

Partial retirement



REPORT by Peter Haan and Songül Tolan

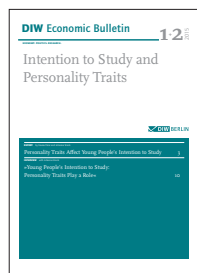
Partial retirement: effects on employment and implications for government budgets

491

REPORT by Claudia Kemfert, Thorsten Burandt, Karlo Hainsch, Konstantin Löffler, Pao-Yu Oei, and Christian von Hirschhausen

Nuclear power unnecessary for climate protection—there are more cost-efficient alternatives

498



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Partial retirement: effects on employment and implications for government budgets

By Peter Haan and Songül Tolan

The demographic change is posing many challenges for government budgets. In the face of a shrinking work force, keeping the number of workers and thus pension contributors at the highest possible level is a key economic policy goal. This could be achieved if people retire from the work force later in life. Partial retirement, the option to work part-time while drawing a pension before reaching the normal retirement age, could create the necessary conditions for reaching this goal. The impact of partial retirement on employment will be simulated below. The results show that unrestricted access to partial retirement can lead to an increase in employment volume and generate positive fiscal effects. The effects on employment are especially positive when the entry age for partial retirement coincides with the early retirement age of 63. Flexible retirement, which came into effect in 2017, allows people to receive a partial pension payout before the normal retirement age while still working. However, the computation behind the amount of pension payouts during flexible retirement is very complex. In addition, the limit to pension payouts in flexible retirement could be considered too strict. This negatively affects the attractiveness of the flexible retirement option. Furthermore, work hours can only be reduced in the case of flexible retirement if the employer agrees. If an evaluation of flexible retirement shows that few people make use of it, policymakers would have to simplify the rules regarding additional income and consider a statutory right to partial retirement before the normal retirement age, with possible exceptions for small businesses.

The demographic change poses a challenge for pension insurance systems. In particular, pay-as-you-go pension systems face the issue of more and more beneficiaries with ever fewer contributors due to an aging population.¹ To counteract this development, multiple reforms have been implemented in Germany since the 1990s which have raised the retirement age and reduced the possibilities of retiring early. These include the introduction of pension deductions for early retirement (1992), raising the early and statutory retirement ages for different population groups (1999, 2007), and creating stricter eligibility requirements for disability pensions (1999). The average retirement entry age since the end of the 1990s has risen from about 62 to 64 as a result of these reforms, among other things.²

Increasing the flexibility of the retirement transition can raise the average retirement age

Increasing rigid age limits is problematic if certain parts of the population fail to extend their employment accordingly. An additional option for changing the retirement age is to increase the flexibility of the retirement transition before the normal retirement age. The advantage of increasing the flexibility is the compatibility of a high degree of individuality in making decisions about retirement and incentives for retiring later in life. People can use this flexibility to adjust their retirement decision to their individual circumstances. There are many different ways to increase the flexibility of the retirement entry age.³

¹ Between 1992 and 2014 alone, the share of the German population over 64 increased from 15.3 to 21.5 percent, one of the highest proportions in the OECD comparison. Cf. OECD (2017): Labour force statistics (available online).

² German Statutory Pension Insurance Scheme (2016): Rentenversicherung in Zeitreihen, pg. 138 (in German) (available online).

³ Models for a flexible retirement transition differ in many aspects, such as eligibility prerequisites, financing, entry age, amount and timing of pension payments, specified working hours, and whether they are organized or supported by the state.

One variant of this increased flexibility is partial retirement.⁴ Partial retirement allows for a reduction in working hours in combination with partial pension payouts before fully retiring. The partial retirement discussed in this week's Economic Bulletin is a stylized partial retirement scheme based on Dutch occupational partial retirement schemes. In this type of partial retirement, a person works 50 percent of a full-time position. Their income is a combination of their part-time wages and partial pension payout.⁵ The part-time wages equal exactly half of the equivalent full-time salary minus the corresponding taxes and social security contributions. The pension share of partial retirement income is equal to half of the equivalent full pension at the time of entry into partial retirement, whereby there are pension deductions in the amount of 3.6 percent on pension payouts for every year people retire before the normal retirement age. During partial retirement, pension contributions continue according to part-time earnings. People in partial retirement receive the other 50 percent of their pension entitlements when they fully retire. Deductions on half the pension remain over the entire term of the pension payout.

