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# Strategic Directions for Cooperation Between Oil and Gas Companies of the Russian Federation and the People's Republic of China in the Context of Decarbonization and Sustainable Development

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**Abstract:** Climate regulation is intensifying worldwide, and the resulting energy transition is reshaping the strategic environment for the oil and gas sector. Russia and China are no exception: their bilateral energy relationship has rested for decades on fossil fuel trade, and decarbonization now presents both a structural challenge to that model and an opening for technological and industrial collaboration. This article maps the strategic directions available to Russian and Chinese oil and gas companies as they navigate low-carbon transformation and sustainable development agendas. Methodologically, the study pairs a qualitative reading of Russian and Chinese regulatory frameworks with a review of technological pathways for cutting greenhouse gas emissions in the oil and gas sector—methane management and associated petroleum gas utilization chief among them, alongside emerging routes such as non-equilibrium plasma processing and low-carbon hydrogen. Carbon regulation instruments receive particular attention for their growing role in shaping cross-border energy projects and investment decisions. What emerges is a sector in transition: Sino-Russian cooperation is edging away from a purely resource-based model toward one that also incorporates decarbonization technology, infrastructure, and regulatory alignment. Whether that shift succeeds will hinge on how well companies on both sides can work across differing regulatory regimes, fold low-carbon technologies into existing value chains, and structure joint projects that clear both an economic and an environmental bar. The paper's findings speak to the broader question of where bilateral energy cooperation is headed under global decarbonization pressure, with implications for long-term strategic planning.

**Keywords:** decarbonization, oil and gas sector, Russian–Chinese cooperation, emissions

## 1. Introduction

Low-carbon energy development and the push to commercialize decarbonization technologies now rank among the forces reshaping the global fuel and energy complex, with the oil and gas sector particularly exposed. For companies in the sector, managing this shift well has become a precondition for staying competitive and for meeting the targets laid out in their own sustainable development strategies. How decarbonization plays out, however, differs sharply from one country to the next—national economies, regulatory frameworks, and technological priorities each shape what works locally. None of that changes the fact that a purely domestic response is not enough: over the long run, these issues demand international cooperation, which opens the door to technological partnerships, cross-border investment, and the integration of national systems for accounting and trading carbon units (CUs).

Within this broader landscape of energy cooperation, few relationships hold as much promise as the one between China and Russia. Both countries have built out extensive regulatory frameworks and active energy-sector strategies with clearly defined objectives, and both bring substantial technological capacity to the table—a combination that gives their dialogue on low-carbon development and sustainability real staying power.

Russia's own commitment to the international climate agenda dates back to its signing of the United Nations Framework Convention on Climate Change (UNFCCC), followed by ratification of the Kyoto Protocol in 2004 and adoption of the Paris Agreement in 2016—a sequence that reflects sustained, not

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token, engagement with the global climate effort. That commitment has since been written into domestic policy as well: through the Climate Doctrine of the Russian Federation, approved by presidential decree in 2023, and the Energy Strategy of the Russian Federation for the period until 2050, approved by government order in 2025.

One result stands out on the carbon regulation side: the Sakhalin Climate Experiment, a pilot project launched in 2022 to bring the Sakhalin Region to carbon neutrality by 2025. It got there early—by 2025, greenhouse gas (GHG) absorption in the region had already overtaken emissions.

Trade in conventional hydrocarbons—oil and gas above all—remains a separate pillar of the relationship and one that bridges the traditional and emerging sides of the partnership. Structural shifts underway in global oil and gas markets have, if anything, given this pillar renewed relevance, a point taken up in later sections of the paper. Natural gas carries particular weight here: the International Energy Agency (IEA) projects meaningful growth in its consumption, and it is widely treated as a transitional energy carrier over the short and medium term [1] as well as a feedstock for blue hydrogen production.

China's own decarbonization push is on a scale without much precedent: a complex system of legal regulation, strategic planning, and market mechanisms now underpins its pursuit of an ambitious climate agenda, anchored by the national "30/60" targets—$CO_2$ emissions to peak by 2030 and carbon neutrality by 2060. Those two numbers effectively set the trajectory for everything that follows in Chinese energy and climate policy, which is moving quickly from a patchwork of plans and government programs toward comprehensive legislation.

China's national Emissions Trading System (ETS), launched in 2021, sits at the center of that market-based push. Around it, low-carbon regulation is arranged as a multilevel structure of strategic planning and binding rules, all aligned with the 2030/2060 targets, with the Action Plan for Carbon Dioxide Peaking Before 2030 (2021) serving as the core state policy document. The literature calls this the "1 + *N*" architecture: one overarching policy paired with sector-specific plans and regulatory acts that track the five-year planning cycle.

That system's legal and operational backbone consists of administrative measures issued by the Ministry of Ecology and Environment (MEE), covering how the ETS functions, how regulatory authority is allocated, what participation requires of companies, and what monitoring, reporting, and verification (MRV) obligations apply. Because MRV and enforcement are built in rather than bolted on, the ETS functions as more than a trading platform—it doubles as infrastructure for managing emissions data at the enterprise and sector level, which in turn raises the stakes on verified emissions data throughout supply chains and corporate climate reporting.

What sets the Chinese approach apart is how tightly the ETS is woven into a broader set of administrative and programmatic tools—energy and carbon intensity targets, efficiency standards, sector-specific modernization roadmaps. Companies feel this not just through the carbon price but through data-quality requirements (MRV), technological specifications on production processes, and efficiency mandates, and the effect is sharpest in energy-intensive sectors that trade internationally and could face cross-border carbon regulation.

Methane regulation is developing fast as its own track, treated in China as a priority short-lived climate pollutant. The national Methane Emission Control Action Plan, published in 2023, formalizes an inter-agency approach spanning the energy sector (coal and oil and gas alike), agriculture, and waste management, and it puts real weight on monitoring and MRV—reporting platforms, sector-specific accounting guidelines. That is what turns methane targets from declarations into something measurable, and climate projects and investments into something verifiable.

Hydrogen policy follows a similar logic. The hydrogen industry development plan covering 2021–2035 frames hydrogen as part of both energy-system transformation and industrial decarbonization, with infrastructure, demonstration projects, and market formation as the near-term priorities. For Sino-Russian cooperation specifically, this matters because China's hydrogen agenda sits inside its wider industrial and climate policy—meaning joint projects, turquoise hydrogen and its derivatives included, will be judged not just on economics but on whether they meet MRV, carbon-footprint, and standards requirements.

Taken together, Russia–China cooperation already spans joint projects, international agreements, and hydrocarbon trade, with plenty of room left for it to go deeper. Making sense of where that relationship stands and where it might head—in oil and gas specifically—calls for a brief look at the historical roots of each country's foreign policy.

Kissinger [2] argues that China's diplomatic strategy only really makes sense read against the country's own traditions, cultural heritage, and historical position—not through a generic international-relations lens.

He frames this in terms of "intellectual games": a strategic culture built around positioning and relative advantage, oriented toward political and psychological dominance rather than open confrontation. That combination—real openness to outside cooperation, paired with a pragmatism traceable to Sun Tzu and Confucian thought that has been folded into state ideology—helps explain why China, driven also by its own need for hydrocarbons, counts among Russia's most significant strategic partners.

Russia, for its part, has never belonged wholly to either Western or Eastern traditions, and at this stage of its development that in-between position makes deepening ties with friendly states—states whose vision of world order lines up with its own—a priority, as set out in the country's current Foreign Policy Concept.

Put together, these dynamics make energy cooperation between China and Russia under the twin agendas of low-carbon development and sustainability look both promising and mutually beneficial—and one that serves each country's own economic and technological interests in the process.

