Renewable Energy Adoption in Enterprises under Carbon Neutrality: Pathways, Barriers, and Strategic Responses

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Abstract：Under China’s “3060” dual carbon goals, enterprises, contributing over 70% of national carbon emissions, are the core subjects of low-carbon transition. This paper systematically analyzes five core pathways for corporate renewable energy adoption: distributed self-generation, green electricity direct connection, green power purchase agreements (PPAs), green electricity certificate (GEC) trading, and microgrid-energy storage integrated systems. It identifies four key barriers constraining the transition: economic viability constraints, renewable energy volatility-related power security risks, domestic policy misalignment and international standard gaps, and supply chain collaborative emission reduction dilemmas. Drawing on domestic and international policy frameworks and enterprise practices, this paper proposes targeted optimization strategies. The findings enrich micro-level research on industrial low-carbon transition and provide actionable guidelines for renewable energy transition of Chinese enterprises.

Keywords: Carbon Neutrality; Low-Carbon Transition; Renewable Energy Adoption; Transition Barriers; Targeted Countermeasures

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1 Introduction

In 2020, China formally committed to the “3060” dual carbon goals, a national strategic pledge to peak carbon dioxide emissions before 2030 and achieve full economy-wide carbon neutrality by 2060 (Energy Economics, 2024). Since then, the low-carbon transformation of the energy structure has become a core pillar of China’s high-quality socioeconomic development. As the foundational microeconomic units of the national economy, industrial and commercial enterprises account for more than 70% of China’s total carbon emissions, positioning them as the key responsible entities for delivering on the dual carbon goals (Energy Economics, 2024). Amid the evolving global climate governance regime, Chinese enterprises simultaneously face dual pressures: rigid domestic regulatory constraints from the “dual control” policy on total energy consumption and intensity, and rising trade barriers from the European Union’s Carbon Border Adjustment Mechanism (CBAM) for export-oriented firms. Against this background, the large-scale adoption of renewable energy has evolved from a discretionary corporate social responsibility initiative to an inevitable strategic imperative for ensuring regulatory compliance, controlling long-term operational costs, and sustaining market competitiveness.

Under this regulatory and competitive background, research on corporate low-carbon transition has expanded rapidly over the past decade. Related studies can be categorized into three primary streams, each with notable contributions but unaddressed limitations. First, macro-level research focuses on national renewable energy policy design, electricity market reform pathways, and aggregate industrial decarbonization potential (Economic Change and Restructuring, 2024). While these studies establish a top-level policy framework for renewable energy scaling, they largely overlook the micro-level decision-making logic and heterogeneous demands of enterprises with varying scales, industry attributes, and resource endowments. Second, firm-level research centers on the measurement of environmental, social and governance (ESG) performance, the construction of corporate carbon accounting systems, and the efficiency of green technology innovation (Energy, 2023). This stream verifies the economic and environmental outcomes of corporate low-carbon behaviors, but rarely interrogates the specific renewable energy adoption pathways that form the operational core of energy structure transformation. Third, technical and economic studies examine isolated renewable energy models, such as distributed photovoltaic investment returns and power purchase agreement (PPA) contract design (M2 Presswire, 2023). However, these works lack a systematic comparative analysis of multiple alternative pathways, and fail to explore targeted response strategies for enterprises navigating multi-dimensional regulatory, technical, and market constraints.

While the aforementioned studies have laid a foundational understanding of corporate low-carbon transition and renewable energy development, two critical and interrelated research gaps remain. On one hand, existing studies have not established a unified comparative framework for heterogeneous renewable energy adoption pathways, failing to clarify the applicable scenarios, cost-benefit characteristics, and compliance effectiveness of different models for diverse enterprise types. On the other hand, there is a lack of targeted analysis of the compound barriers facing enterprises in renewable energy transition, particularly the gap between China’s current green electricity and green certificate systems and emerging international hour-level matching requirements, which has become a material compliance risk for export-oriented firms but remains under-examined in domestic research.