To determine the effects of such a partial retirement scheme, an empirical analysis of retirement behavior is carried out. The simulation depicts the main elements of the German pension system and focuses on West German men born between 1940 and 1947 (Box).⁶

Flexible retirement,⁷ which came into effect in Germany in 2017, is similar to partial retirement in that the income from part-time employment is combined with a partial pension. Partial pension payouts as well as earned income can be drawn starting at the early retirement age⁸ of 63 in flexible retirement. Getting rid of rigid supplementary income limits such as those that were present in an

earlier partial retirement scheme⁹ may have increased the attractiveness of flexible retirement.¹⁰ However, in flexible retirement, there is still a reduction rate of 40 percent of the additional income after the deduction of the 6,300 euro yearly allowance on pension payouts.¹¹ Due to the complexity of this scheme and the high reduction rate, flexible retirement is somewhat less attractive in comparison to partial retirement, which is examined in this study.

Flexible retirement also facilitates working past the normal retirement age, but that expansion is not covered in this Economic Bulletin. Instead, the focus is on the time before reaching the normal retirement age.

Furthermore, there is another important difference between partial and flexible retirement. It is assumed that all people who qualify for early retirement have unrestricted access to partial retirement. However, flexible retirement does not guarantee an unconditional right to work part-time. One may apply to have their work hours reduced when employed at a company with at least 15 employees, but this request must first be approved by the employer. The right to apply for part-time work does not exist in companies with fewer than 15 employees.¹²

Policy simulations based on a structural model

The empirical analysis uses a dynamic structural model that reflects retirement decisions (Box). This model allows for an analysis of the employment effects of partial retirement as well as its impact on government budgets. The model is estimated on the basis of "Biographical data of select social insurance agencies in Germany" (*Biografiedaten ausgewählter Sozialversicherungsträger in Deutschland*, BASiD),¹³ a data set covering the birth cohorts 1940 to 1947. BASiD contains the necessary information regarding employment and earnings histories as well as pension entitlements.

Based on the estimated parameters of the structural model, two stylized forms of partial retirement are

⁴ The most widespread type of flexible transition into retirement in Germany is part-time work for elderly employees (*Altersteilzeit*, ATZ). The legal framework conditions are regulated by the German Partial Retirement Law (*Altersteilzeitgesetz*). Employees aged 55 years or older may apply for ATZ provided they meet the prerequisites. Access is governed by collective agreements or at the company level. Compensation payments of 20 percent and 40 percent of the corresponding full-time equivalent for wages and pension contributions, respectively, is paid. At the latest, the ATZ ends at the time of the normal retirement age. However, people in ATZ often use the block model variant, which in fact equals early retirement. Due to the cessation of financial support by the Federal Employment Agency on October 1, 2010, ATZ is in the process of being phased out (cf. also Bundesagentur für Arbeit (2015): *Arbeitsmarkt in Zahlen. Altersteilzeit nach dem Altersteilzeitgesetz* (in German, (available online)).

⁵ A different division between gainful employment and retirement pay would in principle also be possible.

⁶ Cf. Songül Tolan (2017): The effect of partial retirement on labor supply, public balances and the income distribution: Evidence from a structural analysis. DIW Discussion Paper 1679 (available online).

⁷ Cf. Federal law gazette 2016, part I, 59.

⁸ This term refers to the earliest possible age limit for receiving an early retirement pension.

⁹ The flexible retirement scheme has a predecessor. It enabled a partial pension payout in the amount of one-third, one-half, and two-thirds of the full pension before reaching the normal retirement age. Individual supplementary income limits applied to each payout amount. Exceeding these limits by one cent caused a reduction to the next lower payout amount and corresponding reclaims.

¹⁰ Cf. Martin Gasche und Carla Krolage (2011): Gradual transition to retirement with flexible partial retirement. MEA Discussion Paper 243-2011 (in German) (available online).

¹¹ If the amount of this combined income exceeds the best income of the last 15 years, the individual supplementary income cap will apply. Pension payouts in flexible retirement decrease by 100 percent of the excess amount.

¹² Cf. *Teilzeit- und Befristungsgesetz* § 8 (in German) (available online).

¹³ Daniela Hochfellner, Dana Müller und Anja Wurdack (2012): Biographical data of social insurance agencies in Germany—improving the content of administrative data. *Schmollers Jahrbuch* 132(3), 443–451.