This study's contribution is to bring three analytical strands together that prior work has generally kept apart: institutional-regulatory analysis, quantitative assessment of energy and emission structures, and strategic synthesis, all applied to one specific bilateral partnership under global decarbonization pressure. Rather than treating regulation, carbon markets, emission-reduction technology, and trade-theoretic rationale as separate questions, the analysis here holds them together and works them through to a set of phased, operationally grounded strategic directions—which is where its theoretical and practical value lies.

## 2. Literature Review

The role of anthropogenic emissions in climate change, and the energy-sector transformations it demands, has been studied extensively [3]. Work on China's economic and energy systems specifically shows a positive long-term relationship between GDP per capita, fossil fuel consumption, and $CO_2$ emissions [4, 5]. On the Russian side, Fadeev [6] has made a significant contribution to the import-substitution literature, examining how technological and economic sanctions have affected the Russian oil and gas sector and proposing tools to address some of the resulting challenges. Recent research [7, 8] points to substantial export potential in the Chinese energy economy—a body of research that, taken together, supports the case for a differentiated approach to cooperation and multifaceted trade flows between the two countries.

A related strand of work treats technological sovereignty as a precondition for the resilience of the Russian oil and gas sector, Arctic operations included [9]; its organizational and economic dimensions are worked through in dedicated monographs [10], while other studies weigh the prospects and constraints facing low-carbon development under the geopolitical conditions of the past several years [11, 12].

On renewables, the Russian-context literature covers wind and solar development, the role of state support, and the competitiveness gap relative to conventional sources [13, 14]. Why a resource-rich economy might choose to import rather than build such technologies domestically is a question classical trade theory speaks to directly—comparative advantage [15] and the factor-endowment framework [16–18]—and that theoretical base underpins how technology-transfer strategies between partner states get assessed [7].

At the technology level, the engineering literature has its own pathways for emission reduction in oil and gas. Plasma-based conversion of methane into hydrogen and solid carbon looks promising as a low-emission route [19, 20], building on a substantial body of work on plasma-catalytic methane conversion and dielectric-barrier-discharge reactors [21, 22]; hydrogen production from natural gas with carbon capture has likewise been reviewed as a transitional option [1]. What this literature does less well is connect the technical feasibility of individual processes to the cross-border industrial and regulatory setting they would actually operate in.

Kissinger [2] supplies the strategic and diplomatic reading of China's external conduct through its historical and cultural traditions. What none of this literature does, across its various strands, is bring the regulatory and carbon-market environment, the emission-reduction technology options, and the strategic rationale for cooperation into one analytical frame—which is precisely the gap this study tries to close, by pairing a qualitative reading of the regulatory environment with a quantitative assessment of trade and emission structures and turning the result into a set of phased strategic directions for decarbonization-oriented cooperation.

## 3. Methodology

This study sets out to identify and analyze the strategic directions available for cooperation between Russian and Chinese energy companies against the backdrop of the global energy transition, using a multilevel approach that pairs qualitative analysis of the institutional and regulatory environment with quantitative assessment of economic and environmental interaction. The quantitative side tracks two interrelated dimensions—economic interdependence and environmental impact—through comparative time-series analysis and data visualization. Trade flows in hydrocarbon resources are analyzed using the Statistical Review of World Energy 2025 [23] as the primary data source: an annual review that offers standardized, comparable data on energy production, consumption, and international trade, and from which the key trends in the Sino-Russian energy partnership—and its place in China's energy balance—can be drawn.

The environmental side draws on the Emissions Database for Global Atmospheric Research (EDGAR) [24], which makes it possible to examine the dynamics of energy cooperation alongside changes in the structure of anthropogenic emissions.

The principal input data of the study, together with their sources, coverage, and analytical use, are summarized in Table 1.

The analysis proceeds in three stages. It starts with a qualitative review of both countries' regulatory frameworks, climate commitments, and strategic documents, aimed at identifying the institutional conditions and policy drivers behind bilateral cooperation in low-carbon energy. It then turns quantitative, applying comparative time-series and structural (share) methods to energy production and consumption, hydrocarbon trade, and GHG emissions data over 2014–2024 to characterize the degree and nature of resource interdependence and each country's

**Table 1**
**Principal input data of the study and their sources**

| Parameter | Specification |
|---|---|
| Object of analysis | Strategic cooperation between Russian and Chinese oil and gas companies under decarbonization and sustainable development |
| Time coverage | 2014–2024 (key indicators reported as of 2024) |
| Geographic coverage | Russian Federation and the People's Republic of China; world totals used as a reference |
| Energy and trade data | Statistical Review of World Energy 2025 (Energy Institute) |
| Energy and trade variables | Primary energy consumption by source; production, exports and imports of crude oil and petroleum products; natural gas production, exports and imports (pipeline and LNG) |
| Emissions data | Emissions Database for Global Atmospheric Research (EDGAR); greenhouse gas emissions of all world countries (2025) |
| Emissions variables | $CO_2$ (fossil), $CH_4$, $N_2O$ and fluorinated gases by sector; sectoral shares; gas flaring |
| Emission aggregation | Global warming potential over a 100-year horizon (GWP-100) |
| Bilateral trade data | Value of goods imported by Russia from China by commodity group |
| Quantitative methods | Comparative time-series analysis, structural (share) analysis and data visualization |
| Qualitative methods | Analysis of the regulatory frameworks and strategic-planning documents of both countries |

contribution to global emissions. The final stage synthesizes both strands into a phased set of strategic directions and cooperation principles for decarbonization and sustainable development, grounded in the theoretical framework of comparative advantage and factor endowments.

## 4. Results

Hydrocarbons remain fundamental to both the global energy balance and the energy systems of China and Russia. As of 2024, oil, natural gas, and coal together account for 86.58% of total primary energy consumption worldwide, with nuclear, hydropower, and renewables making up the remaining 13.42%, as shown in Table 2.

**Table 2**
**Structure of global primary energy consumption by energy source (2024)**

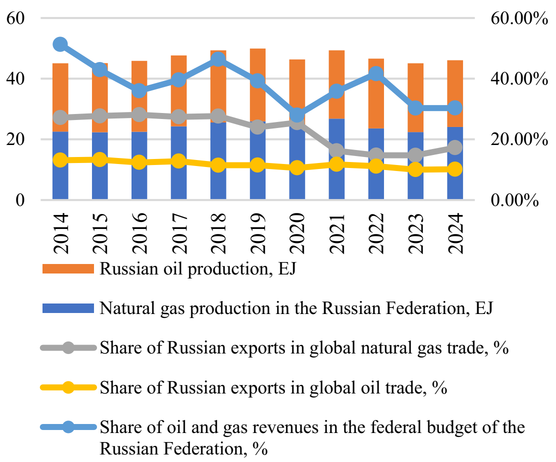
| Resource | Russia | China | Total world |
|---|---|---|---|
| Oil | 7.66 | 32.27 | 199.05 |
| Natural Gas | 17.17 | 15.64 | 148.6 |
| Coal | 3.75 | 92.16 | 165.06 |
| Nuclear energy | 2.35 | 4.92 | 30.74 |
| Hydro electric | 0.76 | 4.88 | 16.03 |
| Renewables | 0.07 | 9.02 | 32.74 |
| Total | 31.77 | 158.88 | 592.22 |

Hydrocarbons account for 88.16% of China's total energy consumption and 89.99% of Russia's.

Where the two countries differ is in where those hydrocarbons come from. Russia meets domestic demand largely from its own production and runs a pronounced export-oriented model: 65.5% of crude oil production and 24.21% of natural gas production are exported, and hydrocarbon export revenues account for 30.32% of total federal budget revenues of the Russian Federation, as illustrated in Figure 1.