Filling these gaps carries important theoretical and practical implications for both academic research and industrial practice. Theoretically, this paper constructs a concise but complete analytical framework of “pathway comparison - barrier identification - experience reference - targeted strategy optimization”, which enriches micro-level theoretical research on industrial low-carbon transition under the dual carbon goals. Practically, it clarifies the core attributes of mainstream renewable energy pathways with quantitative data, identifies binding constraints in the transition process, and proposes evidence-based countermeasures, supporting enterprises in selecting context-appropriate transition models and providing a reference for regulators to refine supporting policies. This paper is organized as follows: Section 2 analyzes core renewable energy adoption pathways; Section 3 identifies key transition barriers; Section 4 summarizes domestic and international experience and enlightenment; Section 5 proposes targeted optimization strategies; Section 6 concludes the study.

2 Core Pathways for Corporate Renewable Energy Adoption

Figure 1 illustrates five primary models of enterprise renewable energy adoption, falling into three categories: on-site self-generation (distributed power), market procurement (direct green power trading, green certificate trading), and park-level integrated solutions (microgrids with energy storage). These pathways differ in investment scale, emission reduction certainty, implementation flexibility, and suitability for different enterprise types, offering diverse options for adoption. Distributed self-generated power is suitable for enterprises with their own power facilities, and the trading of green certificates can be used conveniently by asset-light enterprises to achieve environmental benefits.

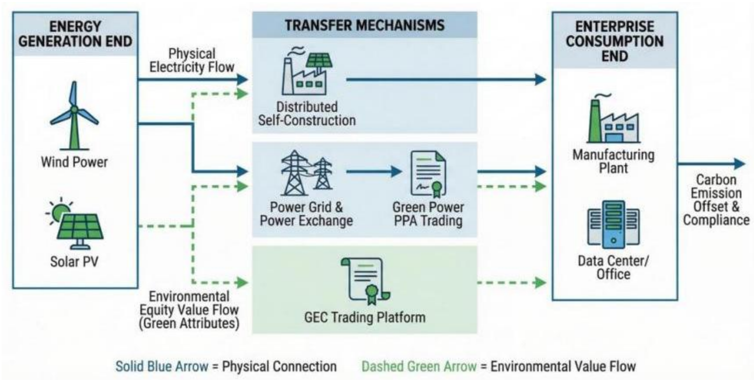

Figure 1: Core Pathways for Corporate Renewable Energy Adoption

2.1 Self-built Distributed Renewable Energy (Self-generation for Self-use)

This model is the simplest and most practical; the enterprise can use its own rooftops, idle factory land, parking canopies, etc., to invest in distributed photovoltaic systems or small-scale wind turbines and prioritize on-site self-consumption, surplus grid connection or support for energy storage, etc. Although the initial capital expenditure is relatively high financially, the levelised cost of electricity (LCOE) over the full life cycle of these projects is much lower than the electricity prices in China's industrial and commercial catalogue. By the end of 2024, the total installed capacity of distributed photovoltaics in China will exceed 350 GW, and among them, industrial and commercial projects will account for more than 60%; at a typical pace, the payback period is about 5-7 years, and the operating cost is 30%-50% lower than the average industrial and commercial electricity price (Frontiers in Environmental Science, 2023). From a compliance standpoint, the "behind-the-meter" model can directly reduce a company's Scope 2 emissions and indirect greenhouse gas emissions from the purchase of electricity, heating and cooling, etc., according to the Greenhouse Gas (GHG) Protocol. The main problems are that there are not enough resources at the site of high-energy-consuming enterprises and the electricity generation is inherently unstable; AI-based generation prediction models have improved the accuracy of short-term forecast by more than 95% (International Journal of Business and Systems Research, 2023).

2.2 Green Electricity Direct Connection

The model enables enterprises to sign direct supply contracts with the nearby wind and photovoltaic stations and then transmit the green electricity via a separate line, bypassing the public distribution network. It is not only in the place of distributed generation, but also a considerable amount of low-cost green electricity can be purchased with transparent physical traceability. Economically speaking, the direct-connection electricity price is usually about 0.02-0.05 yuan/kWh lower than the public-grid industrial price; there are no additional public network fees and line losses, and by the end of 2024, the total scale of installed direct-connection projects in China will exceed 80 GW, with projects concentrated in high-energy-consuming sectors such as steel, non-ferrous metals and data centres (Energies, 2022). A separate line should be added to track the whole power flow, and it will be necessary not to count some environmental items multiple times in carbon accounting. The main problem is that it requires a large enterprise site and has a large power consumption; therefore, it is only suitable for large and medium-sized enterprises with stable long-term load and cannot be used by small and medium-sized enterprises (SMEs) and asset-light firms.

