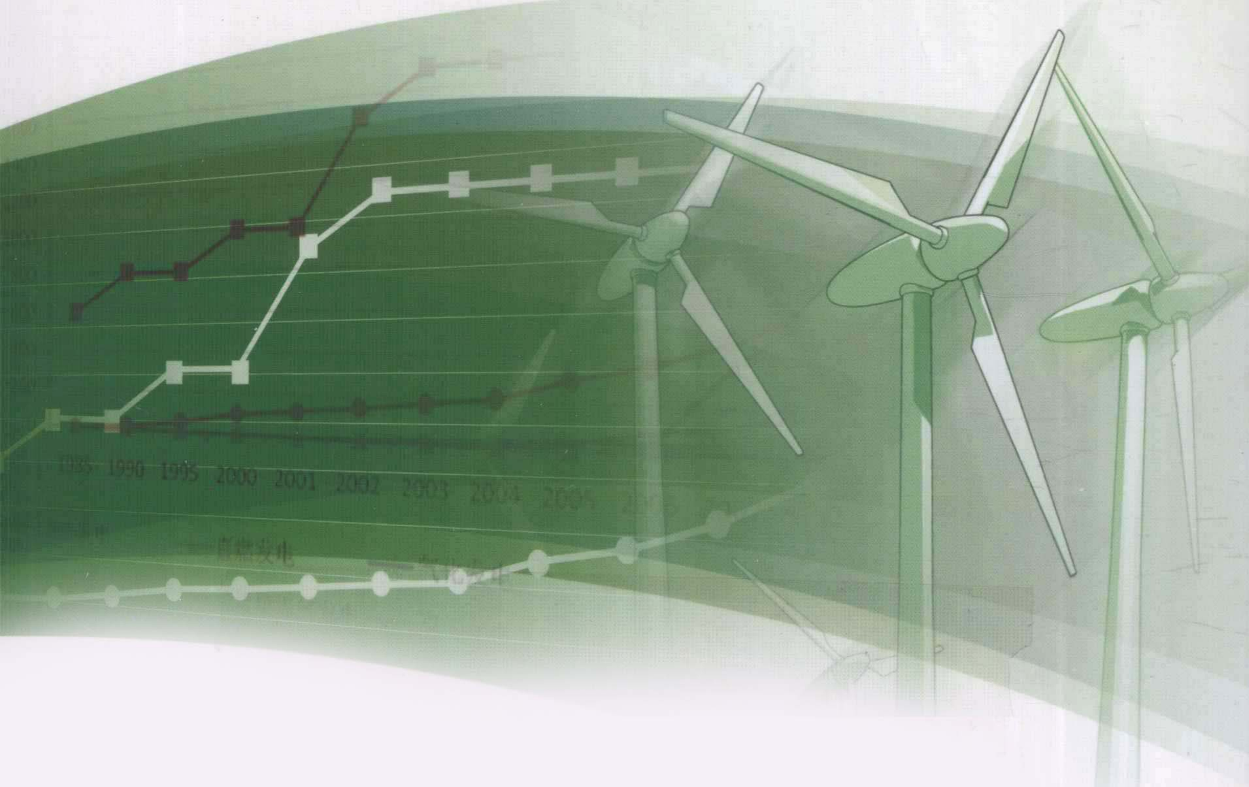
中国可再生能源发电经济性和经济总量

TECHNO-ECONOMIC EVALUATION OF CHINA'S RENEWABLE ENERGY POWER TECHNOLOGIES AND THE DEVELOPMENT TARGET

高虎　樊京春 著



中国环境科学出版社

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中国环境科学出版社·北京

图书在版编目(CIP)数据

中国可再生能源发电经济性和经济总量 / 高虎著.
—北京: 中国环境科学出版社,2010.9

ISBN 978-7-5111-0369-7

Ⅰ. ①我… Ⅱ.①高… Ⅲ.①再生资源:能源—发电
—经济分析—中国 Ⅳ.①TM61

中国版本图书馆 CIP 数据核字(2010)第 180532 号

责任编辑 高 峰
责任校对 扣志红
封面设计 兆远书装

出版发行 中国环境科学出版社
(100062 北京东城区广渠门内大街 16 号)
网 址:http://www.cesp.com.cn
联系电话:010-67112739(第三图书出版中心)
发行热线:010-67125803,67130471(传真)
印 刷 北京东海印刷有限公司
经 销 各地新华书店
版 次 2010 年 10 月第 1 版
印 次 2010 年 10 月第 1 次印刷
开 本 787×1092 1/16
印 张 17.5
字 数 320 千字
定 价 66.00 元