China sits at the other end of that spectrum, meeting most of its energy demand through imports—domestic production falls

**Figure 1**
**Share of hydrocarbon exports in the Russian Federation**



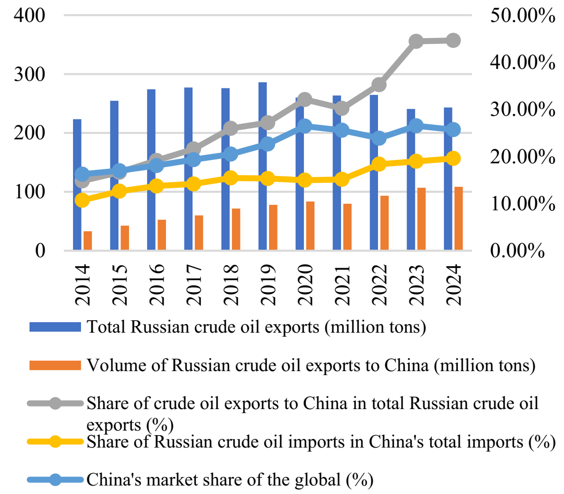

well short of total consumption, which drives large-scale natural gas imports in particular.

Domestic production covered 57.2% of China's natural gas consumption in 2024, down 17.89% from 2014—a clear downward trend that reflects consumption outpacing production and, with it, a growing need for foreign suppliers.

The picture is similar for oil: domestic production covered just 28.2% of Chinese consumption in 2024, a 30.94% decline over the decade that confirms the growing reliance on imported crude.

China trades petroleum products in both directions (Figure 2). Imports reached 110.48 million tons in 2024, down 3.43% from 2023 but still 94.16% above the 2014 level.

**Figure 2**
**Russian crude oil exports and their role in China's oil imports (2014–2024)**



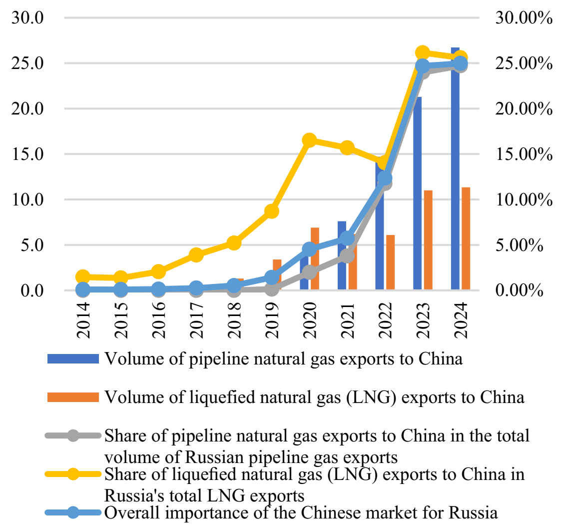

China has become one of the key destination markets for Russian crude oil. Russia supplied 108.47 million tons of crude oil to China in 2024—44.62% of its total crude oil exports and 19.58% of China's total crude import volume—up 227.71% from 2014. Petroleum product exports have followed a similar trajectory: 16.67% of Russia's total petroleum product exports went to China in 2024, amounting to 17.39 million tons.

Natural gas exports to China (Figure 3) totaled 38.1 billion cubic meters (bcm) in 2024, of which 26.7 bcm moved by pipeline and 11.4 bcm as LNG—24.72% and 25.6% of Russia's total exports by each route, respectively. For China, these volumes correspond to 10.79% of total LNG imports and 37.52% of natural gas imports delivered via trunk (mainline) pipelines.

Russia is actively reorienting crude oil, petroleum product, and natural gas exports away from Europe and toward Asia, China in particular—a strategic priority under Russia's current Energy Strategy to 2050 that the data above bears out. Sustaining these supplies gives the relationship a stable foundation from which both countries can pursue their complementary strategic objectives.

China's oil and gas sector functions, in short, as a strategic asset of the Chinese state—supporting a wide range of economic activity while generating tax revenue and employment along the way. It accounts for 19.3% of global oil imports and 19.94% of global natural gas imports, backed by well-developed infrastructure with broad geographic coverage for procurement, delivery, domestic transport, and storage.

**Figure 3**
**Russian natural gas exports to China and the growing importance of the Chinese market (2014–2024)**



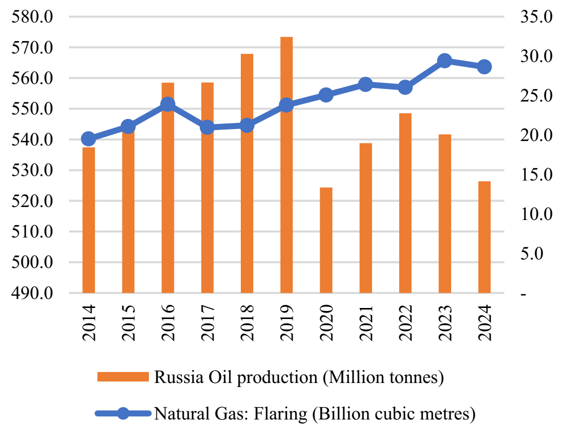

Traditional hydrocarbons are also, of course, among the largest sources of GHG emissions—which sits uneasily with long-term carbon-neutrality ambitions and makes even holding fossil fuel consumption at current levels, let alone growing it, hard to square with those goals.

In China, the power industry accounts for 50.12% of national $CO_2$ emissions and fuel exploitation for 6.31%—the two segments most relevant here. Fuel exploitation also drives a disproportionate share of methane emissions, generating 30.55% of total non-$CO_2$ GHG emissions on a carbon dioxide equivalent basis (Mt $CO_2$eq/yr).

Russia shows a similar pattern, with the power industry contributing 42.42% of national emissions and fuel exploitation 10.87%; fuel exploitation there accounts for an even larger share of methane emissions—46.44% of non-$CO_2$ GHG emissions in $CO_2$ equivalent terms.

A particularly pressing issue is the rational utilization of associated petroleum gas (APG)—one where Russia stands out, as shown in Figure 4: reports put flaring at 28.6 bcm, up 46.73% between 2014 and 2024 even as crude oil production fell 2.05% over the same period; as of 2024, that amounts to 57.8 Mt $CO_2$eq/yr, or 18.04% of global $CO_2$ emissions from gas flaring.

**Figure 4**
**Crude oil production and associated gas flaring in the Russian Federation (2014–2024)**




Globally, the energy sector's emissions break down into fuel exploitation (11.34% of global emissions), industrial combustion (12.22%), power industry (29.39%), transport (18.87%), and processes (9.39%)—together accounting for 78.21% of the global total. This structure covers $CO_2$ (fossil only), $CH_4$, $N_2O$, and F-gases, aggregated using IPCC AR5 Global Warming Potential values (GWP-100 AR5); the distribution of emissions over 2014–2024 is presented in Figure 5.

Russia's imports from China have been trending upward [24] (Figure 6): total import value reached USD 115 billion in 2024, led by machinery, nuclear reactors, and boilers (USD 27.29 billion) and electrical and electronic equipment (USD 15.95 billion).

