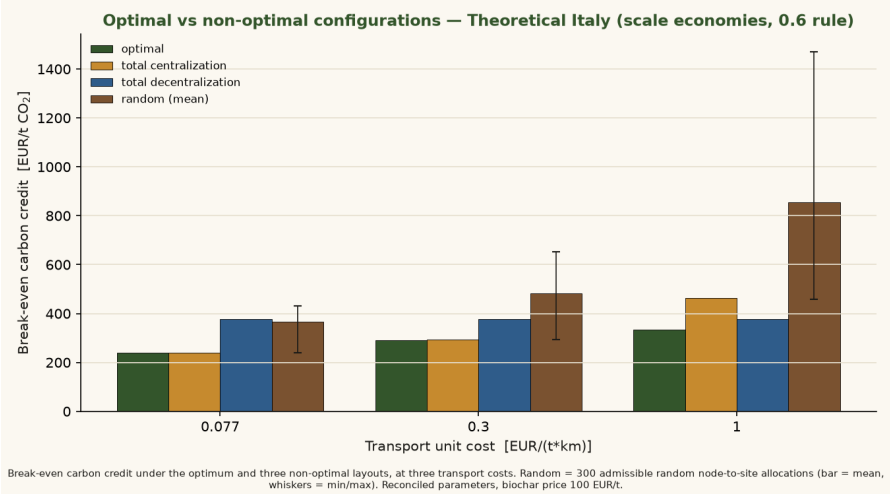


(b) Real Italy (replicated modules)

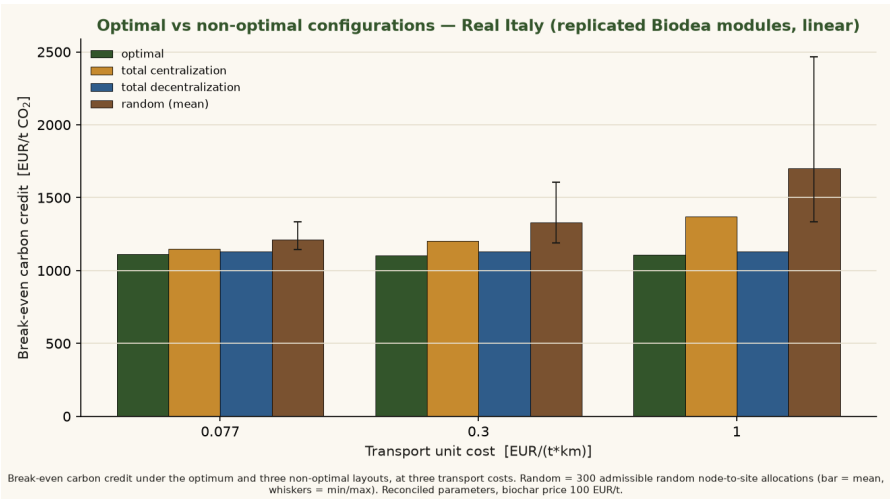
Figure 4.2: Sensitivity of the break-even credit (tornado). Each bar is the credit's range as one parameter moves from its low (green) to its high (ochre) value, the others at base; the dashed line is the base credit. Note the different horizontal scales of the two panels.

own, soften the high cost of the feedstock — the spatial optimisation is structurally weak.

Figure 4.3 collects this comparison across the three transport tariffs.



(a) Theoretical Italy (economies of scale, 0.6 rule)



(b) Real Italy (replicated Biodea modules, linear)

Figure 4.3: Break-even carbon credit under the optimum and three non-optimal layouts, at the three transport costs. *Random* is the mean over 300 admissible random node-to-site allocations (bars = mean, whiskers = min/max).

4.2.2 The merit-order curve

The merit-order curve reads the optimal layout one plant at a time. For each open plant its own break-even carbon credit is computed and then we sort the plants from the cheapest to the most expensive. On the horizontal axis the plants are stacked by cumulative capacity, on the vertical axis sits each plant's break-even credit, so every step is one plant: its width is how much biomass it processes, its height is the credit it would need. A horizontal line at any market credit price splits the plants into those already in profit and those still needing support.

In the theoretical scenario at expensive transport the curve has six steps, rising from about 235 to about 656 € per tonne of CO_2. The cheapest plant is the largest one, which enjoys the most economies of scale; the most expensive is a small, isolated plant that pays a high fixed cost on little biomass. So the curve does say something here: it shows which plants of the optimal aggregation would break even first as the credit price rises, and that even the best of them still needs a credit of a few hundred euros.