序

进入 21 世纪，能源安全和环境保护已成为全球化的问题。各国政府高度重视发展可再生能源，将其作为缓解能源供应矛盾、振兴国家经济、减少温室气体排放和应对气候变化的重要措施。纷纷制定了宏大的发展目标和一系列激励政策，引导、鼓励可再生能源的发展。

2005 年我国颁布了《可再生能源法》。在强大的法律及陆续出台相关配套政策的鼓励和引导下，我国可再生能源产业有了长足的进步，特别是以各类发电技术最为成熟，包括风电、太阳能光伏、生物质能发电等领域已基本跨越产业发展的起步时期，为我国规模化开发利用可再生能源提供了有力保障。即使在“十一五”末期世界金融危机引发全球经济衰退的宏观背景下，我国可再生能源产业和市场仍然保持了持续发展，风电装机连续四年翻番，太阳能光伏电池产量连续三年位居世界第一，各类生物质能发电市场规模稳步扩大。这些成绩标志着我国可再生能源产业开始步入全面、快速、规模化发展的重要阶段。

虽然我国可再生能源产业取得了明显进步，但总体来说，若实现大规模补充和替代常规化石能源，特别是实现 2020 年非化石能源满足 15%能源供应以及 40% ~ 45%碳强度降低的宏大目标，还面临着不少技术、产业、经济方面的挑战。一方面，可再生能源作为一个新兴能源，其经济性一直在不断改善，但当前，还需要在国家政策的支持下，才能参与市场竞争，从而限制了它的进一步应用。另一方面，尽管我国已经制定了较为完善的可再生能源支持框架和宏大的发展目标，但在既有的能源成本核算体系中，可再生能源“环境友好性”的收益并没有被纳入其中，这反过来影响了社会对可再生能源产品处在同一环境水平下经济性的判断，从而影响了市场参与者的行为。

《我国可再生能源发电经济性和经济总量》一书深入剖析了我国各类可再生能源发电的成本，并在考虑化石能源环境外部性的基础上，核算了我国合理的可再生能源经济总量。本书首次绘制了我国可再生能源发电的供应曲

线，提出并建立了衡量环境友好能源项目的新方法、新思路；提出了鼓励配额交易将在很大程度上降低可再生能源的开发成本和有利于支持西部大开发的国家战略实施等观点，还相应地提出多项有可操作性的建议。

本研究在同类研究中具有开创性的意义。本书可以作为能源、价格、财税等决策部门的参考，也可以为地方政府发展可再生能源提供思路，还能为从事和关心可再生能源发展的业界同仁以及社会人士提供新信息和新观点。在当前我国可再生能源事业科学、健康蓬勃发展的大好形势下，本书的出版具有很好的现实意义。希望她能成为各位读者案头的必备书籍，常读常新。

中国工程院院士 黄其励

2010 年 8 月

Preface

In the 21st century, energy security, together with environmental protection has become the global hop topics concerns. The governments attach great importance to developing renewable energy (RE), regarding it as an important measure to mitigate energy supply pressure, recover economy, reduce greenhouse gas emissions and address climate change issues. In this respect, a series of ambitious development goals and incentives have been developed to guide and encourage the RE sustainable development.

The promulgation of "China Renewable Energy Law" in 2005 greatly promotes Chinese's RE industry's development. Especially the generation technology, among which the wind power, solar photovoltaic, biomass power generation have already gone through the starting period, providing sound guarantee for the development of China's large-scale RE development. Even encountering the global financial crisis, China's RE industries and the market still keep a steady development, with the wind power installed capacity doubled for the fourth consecutive year, the production of solar cells ranking first in the world for the third consecutive year and the diversified biomass power generation markets have steadily expanded. These achievements mark the beginning of large-scale development of RE industry.