2.3 Green Power Purchase Agreements (PPAs) and Direct Trading

With the deepening of reform in China's electricity market, Power Purchase Agreement (PPA) transactions at the official power trading center have gradually become popular among medium- and large-scale enterprises, especially data centres, high-end manufacturing and export-oriented enterprises, etc. Through this model, the company can sign medium- and long-term contracts with renewable energy generators in different parts of the country to purchase green electricity. The model has reached a certain scale effect; by 2024, the cumulative amount of medium- and long-term green electricity transactions in China will be 260 TWh (an increase of 82% year-on-year), and the proportion of industrial enterprises in the total will exceed 90% (Environmental Science and Pollution Research International, 2022). Policy-wise, the amount of green electricity trading will be relatively small after the construction of dual-control accounting for enterprise energy consumption; it can provide an initial compliance base, and over the long run, a Power Purchase Agreement (PPA) of 10-20 years will be signed to stabilize electricity prices against market fluctuations. The main problem is that enterprises lack strong robust operational and trading capabilities; if the load forecast is incorrect or they are not familiar with the trading rules, there may be risks of contract non-performance and financial losses.

2.4 Green Electricity Certificate (GEC) Trading

GECs are standardised electronic vouchers issued by the national energy office that serve as the legal basis for the environmental attributes of green electricity. The first advantage of this model is high flexibility; it can separate physical electricity from environmental factors, so enterprises do not need to modify their existing power access structure and only need to purchase GECs from the official platform to complete carbon emission reduction and increase their recognized renewable energy share. This model is more suitable for asset-light enterprises and rental businesses for offices and organisations in areas that do not have direct access to the green electricity supply, etc., so it can lower the threshold for people and organisations to enjoy the environmental benefits of green electricity. By the end of 2024, China's cumulative issuance of GECs will exceed 400 million, and the transaction volume will reach more than 35 million; for asset-light enterprises, the cost of acquiring emission reduction credits via GECs is about 0.02-0.06 CNY/kWh, and there is a simple procurement process that can meet the downstream requirements of customers and international standards promptly (International Journal of Finance & Economics, 2022).

2.5 Microgrid and Energy Storage Integration

A general case of the system of deep decarbonisation is a large industrial park and an energy-intensive cluster. It can build an independent power grid through the combination of distributed photovoltaic, decentralized wind, electrochemical energy storage and intelligent energy management to achieve self-optimisation of the energy schedule and increase the local consumption share of renewable energy. Based on the above practical data, the model can reduce the maximum demand charge of enterprises by 15%-30% through peak shaving and valley filling, increase the local consumption rate of renewable energy to more than 90%, and by the end of 2024, China had over 1,200 operating industrial and commercial microgrid projects with a total installed capacity of more than 15 GW (Applied Mathematical Modelling, 2022). If the public grid fails, the microgrid can enter island mode to keep providing electricity to some basic areas without interruption and ensure the supply of electricity. According to changes in the electricity demand at different times, intelligent control of the power output from renewable energy and energy storage facilities can be optimised.

2.6 Core Barriers to Enterprise Renewable Energy Adoption

Through pathway analysis and industry empirical data, it has been found that the four main obstacles to the green transformation of enterprises are economics, technology and security, policies and standards, and supply chains. As shown in Figure 2, the three primary obstacles to the current reform and development of the economy are financial pressure, technical barriers and policy uncertainty. The scores of all three dimensions are in the upper range of the radar chart, and the peak point is close to the outer boundary. Only the obstacle of a lack of talent is relatively mild compared with the other three factors, and it is a secondary contradiction.

The above results show that, among the current changes in Chinese enterprises, most have already formed a basic pool of transformation talent; however, three main problems in the process of transformation have not been solved: first, considerable financial pressure has been placed on them by high initial investment costs; Second, difficulties in applying new energy and power to industrial production are yet to be resolved; Third, the instability of relevant supporting policies has created an uncertain environment for the long-term planning of enterprise transformation. Therefore, it has been decided to focus on developing corresponding support policies for the next stage, and the design of the solution will be based on these three main problems.