**Figure 5**
**Structure of global greenhouse gas emissions by sector (2014–2024)**

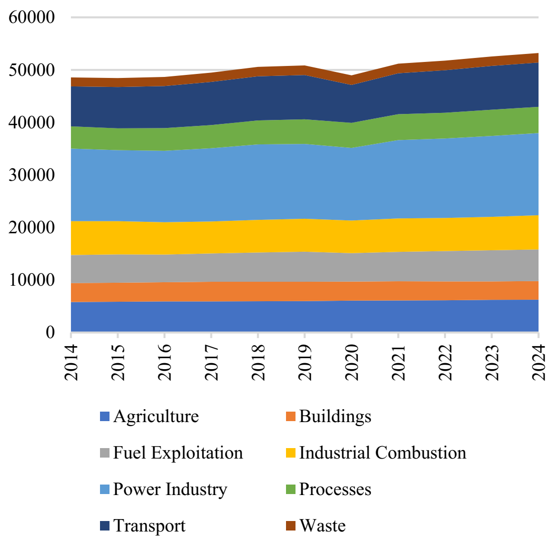
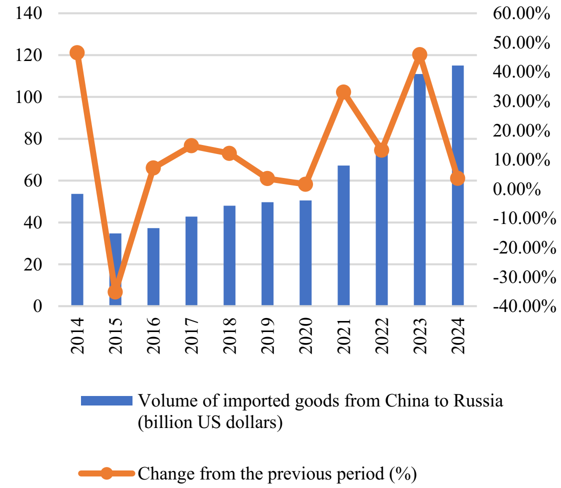



**Figure 6**
**Imports of goods from China to the Russian Federation and year-on-year changes (2014–2024)**



## 5. Discussion

### 5.1. Strategic context: resource interdependence and low-carbon transformation

A fundamental paradigm emerges from the structural trends above. Resource-based interdependence remains stable on one side: hydrocarbon exports are a key revenue source for Russia, and China, as the world's largest energy consumer, gives that trade a growing and reliable outlet. On the other side, global decarbonization imposes a real external constraint—both countries rank among the world's largest GHG emitters, with a meaningful share of that, methane especially, tied directly to fossil fuel extraction, transport, and use. The tension between those two sides is the central contradiction this analysis surfaces: an established resource-based model of cooperation running up against the demands of low-carbon transformation. Going forward, that puts the partnership's future on different footing—its trajectory will depend less on supply volumes than on the two countries' ability to solve technological challenges together.

Looking more closely at each country's energy strategy and emissions profile brings several complementary challenges into view—ones that neither side can address effectively alone, which is exactly why coordinated effort matters here.

For Russia, the central challenge is technological: developing and localizing a new generation of technologies and pushing import substitution far enough to stay competitive and meet climate commitments. Commercializing new technology is the dominant piece of that puzzle, made harder by sectoral restrictions on Russian enterprises that, as Fadeev [6] notes, push the country increasingly toward autonomous technological development.

China's challenge runs the other way: securing energy supply while still hitting its carbon-peaking and neutrality targets. It leads the world in renewable energy investment and yet still depends on hydrocarbon imports to keep its energy system and industrial base stable—which is exactly why reliable Russian supply matters strategically. Its 2060 neutrality target, meanwhile, forces China to "green" its entire energy system, imported resources included, and that creates demand both for technologies that cut the climate impact of oil and gas use and for partners able to supply cleaner hydrocarbons in the first place.

### 5.2. Methane management and associated petroleum gas utilization

Given all this, the natural starting point for Russia–China cooperation on decarbonization and sustainability is pinning down where interaction should be prioritized—those priorities then shape both the methodology and the concrete measures that follow.

Methane is the obvious place to start: its high global warming potential and large share of sectoral emissions give it the greatest synergistic potential for fast climate and economic wins. Priority measures here should include:

1) Joint methane emission monitoring networks built on satellite technologies, sensors, and artificial intelligence;
2) Technologies for capturing APG and putting it to use in power generation or gas-chemical production;
3) Modernized gas transportation infrastructure to cut technological emissions.

The Atlas of Russian Projects for the Production of Low-Carbon and Carbon-Free Hydrogen and Ammonia identifies the shift in geopolitical conditions after 2022 as one of the key challenges these projects have faced. Even so, both the current Concept for the Development of Hydrogen Energy and the strategic vectors set out in Russia's Energy Strategy to 2050 continue to prioritize energy balance diversification, new technology adoption, and diversifying export destinations for gas processing products.

This subsection focuses on methane decomposition in non-equilibrium plasma, one of the more promising and actively developing technological directions worldwide. Its main draw is high energy efficiency, which matters a great deal for remote oil and gas fields trying to utilize APG on-site—though that same remoteness cuts both ways, since it also sharpens the logistical and energy-supply challenges around getting the products, hydrogen and solid carbon, out to market.

The methane decomposition reaction in plasma systems (plasma pyrolysis) follows this chemical equation:

$$CH_4 + Q - (\mathit{plasma}) \rightarrow C(s) + 2H_2(g)$$

where $CH_4$ is methane, natural gas's main component, and Q is the plasma energy input. Even under "cold" plasma conditions—where electrons run hot but the bulk gas stays relatively cool—breaking the strong C–H bond still requires external energy. What comes out is gaseous hydrogen ($H_2$), a candidate low-carbon energy carrier, and solid carbon (C) in the form of technical carbon (carbon black), whose applications range from concrete and asphalt additives to highly conductive carbon depending on purity.

Studies suggest the potential to supply China with carbon produced this way is both significant and structurally sound, resting on stable Chinese market demand, the technological edge of low-carbon production, and both countries' strategic need to decarbonize industry.

Cold plasma has an edge over thermal pyrolysis, which needs temperatures above 1200 °C: it can initiate the reaction using free-electron energy alone. That makes "turquoise" hydrogen production possible without direct $CO_2$ emissions, and it also allows control over solid carbon's morphology—producing higher-value carbon products, which feeds through to project profitability.

In industrial applications, non-equilibrium plasma is a gas state where electron temperature runs well above that of ions and neutral particles, typically produced through electrical discharges at low pressure [19, 21]. Its main advantages include:

1) Superior energy efficiency;
2) Higher thermodynamic efficiency;
3) Inherent carbon capture;
4) Compact and modular design;
5) Tunable product selectivity.

Realizing those advantages, though, takes precise technical tuning and advanced physicochemical modeling, since cold plasma is a non-equilibrium system that classical thermodynamics cannot predict accurately.

This direction ties into the broader industrial push toward digitalization, and under conditions of technological sovereignty it creates a need for domestic modeling tools. The literature points to a few in particular:

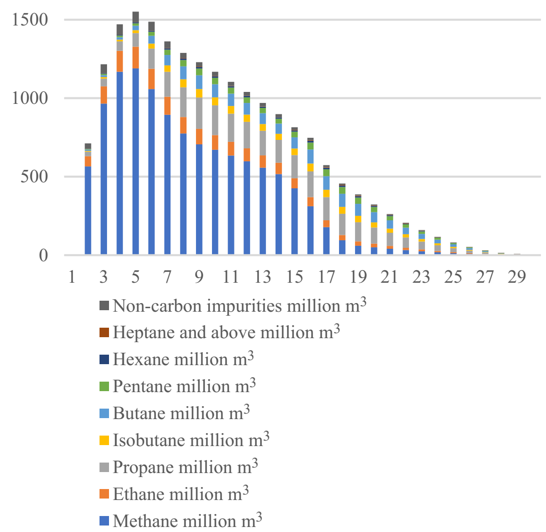
1) Methods for calculating the electron energy distribution function (e.g., two-term approximations of the Boltzmann equation, codes such as bolsig+);

2) Integration of the Navier–Stokes equations (describing gas flows) with Maxwell's equations (electromagnetic fields), similar to capabilities offered by commercial software such as COMSOL Multiphysics (plasma module) and Ansys Fluent;
3) Modeling of electron trajectories and collisions in complex reactor geometries, as well as global kinetic modeling that accounts for all process stages in complex dynamic systems.

Among international precedents, Aurora Hydrogen is worth a closer look: it uses microwave energy to directly heat natural gas without oxygen or water, yielding hydrogen and carbon with no $CO_2$ emissions.