Box

Structural dynamic model of retirement decisions

An economic decision model is used for the empirical analysis.¹ The basic structure of the model goes back to Rust's dynamic decision model (1989),² which is widely used in economic retirement research. It reflects the choice between continuing to work full time and leaving the work force by one of three different retirement paths. These retirement paths are: (1) regular retirement (2) retirement after unemployment, and (3) retirement via partial retirement. The decisions are made under uncertainty. The mortality risk and the risk of involuntary unemployment are explicitly taken into account. The mortality risks are based on the mortality tables from the Federal Statistical Office (*Statistisches Bundesamt*, Destatis). The risk of unemployment is displayed with the help of a regression based on data from the Socio-Economic Panel (*Sozio-ökonomisches Panel*, SOEP).³ The data contain information about layoffs, business closures, and fixed-term contracts.

In addition, the model implements an approximation of the tax and transfer system as well as the rules and conditions of the underlying retirement system. In the absence of household and asset information in the data set, this model does not take

savings behavior into account.⁴ The model's age horizon ranges from 55 to 100 years, but decisions can only be made between 55 and 67 (the normal retirement age). It is assumed that everyone is in retirement at the normal retirement age.⁵ Partial retirement preference assumptions are based on individual decisions regarding part-time work for elderly employees (*Altersteilzeit*, ATZ), taking ATZ's specific institutional rules into account in the estimation process. The decision problem in the model is solved using the dynamic programming method⁶ and the parameters are estimated using the maximum likelihood method based on the BASiD record. Finally, the estimated parameters are used to simulate full access to partial retirement under different conditions.

The underlying data set is limited to West German men as the economically largest group of people with potential access to the considered retirement paths. The employment histories of women and East German persons in the birth cohorts studied show marked differences compared to the employment histories of West German men, which leads to significant differences in their behavior when entering into retirement.⁷ Due to the smaller sample of these groups in the underlying data set, a separate analysis of the groups included in this study is not possible.

¹ For an in-depth discussion of the specifications and estimation results, see Songül Tolan (2017).

² Cf. John P. Rust (1989): A dynamic programming model of retirement behavior. *The Economics of Aging*, NBER Chapters, 359–404. National Bureau of Economic Research.

³ SOEP is part of the DIW Berlin research infrastructure. The survey is carried out by Kantar Public. Cf. Gert G. Wagner et al. (2008): *Das Sozio-ökonomische Panel (SOEP). Multidisziplinäres Haushaltspanel und Kohortenstudie für Deutsche – Eine Einführung (für neue Datennutzer) mit einem Ausblick (für erfahrene Anwender)*. *AsTA Wirtschafts- und Sozialstatistisches Archiv* 2(4), 301–328 (in German) (available online).

⁴ Cf. John Rust und Christopher Phelan (1997): How social security and medicare affect retirement behavior in a world of incomplete markets. *Econometrica* 65(4), 791–831 (available online).

⁵ This assumption is supported by the data. Less than 0.25 percent of this sample is employed after the normal retirement age.

⁶ Cf. John Rust (1987): Optimal replacement of GMC bus engines: An empirical model of Harold Zurcher. *Econometrica* 55(5), 999–1033.

⁷ Cf. Martin Huber, Michael Lechner und Conny Wunsch (2016): The effect of firms' phased retirement policies on the labor market outcomes of their employees. *ILR Review* 69(5), 1216–1248 (available online).

simulated and compared to a baseline scenario without a partial retirement option.

In the baseline scenario, people end their professional life either via a transitory phase of unemployment or by regular retirement starting from the early retirement age of 63 onwards for long-term insured. Deductions for drawing a pension before the normal retirement age apply as mentioned above. The normal retirement age is set at 67 in all scenarios.

The two hypothetical scenarios differ in regard to the entry age for partial retirement. In the first scenario, partial retirement can begin at 60, before the early retirement age (Scenario I). In the second scenario, partial

retirement is first possible starting at the early retirement age of 63 (Scenario II).