Despite all these achievements, the realization of massively supplementing and substituting conventional fossil energy remains facing with many technical, industrial and economic challenges, especially towards the 2020 goal that the non-fossil energy meets 15% of the energy needs and the carbon dioxide intensity should be reduced by 40% ~ 45%. On the one hand, RE development highly depends on the national policy support, which restricts its further application. On the other hand, RE's "environment-friendly" benefits haven't been incorporated into the cost and pricing system, which in turn affects the real economic evaluation of the RE products, and therefore further affects the behavior of market players.

The book "Techno-Economic Evaluation of China's Renewable Energy Power Technologies and the Development Targets" analyzes in-depth the generation costs of China's various types of renewable energy. Based on the evaluation of the environmental externalities of fossil fuels, the research examines China's real economic general quantity of RE power. This book first presents the supply curve of China's RE generation. Furthermore, the new method and ideas for evaluating environment- friendly RE projects are provided.

This book could be used as a reference for energy, pricing, and other policy-makers as well as to provide ideas for local governments to develop renewable energy plans. With the dramatic development of RE industry in China, it is hoped that this book could offer some new information and ideas for the readers.

HUANG QiLi
Academician
Chinese Academy of Engineering
August, 2010

前　言

进入21世纪，能源安全和环境保护已成为全球化的问题。各国政府高度重视发展可再生能源，将其作为缓解能源供应矛盾、减少温室气体排放和应对气候变化的重要措施，纷纷制定了发展战略和一系列激励政策，引导、鼓励可再生能源的发展。围绕传统化石能源的资源性争夺持续影响地缘政治和经济格局的同时，全球范围内，着眼于新能源技术制高点以及未来全球产业布局的新一轮战略性争夺也开始甚嚣尘上，日趋激烈。

虽然同样可以提供电力、燃气、液体和固体燃料，但是，包括可再生能源的资源评价、基础技术、产业能力、行业人员、社会成本分摊能力等在内的多项要素，在全球范围内都还无法为消费者提供可与传统能源相竞争的能源产品——同时满足经济可行、技术可靠、质量稳定等要求，从而大大限制了可再生能源的规模化应用。

总的来看，当前各国可再生能源的能源贡献率还非常低，大部分可再生能源产品离开政策的支持无从发展。对决策者和市场参与者而言，对可再生能源的关注主要集中在两点：一是技术可行性。不同于对“资源”争夺激烈的化石能源，可再生能源资源的开发，必须立足于现代装备制造技术，才能将风力、太阳能、生物质能等自然资源转化为可用及可控的能源；从某种程度上来说，可再生能源产业的发展进程，就是新兴装备技术的发展进程。二是经济可行性。只有可再生能源资源的开发代价低于某种水平，才能让消费者大规模地接纳，从而达到对化石能源的实质性替代。

值得庆幸的是，当前可再生能源基本没有技术、环境等方面不可克服的致命缺陷，从而使得开发可再生能源获得了社会一致的认可和期待。同时，现有技术和实践不断验证了各类技术的可行性，如即使风力发电有噪声、光伏发电产品需要消耗一定的能源、生物质能的发展也依赖于作物的生长等先天性缺陷，但这些领域都具有方向可知的二代，甚至三代技术降低这些负面因素的影响，从而使得通过技术进步改善产品的经济性不断从“可能”变为“现

实”。因而，全球可再生能源产业的成长不断超出社会各界的预期，表现出强势的发展势头。

但令人遗憾的是，包括我国在内的多数国家，在衡量可再生能源产品经济性时，都没有将化石能源的环境外部性成本考虑在内，即化石能源开采、转换和消费过程对环境所造成的不可逆性损害成本都被“忽略了”。因而，所进行的与可再生能源相关的成本效益分析，没有从全社会的角度进行合理的、定量性评价，从而影响了对可再生能源实际经济性的科学判断。这些外部性成本，对于可再生能源而言，都是可以避免的。换言之，这是可再生能源的“隐性效益”，而没有被实际纳入经济性的核算。