That company's process runs on pure methane, though, and APG's composition complicates the picture considerably when the same technology is repurposed as a value-adding processing unit at an oil production site: using APG directly in plasma-chemical systems cuts profitability because of how complex that composition is. The literature describes APG as a mix of methane, ethane, propane, isobutane, butane, pentane, hexane, heptane, and heavier hydrocarbons, plus non-hydrocarbon impurities, with the exact mix shifting across separation stages—captured here through a proposed curve of APG withdrawal, modeled via mathematical interpolation; Figure 7 presents an example of APG composition distribution depending on the separation stage under a normal gas–oil ratio (GOR).

**Figure 7**
**Changes in associated petroleum gas composition at different field development stages**




This study uses a piecewise interpolation approach to model how APG composition and production evolve over an oil field's life cycle, keeping parameter transitions smooth across the early, middle, and late development stages. The GOR is built as a continuous function via piecewise cubic Hermite interpolation, which guarantees both curve smoothness and monotonicity from the defined stage-based key values, while sigmoid-based weighting functions govern how the multi-component gas composition shifts between stages over specified time intervals—each component's instantaneous content is a weighted average of the stage-specific compositions. Annual APG production volume follows from oil production multiplied by the interpolated GOR, and the resulting component-specific production profiles can be integrated for cumulative yields. A moving average filter smooths the composition curves and constraints on the rate of change keep the output quantitatively controlled, giving a framework robust enough to generate realistic projections of methane and other component yields—the basis for the techno-economic and financial analysis, including discounted cash flow (DCF) modeling, that follows.

APG's varied chemical composition means preliminary gas treatment is unavoidable—an additional gas preparation block covering dehydration (water removal), desulfurization (hydrogen sulfide removal), and de-gasolinization (separating out light hydrocarbon fractions that carry their own economic value).

Project design, accordingly, has to account for each field's specific characteristics—the GOR ($m^3/m^3$ or $m^3/t$) and APG composition ("dry" gas dominated by methane versus "wet" gas rich in heavier hydrocarbons) chief among them—since these directly shape the downstream technological parameters and the feasibility of building methane decomposition facilities for hydrogen and carbon production.

The economic assessment of methane pyrolysis relies on the DCF methodology—a standard income-based valuation approach from corporate finance theory that values a project by discounting its expected future cash flows to the present. Here, the model starts from detailed technical projections: annual processed methane volume follows from plant throughput, conversion efficiency, and operating hours, from which the masses of hydrogen and solid carbon produced are calculated using specific yields. Revenue is modeled from selling these products at their respective market prices, plus potential income from CUs based on avoided GHG emissions, with annual operating costs—electricity (accounting for consumption rates and projected price escalation), personnel, property taxes, and other operational expenses—subtracted to get net cash flow before tax; CAPEX depreciation is applied linearly over the equipment's lifetime. Corporate profit tax is then applied to arrive at net cash flow for each forecast year, and a risk-adjusted discount rate—capturing both the time value of money and the project's systematic risk—brings those future flows back to present value. Net Present Value, the primary criterion for investment attractiveness, is the sum of these discounted flows minus the initial CAPEX. The persistent challenge is estimating key parameters reliably at the conceptual stage, since that requires both technical elaboration of the project and market analysis to value its components.

Deploying a non-equilibrium plasma unit industrially means hitting certain technological performance indicators to keep the project profitable, which adds its own layer of complexity. The methane conversion rate—the percentage of feedstock transformed into target products—is one such indicator, and it directly determines how much hydrogen and carbon the process yields.

Catalysts are one route to improving conversion and selectivity, but they bring their own unresolved problems: unpredictable synergistic effects, coking, and a complicated catalyst–plasma interaction. Mitigating coking is itself an active research question—heteroatom doping, strong metal–support interaction (coating the catalyst with nanoparticles to constrain coking), and periodic or continuous plasma exposure with mild oxidizers to clear undesirable products are among the approaches under study—though each carries some risk of catalyst damage and none fully resolves the underlying catalyst–plasma coupling complexity.

Graforce illustrates an alternative path: using the plasma itself as the catalytic medium, with active species—radicals, ions—standing in for a conventional catalyst. That sidesteps the coking problem entirely, and the company's technology can additionally switch between two plasma modes depending on the objective.

Throughput and scalability present a further, related challenge, since the two do not scale linearly together. Cold plasma depends on sustained high voltage generating the electrons that activate gas molecules, and the dominant scaling strategy today is "numbering-up"—running identical plasma modules in parallel—rather than simply building larger units.

Hydrogen transportation is its own persistent obstacle, constraining both deployment and consumption when production happens remotely and limiting export options—liquefaction alone requires cooling to around −253 °C. The immaturity of the hydrogen market compounds the problem.

Selling CUs could add a meaningful revenue stream to the economic model and improve profitability—though this remains high-risk, dependent on successful project registration and on a market environment that the Kept/SIBUR report Russian Carbon Market Overview: Growth Potential currently characterizes as oversupplied.

Factoring CUs into the project's economic efficiency estimate is defensible, then, but only under a conservative scenario that accounts for verification costs and possible delays in sales.

Overall, this is not a short-term commercial play—it is one of several potential development vectors through which the oil and gas industry could pursue climate goals and new project directions that turn a profit under emerging conditions while meeting accepted standards.

The main advantages of this direction for project implementation include:

1) Contribution to decarbonization of the fuel and energy complex: carbon production through plasma-chemical methane decomposition addresses two environmental challenges simultaneously: it utilizes methane (APG) and avoids $CO_2$ emissions from conventional production. This directly contributes to emissions reduction both in Russia (methane) and in China (Scope 3 emissions associated with imported feedstock).
2) Creation of a new commodity value chain: the chain "methane → carbon + hydrogen → export to China" is formed, transforming the resource-based model into a technology-oriented one.
3) Strategic partnership: joint projects in this area (construction of units, R&D) strengthen the energy and technological alliance between the two countries, making it more resilient to external challenges.

What gives this project and its future research directions their significance is the combination of potential upside: displacing high-cost, "dirty" production, diversifying the supply of critical raw materials strategically, and generating synergy with the broader climate agenda.

## 5.3. Renewable energy and carbon capture as complementary directions

Technological progress in renewable energy sources (RES) is a key factor in achieving global climate goals, and China leads the field by a wide margin—its "green" energy capacity accounts for 31.39% of the global total. Domestic production already exceeds internal market needs, which has translated into substantial export potential: China is the world's leading exporter of RES equipment, reaching more than 200 countries and regions on the back of an efficient manufacturing chain and the cost reductions that come with it.

Russia's current Energy Strategy names renewables as one of its strategic vectors, aimed at diversifying the energy balance and bringing in new technology. Growth has been real—80.05% between 2014 and 2024, from 0.644 EJ to 0.804 EJ—but renewables, solar and wind especially, still play a limited role in the national energy balance. Part of the reason is a competitiveness gap against conventional sources under equal market conditions [14], one that simple state subsidization cannot really fix without generating adverse effects elsewhere. Where the academic literature does see potential is in targeted niches: Fadeev et al. [9] point to the Arctic specifically, where renewables could meaningfully supply individual settlements and small-scale industrial facilities, with combined renewable-fossil use enhancing the competitiveness of a number of Arctic projects.

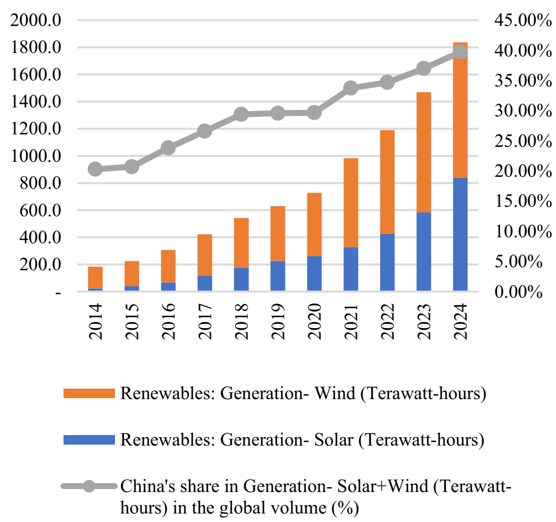
Russia also ranks among the countries with the largest technically achievable wind power potential [13], which means solar and wind development—renewables more broadly—carry real upside for Russia, alongside the technological challenges of developing new technology and substituting for imports.