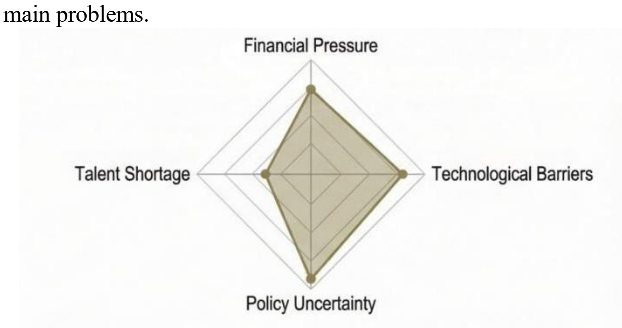

Figure 2: Impediment Factors Weight Analysis in Corporate Renewable Energy Transition

2.7 Economic Viability and Cost Recovery Constraints

Although the cost of grid-side generation for renewable energy is now at the same level as that of coal-fired power at the industry level, many individual enterprises still have serious economic difficulties in the initial stage of the transition. First, Stranded Asset Risks of High-Energy-Consuming Enterprises. China has over 120 GW of total installed capacity for industrial coal-fired captive power plants, most of which started operating after 2010 and will still be in good condition for more than 15 years; if they are prematurely closed due to the shift to new energy, the country will suffer stranded asset losses over 60 billion US dollars (CEC, 2024). Second, there will be an increase in the cost of hidden integration. From 2015 to 2023, although the LCOE of China's utility-scale photovoltaic and onshore wind power decreased by more than 70 per cent and 40 per cent respectively, ancillary service fees, grid connection charges and backup power fees have reduced the cost advantage for end-user enterprises of renewable energy and decreased the expected economic benefits of the transition (NEA, 2024; Guo & Zhang, 2024).

2.8 Renewable Energy Volatility and Energy Security Risks

Renewable energy is inherently intermittent, fluctuating and random, but industrial production requires a stable supply of energy with strong reliability and power quality, so there is a contradiction. Semiconductors, fine chemicals and precision machinery are all very sensitive to voltage sags and frequency deviations in the production process. According to the data released by the International Electrotechnical Commission (IEC) in 2022, even a voltage dip of only 10 milliseconds can lead to an abnormal shutdown of the semiconductor wafer production line and result in losses of more than US$2 million over a short period; In 2021, a power fluctuation accident at an eastern China manufacturing base caused a total economic loss of over US$14 million for the 12 high-precision machining enterprises (China Electric Power News, 2021). Wind and photovoltaic electricity are susceptible to changes in weather; therefore, they cannot provide continuous stable electricity or rotating inertia support, and as more of this green electricity is used by enterprises, there is a risk to the power supply stability.

2.9 Policy Mechanism Defects and International Standard Alignment Gaps

Due to the absence of good domestic multi-market coordination and different standards in China compared with other countries, enterprises have been subject to high material implicit compliance costs and policy uncertainty. Coordination among domestic green electricity trading, the GEC system and China's national carbon emissions trading market (ETS) has not yet been established. According to the 2023 survey, 47% of the export-oriented manufacturing enterprises are at risk of double counting in the environmental attributes of green electricity, and 38% have had problems deducting purchased green electricity from ETS compliance (China Renewable Energy Engineering Institute [CREI], 2023). With the implementation of CBAM and the spread of the RE100 initiative around the world, the standard has been changed from annual total-volume matching to hourly real-time matching of electricity consumption and renewable energy generation. Most of the green electricity trading and GEC issuance in China is settled annually or monthly; therefore, it does not meet the demands of foreign countries. According to a survey, 62 per cent of export-oriented enterprises have found that the domestic green electricity and GECs cannot comply with the EU's hour-by-hour matching rule and thus incur extra carbon costs and export restrictions (CREI, 2023).