本书对各类可再生能源发电技术进行了梳理，细致分析了在我国开展各类发电技术的资源基础、技术条件、产业现状和市场应用前景，特别是在模型工具的支持下，对化石能源的环境外部性进行了量化分析，并在此基础上分析了我国“可经济开发”的可再生能源发电总量：作为最大的发展中国家，我国可再生能源的发展，必须更加注重合理技术的选择，并更多地考虑技术经济性；制定未来的发展目标，也必须更好地考虑环境外部性等因素。在 2009 年我国在国际上做出了非化石能源满足 2020 年 15%能源需求的政治承诺，以及正式提出 2020 年单位 GDP 二氧化碳排放强度降低 40%~45%的定量目标后，全社会对未来我国可再生能源的发展规模和节奏提出了更高的期望和要求，“可经济开发”的总量，无论对于政府制定规划目标，还是市场参与者进行项目开发和产业建设，都具有极大的参考价值。

本书是世界银行 ESMAP 项目资助“我国可再生能源发电经济总量目标评价”课题的研究成果。课题是在世界银行北京代表处能源官员彭喜明先生的指导和帮助下完成的，世界银行能源专家 Noureddine Berrah 对课题研究思路提供了无私的指导，胡明先生对世行开发的 REEAM 模型（可再生能源经济分析模型，Renewable Energy Economic Analysis Model）进行了改进，使得此次研究得以实现。此外，课题得到了国家能源局新能源和可再生能源司的指导和大力支持，国家发改委能源研究所韩文科所长、李俊峰副所长、王仲颖副所长对课题进行了高瞻远瞩的指导，能源所可再生能源发展中心的同事秦世平、时□丽、任东明、胡润青、赵勇强对课题提供了全面的技术支持。此外，中

国水电顾问集团公司、中国风能协会、中国资源综合利用协会可再生能源专业委员会、北京计科能源公司也对课题开展提供了帮助。清华大学的博士生张达参与了课题资料的搜集和分析，这里一并表示感谢。

研究完成时间是2009年底，此次出版增加了2009年可再生能源产业的一些最新信息。由于时间很短，这部分内容没有及时翻译成英文，但并不妨碍英文读者对于研究方法和结论的理解，在此说明。

由于时间和水平有限，文中难免存在错误或疏漏，恳请读者批评指正。

作者

2010年8月

Foreword

In the 21st century, energy security and environmental protection have become the global issues, and aroused all governments' attentions to develop renewable energy (RE). Taking it as an important measure to ease energy supply pressure, reduce greenhouse gas emissions and address climate change, many governments have established strategies and a series of incentives to support RE's development. In pace of the intensive concerns for secured fossil energy supply, strategic deployment and input for new and emerging energy technology become increasingly intensified.

Comparing with fossil energy, renewable energy could already supply electricity, gas, liquid and solid fuels. However, it is a global problem that RE resource evaluation, technology, industrial capability, professionals as well as social cost-sharing capabilities are not mature enough to make the RE products competitive with conventional energies, in terms of cost-effective, credible technology and stable quality, which largely restricts the large-scale application of renewable energies.

On the whole, RE's contribution to the energy mix is very limited and most of its products highly depend on policy supports. For the policy makers and market participants, their attention is on two parts of RE: the technical feasibility and cost-effectiveness. Unlike the fossil energy that cares most about the resource, the development of RE more concerns about modern equipment and technology that could turn wind, solar, biomass and other natural resources into usable and controllable energy. In this respect, the development process of RE industry is somewhat an evolvement process of advanced equipment and technology. On the other hand, only by lowering the development costs to a certain level can the RE be accepted by consumers and become a real alternative to fossil energy.

Fortunately, the current renewable energy doesn't have any fatal technical or environmental shortages, which wins itself social recognition and expectations. Meantime, researches and practices have verified the feasibility of RE technology that makes the realization of lowering the costs of RE products through advanced technology improvement. Under such a circumstance, the global RE industry continues to grow beyond the expectations of the society, showing a strong momentum of development.

The unfortunate part is, in most countries including China, the environmental external costs of fossil energy such as its irreversible damages to the environment in the course of exploration, conversion and consumption haven't been taken into account when evaluating the cost-effectiveness of RE products, to whom could be avoided. Therefore, RE-related cost benefit analysis isn't rational or quantitative enough, which fails to form a scientific judgments of RE's real cost-effectiveness that takes RE's "invisible benefits" into consideration.