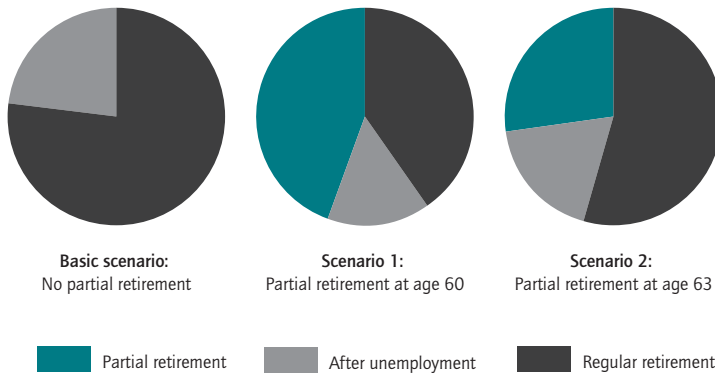
Flexible retirement does not always yield positive employment effects

It is often expected that a more flexible transition into retirement will increase the employment volume. However, positive effects on employment can only occur when the people who would have entered early retirement are motivated to remain in the work force longer due to the possibility of working part-time under partial retirement. Yet the effects on employment can also be negative, such as when the new partial retirement scheme creates incentives for potential full-time workers to enter

Figure 1

Retirement behavior

Percentage share of West German men in different retirement paths



Source: Author's own calculations.

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The share of people retiring regularly or via unemployment decreases with the implementation of partial retirement.

partial retirement early. The age when entering into partial retirement plays an important role in the effects on employment. The sooner the entry into partial retirement is possible and the longer people can spend partially retired, the more people will choose partial retirement instead of early retirement or full-time employment. If the entry age for partial retirement is too low, it can motivate people to switch from full-time employment to partial retirement earlier, which reduces the employment volume, or the total number of hours worked.

If the entry age is too high, people who actually would have opted for partial retirement leave the work force through alternative early retirement options. Thus, the entry age influences how many people would switch from alternative early retirement options as well as full-time employment to partial retirement if partial retirement were to be introduced. Since the first way positively affects employment and the second negatively, the overall effect of partial retirement on employment volume depends on the net effect of these counteracting effects.

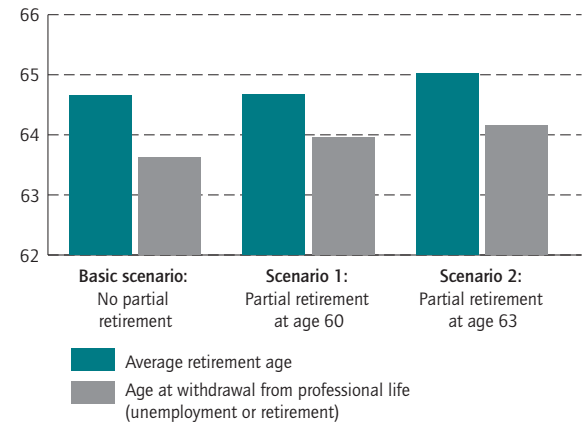
Only partial retirement beginning at 63 leads to an increase in employment volume

The simulation depicts the effects on employment caused by partial retirement beginning at 60 and 63. It shows the respective proportions among the male West German population over the age of 55 in the three possible pension paths (see Box), the average age at retirement (i.e., the beginning of pension receipt), the average age

Figure 2

Employment exit and retirement entry

Average age



Source: Author's own calculations.

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Partial retirement leads to an extension of working lives.

when exiting the work force (entry into unemployment or the beginning of pension receipt), the average annual share of full-time equivalent employment, and the average annual shares of each employment status.

The results of the simulation show that introducing partial retirement changes people's behavior regarding retirement entry. A larger share of the population chooses partial retirement, which reduces the proportion of regular retirees as well as those who enter into early retirement after unemployment.¹⁴ About 44 percent opt for partial retirement when the entry age is 60, whereas this proportion is reduced to 27 percent when the entry age is raised to 63 (Figure 1).

The results also show that partial retirement increases the average retirement age, which varies strongly depending on the partial retirement entry age. With an entry age of 60, the average retirement age increases by only about two weeks from an average retirement age of 64 years and 8 months in a scenario without partial retirement (Figure 2). However, if the entry age is 63, the same as the early retirement age, the average retirement entry age rises by 4.4 months to 65 years. The older the entry

¹⁴ The birth cohorts analyzed in this study have the possibility not only to enter retirement at the normal age, but also to enter early retirement after a period of unemployment. The age limits and deductions for this possibility of early retirement increase gradually between these cohorts. This variation was taken into account in the estimation of the model.

age for partial retirement, the lower the proportion of the population that chooses early retirement. This suggests that partial retirement starting at 63 could counteract potential early retirement (with corresponding pension deductions) through part-time work.

In the simulation, the average age when leaving the work force increases more than the retirement age, as the average unemployment rate decreases from 8.6 to 6.1 percent. More specifically, introducing partial retirement with an entry age of 60 extends the amount of time spent in the work force by around 4 months (from 63 years and 7 months to 63 years and 11 months). This shows that partial retirement has a positive impact on employment because more people opt for partial retirement instead of voluntarily becoming unemployed.