The highest-potential wind zones sit mainly along the Arctic Ocean coast and its islands, stretching from the Kola Peninsula to Kamchatka: roughly 30% of the economic wind power potential is concentrated in the Far East, 14% in the Northern Economic Region, and about 16% across Western and Eastern Siberia [13].

Solar potential is similarly uneven across Russia: annual solar radiation ranges from 810 $kWh/m^2$ in remote northern areas to 1400 $kWh/m^2$ in the south, with sharp seasonal swings on top of that—at latitude 55°, radiation runs 1.69 $kWh/m^2$ per day in January against 11.41 $kWh/m^2$ per day in July [14].

That leaves Russian industry with a real dilemma: build domestic renewable technology or buy it from friendly countries. Foundational trade theory—Ricardo's comparative advantage [15], later formalized by Heckscher, Ohlin, and Samuelson's factor-endowment framework [16–18]—makes a reasonable case for importing existing technology, and the data bear this out: international climate policy, ETS implementation especially, has been shown to stimulate demand for Chinese photovoltaic products across a number of countries, and by 2024 China already produced 39.72% of global solar and wind energy, as shown in Figure 8.

**Figure 8**
**Wind and solar power generation in China and China's share in global renewable electricity generation (2014–2024)**



Renewable energy cooperation, in other words, could become a genuinely new strategic vector—one capable of reshaping both the Russian energy sector's technological landscape and the broader bilateral partnership—provided it rests on a technological-partnership strategy that reflects both sides' national interests. Under sanctions, China is a readily accessible source of competitive solar and wind equipment at scale, letting Russia sustain and even accelerate new capacity commissioning over a relatively short timeframe. But that same convenience is a risk if cooperation stays at the level of buying finished equipment: without real knowledge transfer and domestic capability-building, the relationship would leave Russia dependent rather than strengthened.

A mechanism that balances imports against technological sovereignty is therefore needed—an intergovernmental "Roadmap" for renewables partnership with concrete targets (localizing 65% of the solar module value chain by 2035, for instance), backed by special investment contracts, tax benefits, and incentives. In practice, that means joint ventures with mandatory Russian company participation (Rosatom, Rosseti, and similar), a rising quota for Russian-made components, joint engineering and R&D centers, and a shared system of standards.

Future research could usefully extend into energy and economic modeling—power balance modeling, grid infrastructure and storage needs assessed via models such as MESSAGEix, TIMES (ETSAP), OSeMOSYS, or Calliope—alongside total integration costs and the effects of RES investment on economic growth, employment, related industries, and import-substitution dynamics. Multifactor risk analysis weighing technological-cooperation consensus against state interests remains a critical piece of that agenda.

Building a qualitatively new technological partnership between China and Russia, then, means addressing the following tasks:

1) Put near-term arrangements in place and build an institutional foundation for new directions under the "Energy Cooperation Plan for 2025" and other existing agreements;
2) Stand up working interdisciplinary groups for new energy clusters, tasked with developing and signing a framework agreement on renewable energy and low-carbon technology cooperation, plus a roadmap for new energy projects with technological and economic efficiency indicators attached;
3) Develop and implement pilot solar and wind power projects in remote areas, in line with the roadmap and its target performance indicators;
4) Pursue technological cooperation and localization, set up joint research centers (for hydrogen technologies and renewable materials, among others), and launch assembly and manufacturing facilities for key RES components in Russia;
5) Agree on unified standards spanning hydrogen types, RES certification, and carbon-footprint calculation methodologies, so national systems can be integrated;
6) Bring the countries' cooperation to a qualitatively new level, diversify Russia's energy exports, and lift the share of non-resource energy exports to 15–20% of the total.

$CO_2$ injection into geological formations (CCUS) deserves consideration too as an important climate-project direction. As a process, GHG sequestration runs through compressing $CO_2$ to a supercritical state, transporting it by pipeline to the storage site, and injecting it deep underground into reservoirs. China's geological formations—deep saline aquifers, depleted oil and gas fields, coal seams, shale formations—hold significant $CO_2$ storage potential that is not yet fully mapped, and doing so is a priority task.

As the world's largest $CO_2$ emitter, China cannot really meet its stated climate goals without CCUS technologies—they are a strategic necessity, not an option.

Geological requirements for $CO_2$ storage zones include: reservoirs need high porosity to hold large volumes of carbon dioxide, aquifer rocks need enough permeability for $CO_2$ to enter subsurface formations through injection, and impermeable cap rocks need to sit above the storage reservoirs to prevent surface leakage. Depth matters too—reservoirs deeper than 800 m let injected $CO_2$ transition into a fluid state (neither fully liquid nor gas, easily compressible, with liquid-like density), though depths beyond 4000 m become economically inefficient. Reservoir density in the region needs to be high enough, and so does the connectivity between emission sources and storage sites.

The southern Far East looks most promising for subsurface development, along the Khabarovsk–Vladivostok railway corridor and possibly the Khabarovsk–Komsomolsk-on-Amur route, where granitoid mountain massifs may offer the best-suited formations.

On the Chinese side, potential concentrates in a few key regions: the Sichuan and Ordos basins stand out as priority areas for enhanced gas recovery using $CO_2$, while oil fields matter too, since enhanced oil recovery (EOR) with $CO_2$ injection is China's most commercially mature CCUS pathway [25]. What remains unresolved is injection-rate capacity—the maximum annual volume of $CO_2$ that wells can safely take without risking reservoir integrity or inducing seismicity—a parameter that depends on detailed geological data (permeability, porosity, structure) that is often incomplete.

Russia's complementary strengths in geology and oil and gas engineering open a path toward joint R&D and pilot projects here, though realizing that will depend on overcoming geopolitical, regulatory, and financial barriers and giving CCUS a clear place in both countries' national climate strategies. Russia does have $CO_2$ storage potential—depleted oil and gas reservoirs, for one—but faces its own constraint in the long distances between production and processing sites, which would require dedicated pipelines and infrastructure to move $CO_2$ back to storage locations. Over long enough distances, that makes the CCUS pathway economically and technologically inefficient, so geography and distance need to be weighed explicitly in any transboundary storage assessment—including the possibility of using Russia's extensive, well-studied sedimentary basins to store $CO_2$ captured in China's border industrial regions, which would in turn require its own legal and commercial models to be built from scratch.

Given the current technological, economic, and political constraints, a mixed decarbonization model is called for [10]—one built to sustain mutually beneficial cooperation between international and national organizations as they coordinate national programs and work through shared challenges in global energy-sector climate governance. Developing Russia's regulatory system along these lines should cover the following organizational and technological directions:

1) A legal and regulatory framework for carbon regulation via carbon quota trading;
2) A regulatory framework for introducing a carbon tax, alongside non-financial reporting standards and integration into international green initiatives;

3) A legal and regulatory framework for GHG monitoring, reporting, and control, harmonized with international requirements and standards;
4) Flexible financing mechanisms for production modernization and low-carbon technology deployment aimed at reducing carbon intensity;
5) A regulatory framework for project activities that reduce emissions and/or expand the absorption capacity of natural GHG sinks.