It is worth being honest about how much this curve can tell, because it is far less informative than the same curve in reference article. In Grimm's sludge chains the plants are genuinely heterogeneous — some run on paper sludge with a gate fee, others on sewage sludge — and their break-even credits spread from clearly negative (profitable with no credit) to strongly positive, so the merit order really orders very different plants. Here the picture is flatter, and for a structural reason: the feedstock is bought at an almost national price, and the electricity revenue is proportional to the biomass, so the plants differ only in size, not in kind. The whole spread of our curve comes from economies of scale alone, and every plant sits well above zero: relaxing those hypotheses in more complex models, by allowing a selection of the technologies, can restore its informative value. In the realistic scenario, where the plants are identical replicated modules, the curve would be essentially flat and would carry no information at all.

For this reason the curve is shown only for the theoretical scenario at expensive transport, where at least six plants of different size exist (Figure 4.4); it should be read as an illustration of the scale effect, not as a load-bearing result. The message of this chapter rests on the sensitivity analysis and the price sweep, which show that the credit is governed from outside the network — by the feedstock price — far more than by which plants are opened.

4.2.3 Competitiveness with carbon black

The remaining question is whether biochar can be made competitive at all — whether, by combining a plausible price with the carbon credit, the chain can break even in the range that a carbon-black substitute would command. Figure 4.5 sweeps the biochar price across the whole range from 0 to 3 € per kilogram —

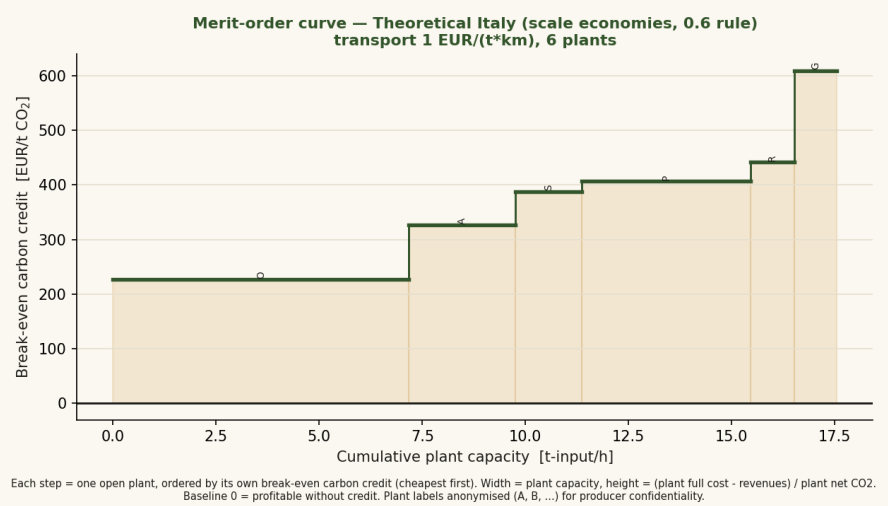
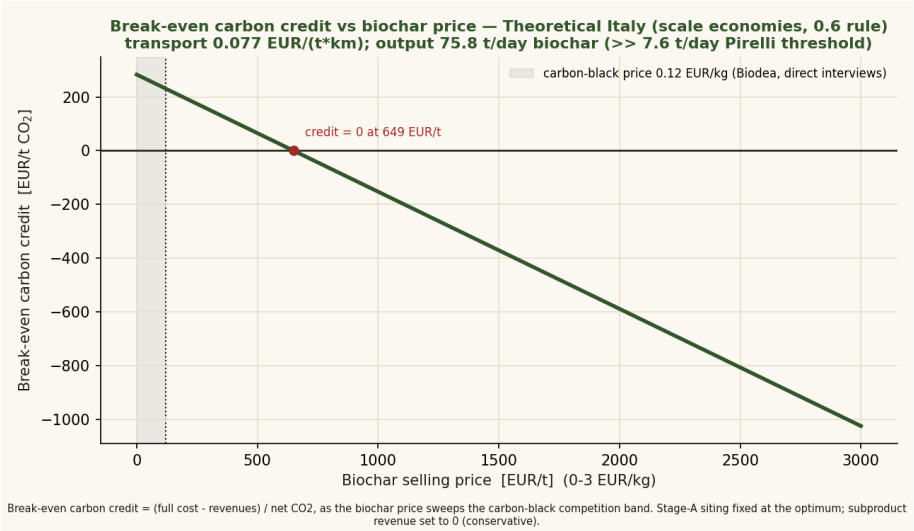
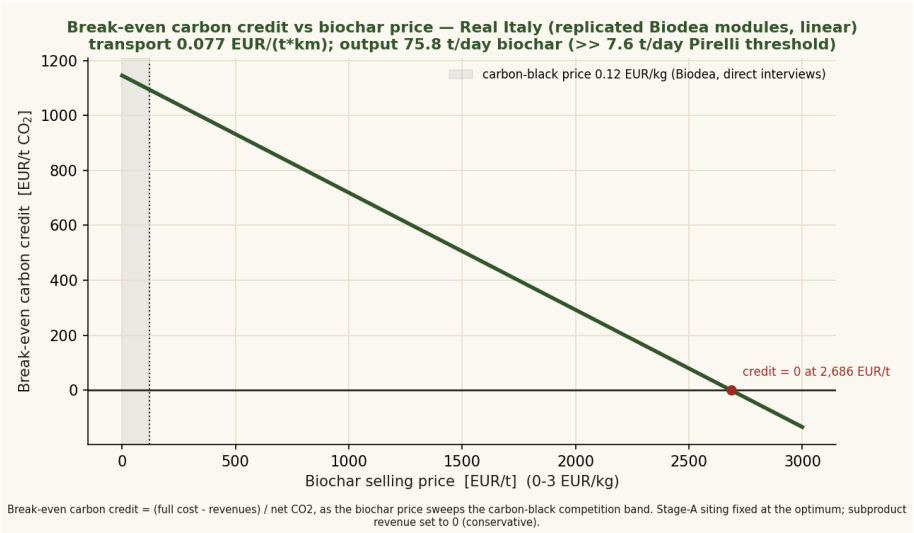