With an entry age of 63 (Scenario II), the proportion of unemployed persons increases in comparison to an entry age of 60 for partial retirement (Scenario I) but still remains below the level of the baseline scenario without partial retirement (Figure 3). Despite a higher proportion of unemployed persons when partial retirement has a later entry age, the study concludes that the average working life and employment volume expressed in full-time equivalents increase. The average age when exiting the work force increases by 6.5 months (from 63 years and 7 months to 64 years and 2 months) when it's possible to enter partial retirement at 63. This also impacts the employment volume.

With an entry age of 60 for partial retirement, the average employment volume is below the level of the baseline scenario without partial retirement. However, the employment volume increases by 3.4 percent compared with the baseline scenario when the entry age for partial retirement is set at 63. In this scenario, the proportion of full-time workers is even higher than in the baseline scenario, despite the increase in partial retirement. The proportion of full-time workers is greater than the share in the baseline scenario until partial retirement is possible. This indicates that some people would work full-time for more years in anticipation of a partial retirement. Leaving the work force earlier would result in a loss of the partial retirement option. Thus, partial retirement that begins at the entry age for early retirement leads to substantially higher employment than a scenario without partial retirement (Figure 4).

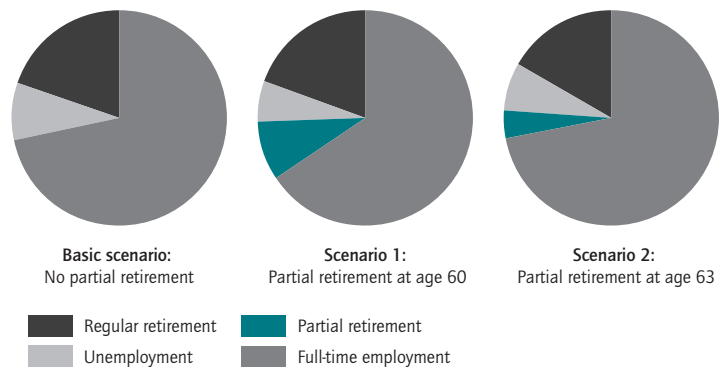
Partial retirement has positive effects on government budgets

To calculate the fiscal consequences of the simulated partial retirement schemes starting at the ages of 60 or 63, the scenarios with partial retirement beginning at 60 (Scenario I) and at 63 (Scenario II) are lacking

Figure 3

Employment effects

Percentage share of West German men between ages 55 and 67



Source: Author's own calculations.

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The share of people in full-time employment increases in a partial retirement regime with an entry age of 63.

partial retirement compared with the baseline scenario. In terms of costs, the calculations include pension payouts and unemployment payments, and on the revenue side, social security contributions and income tax payments. The table displays average payments in euros per person starting at age 55 until death. Both partial retirement scenarios have a positive effect. With an entry age of 60, introducing partial retirement leads to an increase in public revenues by 3.3 percent per person; with an entry age of 63, it leads to an increase by 3.2 percent per person, which equates to a total of around 6,000 euros per person.