2.10 Supply Chain Collaborative Emission Reduction Complexity

In light of the dual-carbon objectives, leading enterprises are facing more and more pressure to control not only their own operating emissions (Scope 1 and 2) but also Scope 3 emissions; these are all indirect greenhouse gas emissions that occur in the upstream and downstream links of a company's value chain and are not included in Scope 2 emissions, as per the GHG Protocol. For most manufacturing and brand enterprises, Scope 3 emissions are the largest part of their total carbon footprint; thus, supply chain collaborative emission reduction needs to be carried out in the process of the new energy era. There are two problems here. First, there is a serious lack of transformation ability in the main enterprise and its suppliers. Leading consumer electronics companies have more than 75% of their total carbon footprint in Scope 3 emissions, and more than 80% of their component suppliers are small and medium-sized enterprises (SMEs) with less than 5% renewable energy use; thus, it is difficult for these companies to achieve their goals of renewable energy. Second, there is information asymmetry. There is no unified supply chain carbon accounting platform and data-sharing mechanism; therefore, the main enterprise cannot obtain timely and accurate information on the use of renewable energy by hundreds or even thousands of suppliers for effective management and traceability of supply chain emissions.

3 Domestic and International Experience and Enlightenment

To solve the above problems, in this section, based on the policy systems and leading enterprise cases of China and other places, some effective ideas for Chinese enterprises will be proposed. China has released a number of policies in recent years to support distributed power generation, promote the construction of a green electricity market, fully build out the grid-connected infrastructure for the national electricity system (NEA, 2024), and reduce administrative obstacles for green electricity direct-connection projects at the local level. The new Renewable Energy Directive (RED III) of the European Union will introduce a comprehensive Guarantee of Origin (GoO) system to monitor the supply of green electricity at the hourly level and meet the demands for CBAM; at the same time, the US government has provided federal tax incentives for renewable energy projects to reduce the investment costs of enterprises (IEA, 2024). Apple Inc. is a leading company around the world that has achieved 100% renewable energy for all its global operations and introduced a "24/7 Carbon-Free Energy" plan to meet the varying demands of different times; Baosteel and CATL in China are typical cases that have built all-weather renewable energy facilities and started to supply green energy to the supply chain to promote upstream decarbonisation (Apple Inc., 2024; Baosteel, 2025; CATL, 2024).

Three basic enlightenments can be drawn. First, based on the size and nature of the business as well as other factors, select a development direction for renewable energy. Second, in light of the strengthened demands from the overseas market, the export-oriented enterprise should proactively organise hourly renewable energy matching. Thirdly, given the large scale of the leading enterprise, it can take the initiative in supply-chain collaboration to provide support for small and medium-sized enterprises by jointly purchasing, offering technical assistance and financial aid, etc.

4 Targeted Optimization Strategies Corresponding to Barriers

In response to the above four main obstacles, this section will present targeted optimisation plans one by one.

4.1 Alleviate Economic Viability Barriers Through Targeted Green Financial Innovation

Financial assistance will be given to reduce the burden of initial investment and stranded asset risk, etc. First, the bank can introduce new green loan products to help enterprises finance the construction of new-generation power plants, and extend the repayment period and reduce the interest rate of "carbon-neutral loans". Secondly, in order to advance the construction of carbon-neutral bonds, the financing interest rate will be based on the quantity of renewable energy used by enterprises and the emission reduction results they have achieved; at the same time, a transition financing system for energy-intensive industries should be established to support the orderly disposal of fossil fuel assets and reduce the risk of stranded assets. In addition, the relevant department in charge of the government can establish a special fund for the transformation of renewable energy to provide subsidies and low-interest loans to small and medium-sized enterprises for their renewable energy projects, and the power regulator can optimise the ancillary service cost-sharing mechanism to reduce the operating costs of enterprises using renewable energy.

4.2 Mitigate Energy Security Risks Through Technology Integration and AI-Empowered Management

The joint application of energy storage, digital technology and artificial intelligence is being promoted to address the fluctuation of renewable energy and improve the stability of power supply. Firstly, the company can increase investment in intelligent energy management systems and apply Internet of Things (IoT), big data, artificial intelligence (AI), etc., to predict the demand and output of renewable energy more accurately and achieve dynamic balancing of energy supply and demand. Second, accelerate the scaled application of energy storage technology: According to the load characteristics of enterprises and the output of renewable energy, reasonably arrange electrochemical energy storage facilities to reduce on-site energy consumption, smooth out fluctuations in power output, provide backup power support, and for enterprises with high power quality requirements, design dual power supply and multi-energy complementary systems to reduce the risk of production interruption due to power fluctuations. At the same time, the government can increase investment in the research and development of fundamental technologies for the long-term development of energy storage and provide technical support for enterprises.