Figure 4.4: Per-plant merit-order curve for the theoretical scenario at $\tau = 1\,€/(\mathrm{t\,km})$ (six plants). Each step is one open plant, ordered by its own break-even carbon credit (cheapest first); the step width is the plant capacity and its height is (plant full cost − revenues) divided by the plant's net CO_2. The baseline 0 marks profitability without a credit.

spanning, and far exceeding, the carbon-black reference price — and reads off the break-even credit at each point, with the layout fixed at its optimum and the by-product revenue still at zero.



(a) Theoretical Italy (economies of scale)



(b) Real Italy (replicated modules)

Figure 4.5: Break-even carbon credit as the biochar price sweeps from 0 to 3 €/kg. The shaded band marks the carbon-black reference price, 0.12 €/kg (from Biodea's direct interviews). A negative credit means the chain is profitable with no credit at all. Note the different vertical scales. The near-linearity is a consequence of the model: it follows from the negligibility of the spatial optimisation relative to the feedstock and biochar parameters.

The two scenarios, unfortunately, do not diverge substantially. In the theoretical chain (Figure 4.5a) the credit falls through zero at 671 € per tonne, that is 0.67 € per kilogram: the zero crossing lies well above the carbon-black reference price of 0.12 € per kilogram, so at a carbon-black-competitive price even the theoretical chain still needs a credit of a few hundred euros per tonne. The economies of scale lower the credit but, at the price carbon black commands, do not remove it. In the realistic chain (Figure 4.5b) the same curve crosses zero only at about 2.69 € per kilogram, far above the band; within the carbon-black range the fragmented chain still needs a carbon credit of roughly 700 to 900 € per tonne of CO_2, or else a biochar price near 2.7 € per kilogram — imaginative, creative, totally unrealistic — to break even. Without exploiting the scale economy, competitiveness with carbon black cannot even be dreamt of.

The contrast answers the central question of the thesis. The hope was that whether wood-chip biochar can compete with carbon black would depend not on the biochar itself, but on whether the chain that makes it reaches scale. But even with scale — even breaking today's fragmented Italian *filière* through some optimised centralization — it needs either a large carbon credit or a price well above what carbon black commands.

At least the work on the data puts the very first question in its place: the biomass is physically sufficient, even counting only the real, actually processed wood chips of the actual answers — production is ten times the required threshold — but sufficiency of quantity is not competitiveness, and competitiveness did not turn out to be a question of scale economics so much as of low-price feedstock availability.