In this book, all kinds of RE power generation technology in China are carefully analyzed, covering their resource potential, technology availability, industry basis and market prospects. Using certain models, this book has also quantitatively analyzes the environmental externality of fossil energy and accordingly come up with the general economical generation capacity in China. In 2009, China has committed to achieve the goal that non-fossil energy sources meets the energy needs of 15% and reduces carbon dioxide intensity by 40% to 45% in 2020, which brings forward higher expectation and demands for scaled and fast RE development in China. As a developing country, China needs to develop the REs in a more rational and economic way. The establishment of future targets should also take the environment into more consideration. The evaluation of general economical developable generation capacity may provide a good reference for the policy making, project development as well as industry construction.

The project is completed at the end of 2009 and drafted in Chinese. This part was a translation on basis of the Chinese version. Some latest information of 2009 RE industry are updated in this book prior to the publication. Owing to the limited time for translation work, the newly added paragraphs are not available in the English version, however, definitely does not hinder the readers to understand the contents. It is hoped that the book could provide research references for the readers and it is highly appreciated for any kind feedbacks.

Angust 2010

执行总结

我国当前处于可再生能源规模化发展的初期阶段，与常规能源相比，可再生能源产品仍具有成本较高、市场竞争力较弱和规模较小等特点。截至2009年年底，全国可再生能源年利用量总计为2.7亿tce（不包括传统方式利用的生物质能），约占一次能源消费总量的8.7%，其中不包括大水电在内的可再生能源发电装机总量约8 592万kW。

为了更好地支持和引导可再生能源的发展，我国已经建立了可再生能源的政策框架，已颁布的中长期可再生能源发展规划及酝酿中的产业促进目标，装机容量合计为130 GW和269 GW，折算为电量分别为5 329亿kWh和8 569亿kWh。

不过，当前我国可再生能源总量发展目标的制定，都是建立在可再生能源"市场内部成本"的考虑之上，在当前能源产品的市场形成机制中，没有将常规能源的"环境外部性"成本考虑在内，从而影响了对可再生能源实际经济性的判断，进而会影响"可经济开发"可再生能源总量的确定。

本项研究为了真实评价可再生能源发电的经济性，在分省项目统计的基础上，对所有项目的开发成本进行了核算，描绘了全国（及省级）可再生能源"可开发电力总量"与"开发成本"之间的对应关系，建立起了可再生能源电力的"供应曲线"，并通过计算常规电力（主要是煤电）的环境外部性成本，得到了实际的发电经济可开发总量。

本书的主要研究结论为：

（1）通过基于不同的煤电环境损害标准，本文考虑了"低环境"和"高环境"两个基础方案，得出未来我国可再生能源发电的"经济总量"分别为6 368亿kWh和10 791亿kWh，装机容量为160 GW和314 GW，分别可替代1.97亿tce和3.34亿tce。

（2）燃煤发电的环境损害随经济发展水平、人口密度等因素的增加而增加。两个环境方案中的全国平均燃煤发电（单位发电量）外部性成本分别为

0.156 元 /kWh 和 0.873 元 /kWh；考虑燃煤发电的平均发电成本后，两个环境方案下，全国燃煤发电的真实社会成本分别为 0.511 元 /kWh 和 1.23 元 /kWh。

（3）通过对"高环境方案"结果的测算，2020 年我国发展可再生能源的年环境效益为：减排二氧化硫 98 万 t，氮氧化物 70 万 t，颗粒悬浮物 47 万 t，而对二氧化碳的减排量高达 3.0 亿 t。

（4）敏感性分析显示，煤炭成本、环境损害标准都会影响本文确定的"经济性"基准，因而也是研究的关键敏感性因素。在不同的环境标准下，可再生能源成本的降低对研究结果的敏感性程度有所差异，环境标准越低，成本下降的敏感程度越高。

为了更好地促进可再生能源的发展，本文建议：

（1）应合理评价发展可再生能源的真实社会经济成本，并以此不断调整可再生能源总量目标，落实实现总量目标的措施。

（2）在当前电力价格机制还没有考虑煤电环境外部性的情况下，对于风电和光伏发电来说，必须在推动技术进步、不断促进生产成本下降的同时，继续给予持续稳定的价格补贴政策，才能进一步有效推动这些资源的开发。

（3）为了更好地鼓励对发电量的考核，同时兼顾促进制造业的发展，建议设定总的发电量（TWh）目标，同时设定各个产业发电装机规模（GW）目标。

（4）由于产业化进程存在差异，对于未来成本存在较大不确定性的技术，宜于结合实际需要采取合适的电价政策，特别是对于处于产业成长期的光伏而言，电价政策的制定更需要有特殊考虑。