## 5.4. Principles and a phased roadmap for cooperation

Chinese–Russian oil and gas cooperation, then, is multifaceted and carries real potential thanks to complementary competencies and state-level climate objectives on both sides. In the short term, Russia functions as a reliable hydrocarbon supplier—good for China's energy security, and a key export revenue source for Russia. But decarbonization and sustainable development, understood as a qualitative transformation of socioeconomic systems rather than a threat to their functioning, mean that long-term cooperation cannot stay as it is: the contradiction this study's data keeps surfacing, between an established resource-based model and the demands of energy transformation, has to be resolved.

The climate-project directions examined above are genuinely hard to substantiate and develop even at the conceptual stage, especially economic efficiency assessment. Part of the difficulty is technical: many relevant technologies still sit at the R&D or experimental stage, and evaluating their parameters and forecasting outcomes for industrial-scale deployment carries substantial investor risk. Part of it is structural: no cross-border CU market exists yet between Russia and China, and given the uncertainty around even the national-level outlook, building project economic models that factor in CU trading is either impossible or highly risky right now.

That said, CU trading from climate projects is already on the agenda of intergovernmental commissions with China and other friendly countries, alongside active discussion of joint carbon-footprint-reduction projects. As of 2025, though, the institutional environment for this agenda is still taking shape, and it will likely rest on a multi-layered system of documents running from foundational international agreements (the UNFCCC, the Paris Agreement) down through regional strategies, national laws, and voluntary standards.

Any qualitatively new form of interaction between Chinese and Russian oil and gas companies has to line up with each country's national objectives and its technological and energy sovereignty. Effective cooperation in this new context, in other words, needs partnerships built on the following principles:

1) Strategic rationale and national priorities. Joint projects need to track long-term climate targets (carbon neutrality for both China and Russia by 2060) and tackle each country's key energy-transition tasks, feeding into technological modernization and export diversification.
2) Market-oriented governance. Oil, gas, and energy companies should drive technology deployment and lead these partnerships day to day, with the state playing a strategic supporting role rather than a managing one.
3) Technological pluralism and innovation. The partnership needs to stay open to a wide range of technological solutions—renewable energy and hydrogen through to CCUS and methane monitoring—rather than betting on one path.
4) Horizontal cooperation and synergy. Extending links beyond the traditional oil and gas sector—bringing in renewables, electric mobility, IT, and finance companies—is a priority for building genuinely integrated solutions.
5) State incentives for private investment. A favorable investment climate, built through subsidies, guarantees, and green finance, is what lowers risk enough for private investors to commit.
6) Inclusiveness and multilevel participation. Partnerships should span company sizes, from the largest national corporations down to small and medium innovative enterprises, keeping the ecosystem flexible and open to new developments.
7) Transparency and openness of results. Publishing non-confidential results from joint R&D, successful pilots, and shared standards builds knowledge, develops the market, and earns trust over time.
8) Program- and target-based management. Hitting decarbonization goals takes a clear roadmap: specific measurable tasks, defined implementation stages, and clearly distributed responsibility among participants.

**Roadmap for Russia–China Cooperation in Decarbonization and Climate Projects: A Phased Action Framework (2028–2050)**

Stage I. Building the Institutional Framework for Cooperation (2028–2034)

1) Signing an intergovernmental "Agreement on Strategic Cooperation in Energy Decarbonization"
   a. Document type: Intergovernmental agreement
   b. Responsible parties: Ministry of Energy of the Russian Federation; Ministry of Commerce of the People's Republic of China (PRC); Ministries of Foreign Affairs
   c. Target timeline: 2028
   d. Expected outcome: Formalization and fixation of common goals and obligations at the intergovernmental level
2) Establishing a bilateral working group on climate regulation and CU trading
   a. Document type(s): Decision of a joint commission; energy cooperation strategy in the context of decarbonization; technology roadmaps and identification of anchor customers
   b. Responsible parties: Ministry of Economic Development of the Russian Federation; MEE (China); Central Bank of the Russian Federation; People's Bank of China (PBOC)
   c. Target timeline: 2030
   d. Expected outcome: Systematization of strategic cooperation vectors, required technological developments, and stakeholders
3) Establishing a joint "Green Investment Fund" to finance R&D and pilot projects
   a. Document type(s): Founding agreement; investment declaration
   b. Responsible parties: China Development Bank; Ministry of Economic Development of the Russian Federation; corporate investors
   c. Target timeline: 2032
   d. Expected outcome: Creation of a financing mechanism aimed at supporting innovative projects, defining budgets and key indicators and investment criteria

4) Developing and harmonizing product carbon-footprint measurement methodologies Life Cycle Assessment (LCA)
   a. Document type(s): Agreement on mutual recognition of methodologies; adopted legal and regulatory framework
   b. Responsible parties: Rosstandart; Standardization Administration of China (SAC) (China); profile companies (sector-specific companies)
   c. Target timeline: 2034
   d. Expected outcome: Approval/establishment of a cross-border CU market

Stage II. R&D and Pilot Project Development and Implementation (2036–2042)

5) Joint inventory of emission sources and CCUS potential at upstream oil and gas sites and other facilities
   a. Document type(s): Technical report; potential map
   b. Responsible parties: Gazprom; Rosneft; China National Petroleum Corporation (CNPC); Sinopec; research institutes
   c. Target timeline: 2036
   d. Expected outcome: CCUS project "heat map" with key techno-economic performance indicators

6) R&D to adapt $CO_2$ capture technologies
   a. Document type(s): R&D program; patents
   b. Responsible parties: Gazprom Neft; SIBUR; SINOPEC; R&D centers
   c. Target timeline: 2038
   d. Expected outcome: CCUS project documentation

7) Analysis of CCUS value-added chains
   a. Document type(s): Marketing study; business model
   b. Responsible parties: Gazprom Neft; SIBUR; SINOPEC; R&D centers
   c. Target timeline: 2038
   d. Expected outcome: Report on the potential use of $CO_2$ in gas chemistry and EOR

8) R&D to develop and adapt "turquoise hydrogen" production technologies from APG at oil production sites
   a. Document type(s): R&D program; patents
   b. Responsible parties: Gazprom; Rosneft; CNPC; Sinopec; research institutes
   c. Target timeline: 2038
   d. Expected outcome: "Heat map" of turquoise hydrogen projects with key techno-economic performance indicators

9) Study of the potential for RES deployment in Russian regions
   a. Document type(s): Marketing study; business model; technical report
   b. Responsible parties: Ministry of Industry and Trade of Russia; Ministry of Economic Development of the Russian Federation; MEE (China); industry companies
   c. Target timeline: 2038
   d. Expected outcome: Report on the technological and economic potential of RES deployment with techno-economic performance indicators

10) Agreement on importing RES technologies into Russia
   a. Document type: Sectoral agreement
   b. Responsible parties: Ministry of Industry and Trade of Russia; Ministry of Economic Development of the Russian Federation; MEE (China); industry companies
   c. Target timeline: 2040
   d. Expected outcome: Agreement on RES technology supply taking into account national interests in technological sovereignty

11) Joint venture for integrating RES into Russian regions
   a. Document type: Joint venture
   b. Responsible parties: Regional authorities; specialized RES organizations
   c. Target timeline: 2040
   d. Expected outcome: Establishment of organizations with joint investment in RES-related activities

12) Scoping alternative research directions
   a. Document type(s): Marketing study; R&D program; patents
   b. Responsible parties: Energy companies and other stakeholders
   c. Target timeline: 2038
   d. Expected outcome: Reports on the technological and economic potential of decarbonization directions with techno-economic performance indicators

13) Implementation of pilot projects based on R&D results
   a. Document type(s): Technical report; potential map of innovation projects
   b. Responsible parties: Industry customers and R&D centers
   c. Target timeline: 2042
   d. Expected outcome: Report on the techno-economic and environmental potential of projects selected for development

Stage III. Pre-Commercial Deployment, Monitoring, and Evaluation (2045–2047)