4.2.4 Further scenarios: the scale ceiling

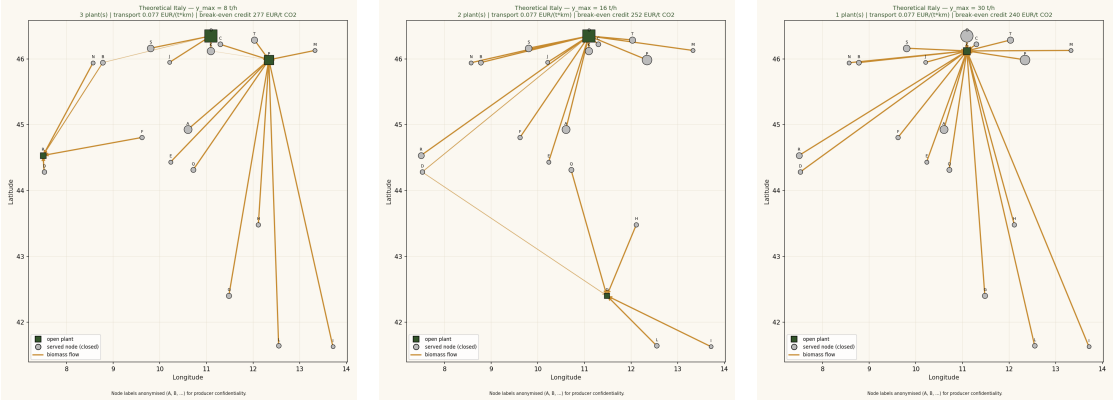
The scenarios above fix the admissible plant-size window at its base value. A last set of runs varies the upper bound $y_{\max}$ of that window — the largest plant the theoretical chain is allowed to build — from 8 to 30 $\mathrm{t\,h^{-1}}$, holding everything else at base, to check that the model responds to the scale ceiling as the economics predict. Table 4.8 reports the outcome at the base transport tariff.

The pattern is exactly the one the scale story predicts. As the ceiling is raised, the optimiser is allowed to concentrate the biomass into fewer and larger plants: the number of plants falls from three to one, the annualised fixed cost drops from 9.0 to 6.1 M€ per year, and the break-even credit falls monotonically from 285 to 252 € per tonne of CO_2. Beyond $y_{\max} = 20$ $\mathrm{t\,h^{-1}}$ the whole biomass already fits into a single plant, so raising the ceiling further changes nothing. Again, the effect is bounded by transport: at the costly tariff $\tau = 1.0$ the optimum opens six plants and the credit settles at 346 € per tonne *regardless* of $y_{\max}$, because the haulage cost of concentrating the whole region's biomass into one site outweighs

Table 4.8: Effect of the plant-size ceiling $y_{\max}$ on the theoretical chain, at the base transport tariff $\tau = 0.077$ €$\,t^{-1}\,km^{-1}$. The variables held fixed are the same in every row: biochar production (27,676 t per year), the biochar selling price (100 €$\,t^{-1}$), the material (feedstock) cost (15.5 M€ per year, at a near-uniform producer price) and the revenues (7.5 M€ per year). The layouts of the $y_{\max} = 8,16,30$ cases are shown in Figure 4.6; the complete set of layouts for all the additional scenarios is collected in Appendix A.1.

$y_{\max}$ [$t\,h^{-1}$]	**Plants**	**Fixed cost** [M€/yr]	**Credit** [€/t CO_2]
8	3	8.97	284.9
12	2	7.86	268.4
16	2	7.14	262.4
20	1	6.06	252.2
30	1	6.06	252.2

the scale saving. Two things follow. The model behaves correctly — more available scale lowers the credit exactly where transport lets the chain concentrate, and the transport cost caps that benefit — and the size of the effect is again modest: across the whole range of $y_{\max}$ the credit moves by less than 35 € per tonne, an order of magnitude below the swing driven by the feedstock price.



(a) $y_{\max} = 8$: three plants **(b)** $y_{\max} = 16$: two plants **(c)** $y_{\max} = 30$ (base): one plant

Figure 4.6: Optimal layouts of the theoretical chain as the plant-size ceiling $y_{\max}$ is raised, at base transport $\tau = 0.077$ € t^{-1} km^{-1}. As the ceiling relaxes the optimum concentrates the biomass into fewer, larger plants: three at $y_{\max} = 8$, two at 16, one at 30.