（5）在市场发展初期，固定电价政策比较适合促进产业的发展；随着市场规模的扩大，以及市场主体参与程度的不断深入，可以考虑结合配额制政策的实施。

Executive Summary

Renewable energies, inclusive of the wind power, solar power, biomass power etc, remain the initial stage to be developed in China. It is featured by the high cost, less market competitiveness and small market size. By end of 2008, China witnessed the contribution of the entire RE (excluding the traditional biomass utilization) with a total of almost 250 million tons of coal equivalent (TCE), amongst of which hydro contributed close to 200 million TCE and other REs provided 50 million TCE. This increased the share of RE from 7.5% in year 2005, when the CREL was announced, to 9% in year 2008. Notably, the capacity of RE power (excluding large hydropower) is aggregated to 66.47 GW.

China has established the RE-promotion policy framework, which can be highlighted by the medium- and long-term development targets and the more ambitious promotion targets that is still under draft. As per these planning, by year 2020, the installed capacity of non-large hydropower RE power in China could be aggregated to 130 GW and 269 GW, with the electricity output of 532.9 TWh and 856.9 TWh respectively.

Nevertheless, the existing RE planning work in China, all built upon the cost analysis system that ignore any *externality cost*. As such, the existing power tariff system don't take consideration of the environmental damages imposed by burning fossil fuels, which has extensively been recognized as the benefits of exploring RE. Accordingly, the real cost-effectiveness of RE power was not appropriately estimated, and further, will impact the planning process to identify the optimal RE power quantity.

The study, in order to investigate the real cost-effectiveness of RE power in China, makes the cost analysis of all of the RE power projects on a provincial-statistical basis, and depicts the national RE power supply curve, which shows the relationship of development cost and RE power quantity. By monetizing the externalities of coal-fired power (dominant in China), the actual national optimal, i.e. economically-viable RE quantity is derived from the curve.

The key conclusions in this study are as following:

- Two base cases, i.e. *Dark Green Case* (DG) and *Light Green Case* (LG), are created on basis of different external cost criteria, to better reflect the different scenarios of environmental concern in the future. The optimal RE power is 636.8 TWh and 1 079.1 TWh for the two cases respectively, with the power capacity of

160 GW and 314 GW, which could be as much as 197 million TCE and 334 million TCE.

- There are great disparities for external cost of coal-fired power in different provinces, impacted by factors like economical level, population density etc. The national average external cost of coal fired-power is estimated to be 0.156 Y/kWh and 0.873 Y/kWh under two cases. Accordingly, the actual social cost for coal-fired power in China is 0.511 Y/kWh and 1.23 Y/kWh.
- The LG case shows that by year 2020, the environmental benefits by exploring the RE power could help to reduce: SO_2 by 980 000 tons, NO_x by 700 000 tons, TSP by 470 000 tons and 300 million tons of CO_2 annually.
- The key factors that will impact the baseline of this study are the coal price, external cost, production cost of RE power etc. A sensitive analysis illustrates that coal price and external cost of coal-fired power will impose the same influence in determining the optimal RE quantity. Whereas, the sensitivity of the optimal quantity on the RE power cost will get less when the environmental criteria is getting higher.

The following recommendations are put forward in this study:

- There is a need to evaluate the actual cost of RE power by considering its environmental benefits during the RE power planning process.
- Under the current circumstances that no externality is considered, there is a need to provide stable and continuous subsidy policy instruments, i.e. favorable tariffs, for wind power and solar PV power, even their production costs are showing an obvious reduction trend by technology improvement and market scale-up.
- The total electricity output target (TWh) for RE power, further on the installed power capacity (GW) target, are recommended to be created in order to clearly evaluate the energy contribution from the RE power, as well as to guide the individual RE market and respective manufacturing industry.
- A differentiated pricing system is suggested to be established, to better reflect the disparities of RE industrial process. Particularly for those power technologies whose costs are facing great uncertainties, e.g. solar PV power, the pricing system needs to pay special attention to allow the industries' growth.

At the initial stage, a feed-in-tariff policy favors the growth of an industry. With the expansion of the market and the deep participation of majority market players, a tradable quota system could be a more cost-effective approach to follow.

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