14) Deploying technologies at relevant sites based on reports and forecast potential
   a. Document type: Project documentation
   b. Responsible parties: Industry customers and R&D centers
   c. Target timeline: 2045
   d. Expected outcome: Report on the techno-economic and environmental effects of projects selected for development; project "heat map"

15) Developing plans for industrial deployment of innovative technologies at industrial sites considering scale
   a. Document type: Project documentation
   b. Responsible parties: Industry customers and R&D centers
   c. Target timeline: 2047
   d. Expected outcome: Industrial deployment plan for innovative technologies in line with effects reports and project heat maps

16) Study of the national and cross-border CU trading market
   a. Document type: Marketing study
   b. Responsible parties: Industry customers and consulting companies
   c. Target timeline: 2047
   d. Expected outcome: Report on the effectiveness and potential of the CU market and the possibility of building project economic models that incorporate it

Stage IV. Industrial Scaling of Technological Projects (2050)

17) Deployment and expansion of technologies at relevant sites based on reports and forecast potential
    a. Document type: Project documentation
    b. Responsible parties: Industry customers
    c. Target timeline: 2050
    d. Expected outcome: Report on the techno-economic and environmental effects of implemented projects.

Cooperation built on these principles serves each country's national interests most fully, enabling effective communication and joint projects across the areas identified here—methane decomposition in non-equilibrium plasma, renewable energy deployment (solar and wind particularly), and $CO_2$ sequestration in geological reservoirs. None of this is meant to box in the multivector nature of China–Russia technological cooperation; these are simply some of the potential avenues consistent with decarbonization and sustainable development goals.

Drawing on the empirical results and the comparative analysis of regulatory frameworks, emissions structures, and technology pathways presented above, the following recommendations aim to strengthen Russia–China oil and gas decarbonization cooperation while preserving each side's energy security and technological sovereignty.

1) Reframe bilateral cooperation from "volume-based trade" to "carbon-performance partnership." The contradiction identified above, between the resource-based cooperation model and low-carbon transformation, means bilateral energy cooperation needs measurable carbon-performance targets sitting alongside supply commitments—in practice, prioritizing projects and contracts that explicitly cut lifecycle emissions, methane above all, and build verifiable MRV requirements into the commercial terms themselves.
2) Make methane the partnership's primary short-term decarbonization lever. Fuel exploitation and methane already account for a large share of sectoral emissions, and methane mitigation moves fast—so the first joint decarbonization package should focus on Leak Detection and Repair (LDAR) programs, reducing technological leaks across gas infrastructure, and cutting APG flaring at upstream sites. Given how much higher Russian flaring trends run than China's, this should be treated as the single highest-impact near-term measure.
3) Build a joint MRV architecture compatible with China's ETS and Russia's emerging carbon regulation. That starts with harmonized MRV rules for oil and gas emissions ($CO_2$ and $CH_4$) and product carbon footprints—practically, a bilateral MRV protocol for upstream and midstream operations, aligned with China's national ETS requirements and integrable with Russian registry practices. Without compatible MRV, neither cross-border climate projects nor "cleaner hydrocarbons" claims can be validated at any scale.
4) Pilot "methane-to-hydrogen-and-carbon" technologies only at sites where logistics and gas composition support economic viability. Non-equilibrium plasma methane decomposition is promising, but its feasibility hinges on conversion performance, scale-up constraints, energy supply, and how much APG composition varies—so pilots should be limited to sites with reliable power, economically justified APG pre-treatment (dehydration, desulfurization, Natural Gas Liquids (NGL) separation), and realistically solvable hydrogen/solid carbon logistics. Technology choices should be benchmarked against plasma configuration conversion ranges and proven through staged demonstration before any scale-up.
5) Treat renewable energy cooperation as a technology-transfer and localization program rather than straightforward procurement. China's manufacturing and export capacity in solar and wind equipment offers a short-term opening to accelerate deployment in Russia, remote and niche applications especially (Arctic settlements, industrial sites)—but to avoid dependence, cooperation needs localization milestones (rising shares of domestic components and engineering capability) and joint ventures with mandatory Russian industrial participation built in. A "purchase-only" model would not build lasting sovereignty or competencies and should be avoided.
6) Prioritize CCUS in geographically rational clusters, and avoid defaulting to "long-distance reverse logistics." CCUS cooperation should focus on storage sites that keep transport distance and infrastructure costs down, since moving $CO_2$ back over large distances can undermine both economic and technological feasibility—site selection should rest on storage integrity criteria (depth, porosity, permeability, caprock quality) and realistic injection-rate capacity, and transboundary concepts should only be pursued where cross-border industrial regions and storage basins are geographically compatible and bespoke legal and commercial frameworks are achievable.
7) Sequence a bilateral CU mechanism to come only after MRV convergence and credible demand have formed. Economic models that lean on CU revenue are, this study shows, highly sensitive to market uncertainty and oversupply risk—so any bilateral mechanism should move in stages: MRV alignment and registry interoperability first, controlled-scope pilot transactions second, gradual scaling third, once stable demand and clear compliance drivers are in place. Project appraisals should build in conservative assumptions, verification costs, and settlement delays from the outset.
8) Institutionalize cooperation through a binding roadmap with measurable deliverables and shared responsibility. Turning strategic alignment into implementable projects calls for a structured, stage-based roadmap specifying priority technology tracks (methane, Variable Renewable Energy (VRE), CCUS), responsible institutions and companies, timelines, KPI frameworks (emissions reductions, verified carbon intensity, localization ratios), and financing instruments—with progress reviewed through an intergovernmental mechanism that keeps industry closely involved to ensure market-oriented execution.
9) Strengthen financing instruments to de-risk pilots and speed up industrial adoption. Many decarbonization technologies remain highly uncertain at this early stage, so joint mechanisms should pair public strategic support with private execution—green finance, guarantees, special investment contracts—and prioritize pilots with clearly quantified environmental effects and realistic scaling pathways over purely declarative project concepts.

Taken together, these recommendations give Russia and China a way to resolve the strategic contradiction this study identifies—keeping the energy security and economic benefits of cooperation intact while shifting toward a measurable, technology-driven, MRV-verified low-carbon partnership consistent with both countries' climate objectives.

## 6. Conclusions

The Russian and Chinese experience examined here shows the technological constraints on decarbonizing their oil and gas cooperation to be real, but not insurmountable. Methane abatement, APG utilization, plasma-based hydrogen production, renewable energy deployment, and carbon capture and storage are each held back by the maturity of the underlying technology, by the geography of remote fields and long transport distances, and by the sheer difficulty of proving economic viability while many solutions still sit at the research and demonstration stage. Institutional gaps compound these technological ones: the two countries' regulatory regimes differ in design and maturity, no cross-border CU market yet exists, and MRV practices remain unharmonized—all of which leaves the appraisal and financing of joint climate projects on uncertain footing.

Even so, the strategic prospects for cooperation look favorable. Russian resource and engineering competencies complement Chinese manufacturing scale, technological capacity, and market demand well enough to find a gradual shift from a purely resource-based partnership toward one oriented around technology and performance. Getting there will mean aligning bilateral cooperation with both states' long-term climate objectives, building shared institutional and verification infrastructure, and sequencing joint efforts so that institutional groundwork comes before technological pilots and industrial scaling rather than after. On those conditions, Russia and China can preserve both energy security and the mutual benefits of their energy trade while making measurable progress toward decarbonization and sustainable development.

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## Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

## Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

## Data Availability Statement

The data supporting the findings of this study are publicly available in the reference list.

## Author Contribution Statement

**Ilyinsky Alexander:** Conceptualization, Methodology, Supervision. **Ushpik Iliya:** Conceptualization, Software, Formal analysis, Investigation, Resources, Data curation, Project administration. **Temurkaeva Sibilla:** Conceptualization, Software, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization.

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