4.2.5 Further scenarios: the transport tariff

Symmetrically to the scale ceiling, it is worth isolating the effect of the transport tariff on the theoretical chain, with everything else at base. Table 4.9 reports it; the layout of the first case ($\tau = 0.077$, a single plant) coincides with Figure 4.1a and that of $\tau = 1.0$ (six plants) with Figure 4.1b, while the $\tau = 0.3$ layout (four plants) and the full set are collected in Appendix A.1.

Table 4.9: Effect of the transport tariff τ on the theoretical chain, everything else at base: biochar production (27,676 t per year), biochar price (100 €$\,t^{-1}$), material cost (15.5 M€ per year) and revenues (7.5 M€ per year) are unchanged in every row. The first-case layout ($\tau = 0.077$) is Figure 4.1a.

$\boldsymbol{\tau}$ [€/(t km)]	**Plants**	**Fixed cost** [M€/yr]	**Transport** [M€/yr]	**Credit** [€/t CO_2]
0.077	1	6.06	1.76	252.2
0.3	4	9.18	2.74	310.9
1.0	6	11.66	2.71	345.8

To sum up, the Italian wood-chip supply can physically feed a chain producing ten times the reference demand, but a statement on quantity alone says nothing. Optimising the geography barely moves the break-even credit: transport is among the weakest parameters, and the credit is set from the "downstream" parameters rather than the "upstream" parameters of the network. The fragmented real chain needs a credit of several hundred euros per tonne of CO_2, or a far higher biochar price. Competitiveness turns out to be, thus, partly a matter of (exploiting) scale, not of logistic optimisation.

Outlook: next scenarios

Two directions would make the model more realistic, each by relaxing an assumption made here for tractability.

The first concerns the *geography*. The model can be extended as soon as data on more nodes become available: the two simplifications made on transport and on the biomass price — a single flat tariff and a single producer price — can be dropped, making both node- and road-specific, so as to push the realism of the spatial optimisation further. A second geographical extension is the addition of candidate sites *between* the biomass nodes, points that serve only as plant locations and not as sources: a new and possibly more favourable configuration, better able to absorb the transport cost, can emerge from this larger set of sites.

The second concerns the *technology*. The model can be extended by optimising over the conversion technology as well. One could posit plants subject to scale laws in which, at equal capacity, more biochar is produced and less energy is sold, possibly together with a higher biochar yield; the electricity revenue would enter, so that it no longer escapes the optimisation, as a genuine lever of competitiveness. This points towards the suggestion, made by the supervising professor Chiaramonti at the Politecnico, of moving to a pyrolysis–pyrolysis technology rather than pyrolysis plus gasification [52].

Table 4.10 orders these proposals, and for each names the hypothesis of the present model that would be relaxed and the equation or parameter it touches.

Table 4.10: Proposed extensions of the model, the hypothesis each one relaxes, and the equation or parameter of the present formulation it acts on.

Proposed extension	**Relaxation applied**	**Equation / parameter involved**
Node- and road-specific transport	now the tariff and the distance are specific to each node and road	τ constant, Eq. (4.13); d_{ij} great-circle, Eq. (4.14)
Node-specific biomass price	now each producer node carries its own biomass price	π_i in Eq. (4.11)–(4.12)
Plant-only candidate sites between nodes	now sites may also lie between producers, $\mathcal{J} \supsetneq \mathcal{I}$	index set $\mathcal{J}$ (Table 4.1)
Scale-dependent energy and yield	now yields and electricity depend on the plant scale	ρ_{bc}, ρ_{en}; E in Eq. (4.17)
Technology as a decision (pyrolysis–pyrolysis)	now the conversion technology is chosen by the model	fixed-cost block, Eqs. (4.3)–(4.10)
Process- and end-use LCA	now conversion and end-use emissions are counted	e_{pr}, e_{cap}, e_{use} in Eq. (4.19)
Energy counterfactual on the feedstock	now the feedstock energy counterfactual is subtracted	$\mathrm{CO}_2^{\mathrm{net}}$, Eq. (4.20)

Chapter 5

Conclusions and Future Development

This research has reported the state of the Italian supply chain as a whole: the emerging picture is one of small, sparse producer nodes associated with even more sparse and rare plant nodes. Scientific works focus on European, rather than Italian, scenarios, industrial residues as feedstock, or financial analysis of saleable products in the biomass valorisation industry with a long time series of historical data on prices and production. Data about biochar plants and the biomass they use are rare, often incoherent, and associated with theoretical estimations linked to few main sources.