4.3 Improve Policy Coordination and International Alignment via Multi-Market Synergistic Mechanism

To solve the problem of domestic multi-market misalignment and the lack of hour-level matching in international hour-level alignment standards, regulators and enterprises should work together to optimize the synergistic mechanism and promote international alignment. First, national authorities should clarify the unified recognition of the environmental value of green electricity across the country, define the "zero-emission" attribute of green electricity consumption in the unified carbon accounting system, establish GECs as the sole legal voucher for the environmental attribute of green electricity, and standardize the full-life management of GECs to address the fundamental problem of double counting. Figure 3 shows the synergistic operation flow of China's green electricity market, GEC market and ETS, and the main logic is to realise unified verification and one-time write-off of environmental attributes to avoid repeated deduction. Second, to achieve automation, an open-data interface can be established between the power-trading centre and the carbon-trading centre to send green-electricity-transaction data to the carbon-emission-reporting system automatically and thus reduce the cost of enterprise compliance, etc. Thirdly, speed up the progress of alignment with foreign standards. The regulatory authorities should improve the accounting and traceability system for green electricity and GECs to the hour level, introduce standardised hourly GEC certificates, and export-oriented enterprises need to proactively carry out hourly matching pilots and construct internationally compliant accounting systems to avoid extra carbon costs.

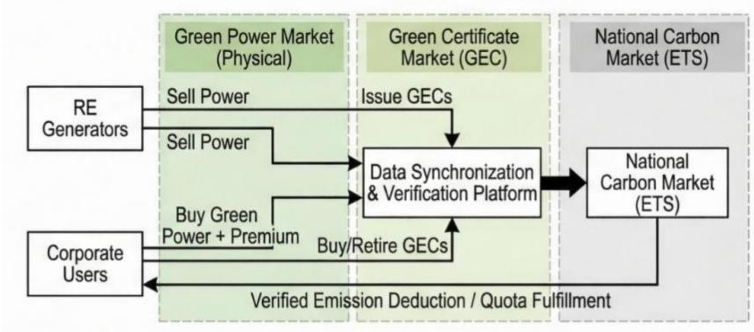

Figure 3: Synergistic Operation Flow Design of China's GreenPower, Green Certificate, and Carbon Trading Markets

4.4 Promote Supply Chain Collaborative Emission Reduction Through Green Supply Chain System Upgrade

To address the imbalance in transformation capacity and information asymmetry of the supply chain, the leading enterprises in the chain should take the initiative to build a regular collaborative emission reduction system. First, the proportion of renewable energy and carbon emission levels of the enterprise should be included in the standard for supplier access, performance evaluation and incentive mechanisms, a clear low-carbon procurement threshold and a grading incentive system should be established to motivate suppliers to increase the use of renewable energy. Second, the leading enterprises should build a green management and carbon data-sharing platform for the supply chain to provide technical support, talent training, low-carbon solution assistance, etc., and boost the low-carbon development capabilities of upstream and downstream small- and medium-sized enterprise suppliers. At the same time, explore the "joint procurement" model for green electricity and GECs, have the main enterprise negotiate with renewable energy generators on behalf of the entire supply chain to obtain preferential prices through economies of scale, thus reducing the cost of green power acquisition for small and micro enterprises. The industry association can also promote the construction of an all-round carbon accounting norm and data management system for the supply chain, realise real-time monitoring of emissions and renewable energy data in the supply chain, etc.

5 Conclusion

To achieve carbon neutrality, there will be fundamental changes in the whole of China's energy system; thus, for enterprises, using renewable energy is no longer an option but a necessary strategy to meet the new demands of environmental protection, economic development and social progress. The five main pathways of enterprise adoption of renewable energy in this paper will be studied systematically, the conditions for their application, their economic attributes and compliance effects will be clarified, and four binding constraints on the transition will be identified: lack of economic feasibility, energy security risks due to fluctuations in renewable energy, misalignment of policies and standards, and complexity of supply chain collaboration for emission reduction. According to policies and enterprises abroad and at home, specific optimisation plans will be proposed in this paper to directly address the problems mentioned above. The aim of this paper is to add new theoretical ideas to the microscopic study of corporate renewable energy decisions in the background of dual-carbon goals and provide some practical references for enterprises with different endowments on how to choose a reasonable transition path and deal with binding constraints.

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