After a careful analysis of all the main data sources and the understanding of their limits, the proposed solution was to carry out interviews of actual Italian biomass (wood-chip) and biochar producers whose existence is recorded in official and public registries (AIEL [24], CREA [22]). The majority of them are difficult to reach (20% of the wood-chip producers answered, only five biochar producers answered a few questions, and only one extensively). The responding wood-chip nodes alone declare a total capacity of approximately 219,000 t/yr as received (wet), i.e. about 138,400 t/yr of dry biomass — a lower bound, since only about one in four producers answered, so the real national figure is considerably larger. Under the enthusiast hypothesis, even that minimum yields a biochar production of 27,676 t/yr (75.8 t/day), against a preliminary interest expressed by a single Pirelli plant of 7.6 t/day (about 2,770 t/yr) — an exploratory enquiry on the feasibility of supply, not an industrial-scale demand calculation [23]. The available biomass is abundant and sufficient to, theoretically, satisfy even more than that modest initial request; the actual capacity and the price of biochar do not allow that theory to find realisation in practice.

The classical solution is to monetise the subtracted carbon dioxide with a financial

asset called carbon credit, whose market, functioning, and concrete exploitability have been covered in detail: there are records of revenues obtained from selling biochar credits in the industrial context (Chapter 3, the Novocarbo case on the Puro.earth registry [57]), but no such transaction has been successfully realised in Italy yet.

The quest for biochar competitiveness has led to the core questions of this thesis: what would the break-even carbon credit be for a spatially optimised, data-based Italian supply chain? Can it guarantee a competitive biochar price? To explore these questions, a simple model has been developed in a two-step process; in the first step a cost function has been defined with scale- and geography-dependent parameters; the engine of the optimisation lay in the tension between exploitation of the advantages of scaling-up economies and the cost of transportation associated with carrying the biomass towards centralised nodes. In the second step an LCA computation on the biochar produced by the optimised chain computed the break-even credit.

The sensitivity analysis reveals that the transportation cost is the least important parameter in determining the final credit cost: the optimisation turned out weak with respect to the feedstock parameters. Multiple scenarios have been investigated, leading to a credit of 252 to 1,110 EUR per tonne of CO_2 to make the chain sustainable, with biochar prices in the carbon-black-competitive range (around 0.12 EUR/kg). Further improvements to the model have been proposed by relaxing some of the choices made.

Many unrealistic and conservative assumptions have been stated in order to explore the model results, most importantly: all the biomass of a node has been supposed to be destined to biochar production, and all the biochar produced has been supposed to be sold. This does not reflect the contemporary Italian reality: wood-chip biomass is mostly dedicated to heating (private or industrial), Italian biochar producers do not have their main business in selling biochar but energy, biochar is only one of the valorised by-products of pyrogasification, and a significant portion of the actually produced biochar is now stocked: Biodea alone reports 57 m^3 of unsold biochar in storage [23] — with a single module processing roughly 401.5 t/yr of biomass at a biochar yield of about 20%, that stockpile represents one to two and a half months of production, a significant fraction of the yearly output sitting idle without generating revenue.

As a final consideration: Italy has at its disposal sufficient residual and waste biomass to run a supply chain satisfying the industrial requests whose interest already exists, although not sparked yet; this is possible even without exploiting biomass that does not derive from waste, and this settles the concerns of the cautious position introduced at the beginning of this work. However, the journey to unlock this market potential is more a mixture of unclear and expensive bureaucracy, lack of knowledge in the sector, and absence of trust in the carbon-credit market's

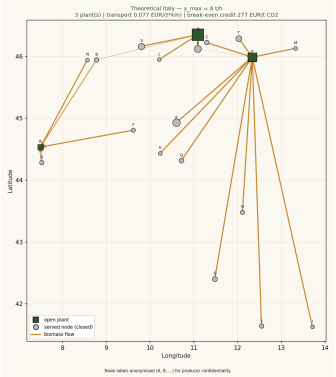
exploitability, rather than a merely "lack of installed capacity". If I were to suggest a direction for possible innovation, it would be in the latter: the realisation of a small, well-documented, and complete biochar carbon-credit selling project "from cradle to grave", like the LCA analysis it requires, that could spark trust and interest in the main players of this supply chain.

Appendix A

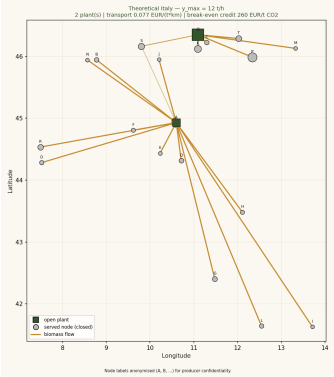
Supplementary results

A.1 Additional graphs

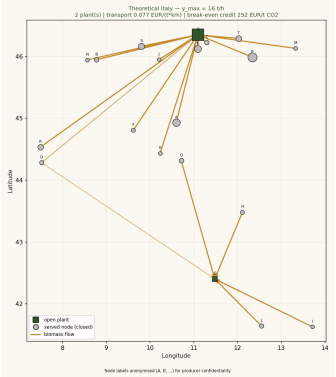
This appendix collects the optimal Stage-A layouts of the additional scenarios of Chapter 4 — the plant-size-ceiling sweep of Section 4.2.4 and the transport-tariff sweep of Section 4.2.5, whose headline figures are in Tables 4.8 and 4.9. All maps are for the theoretical chain; open plants are green squares, closed nodes served by a plant are grey circles, and the ochre lines are biomass flows.



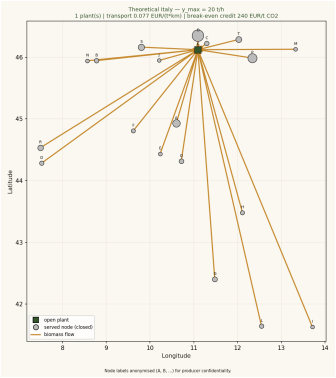
(a) $y_{\max} = 8$: three plants



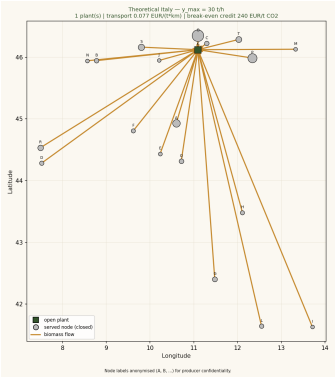
(b) $y_{\max} = 12$: two plants



(c) $y_{\max} = 16$: two plants

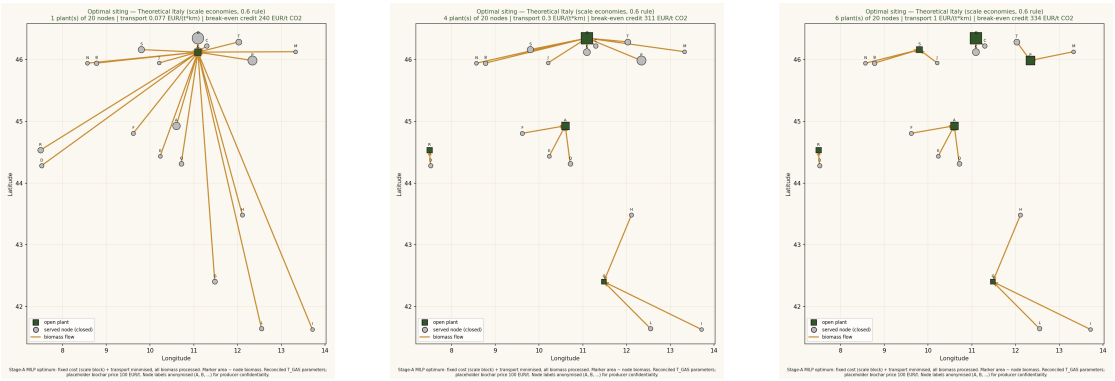


(d) $y_{\max} = 20$: one plant



(e) $y_{\max} = 30$: one plant

Figure A.1: Optimal layouts of the theoretical chain over the plant-size-ceiling sweep, at base transport $\tau = 0.077$ €$\,\mathrm{t}^{-1}\,\mathrm{km}^{-1}$ (Table 4.8). As the ceiling $y_{\max}$ is raised, the optimum concentrates the biomass into fewer, larger plants.



(a) $\tau = 0.077$: one plant **(b)** $\tau = 0.3$: four plants **(c)** $\tau = 1.0$: six plants

Figure A.2: Optimal layouts of the theoretical chain over the transport-tariff sweep, at the base plant-size ceiling (Table 4.9). As transport becomes dearer, the optimum splits into more, smaller plants.

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