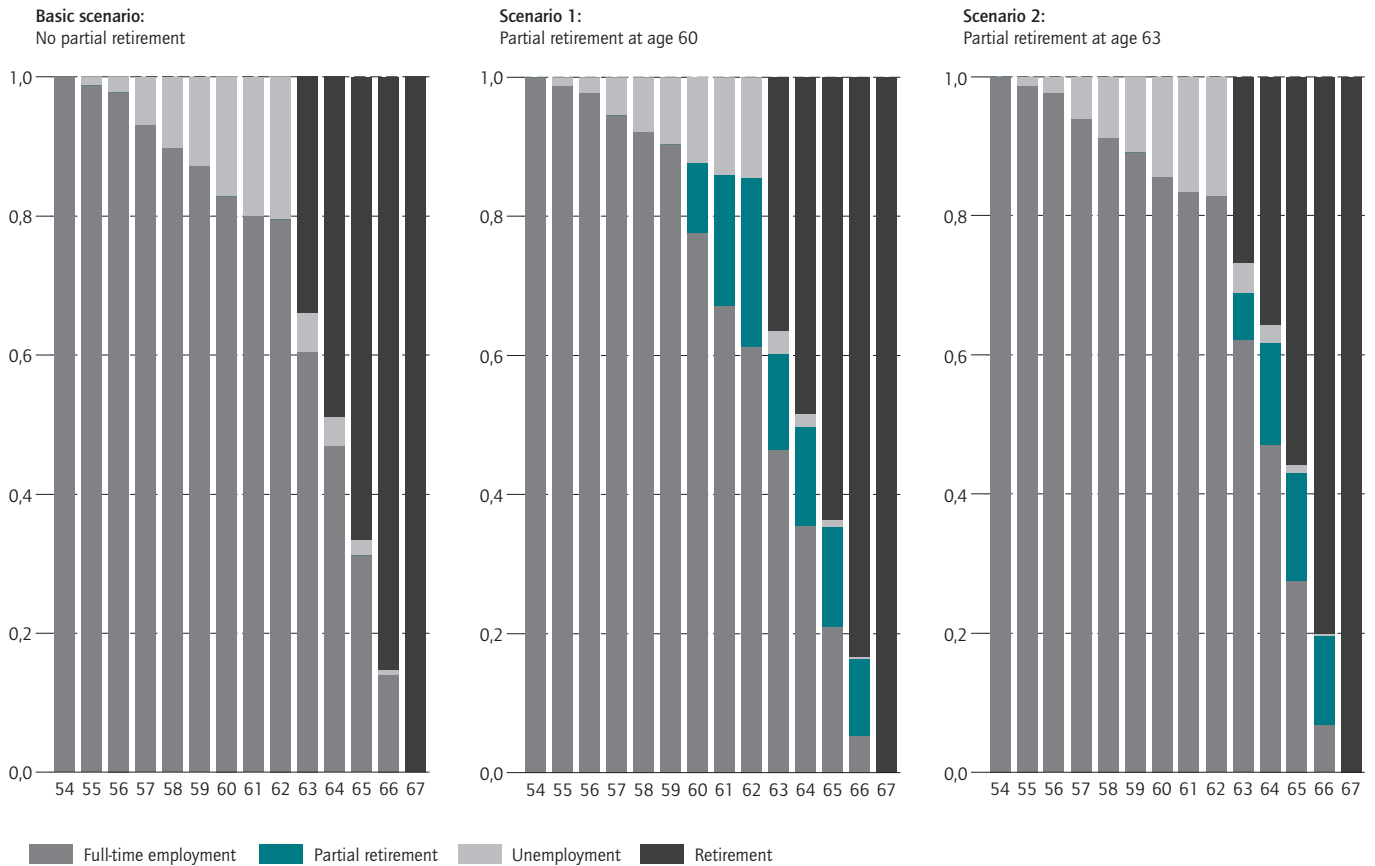
The differences in the fiscal implications between partial retirement beginning at 60 and at 63 are depicted in individual financial positions. Partial retirement beginning at 60 leads to a reduction in pension payouts by an average of 9,000 euros per person over the duration of the payout, whereas partial retirement beginning at 63 does not significantly alter the amount of the average pension payout. A reduction in pension payments has a positive effect on government budgets, but that also means that individual pensions decrease and thus lead to lower incomes in old age.

Furthermore, the analysis shows that the retirement age increases in case of partial retirement. Therefore, in these scenarios, pensions are paid out for a shorter average time. The reduction in pension payouts can thus be attributed to three factors. Those in partial retirement receive a part of their pension with deductions, collect only part of their earnings points every year they're in partial retire-

Figure 4

Age effects in employment states

In percent for each employment state



Source: Author's own calculations.

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The average time in full-time employment is prolonged in a partial retirement regime with an entry age of 63.

ment, and receive their pension payouts over a shorter period of time than in a non-partial retirement scenario. Above all, deductions for a pension begun at 60 can make up a significant part of the reduction, since the deductions in this case amount to 25.2 percent of the pension.

With regard to social insurance contributions and income tax payments, partial retirement starting at 60 leads to a reduction of 5,600 euros per person, whereas the contributions and payments increase by a total of approximately 4,100 euros per person when partial retirement begins at 63. This is due to higher full-time employment when partial retirement starts at age 63.

In summary, the increase in government budgets is due to reductions in pension payouts in the case of partial retirement beginning at 60, whereas it is due to higher

employment and consequently higher social security contributions and income tax payments in the case of partial retirement starting at 63.

Conclusion: Policies should increase promotion of partial retirement

The four analyses presented here show that unrestricted access to partial retirement can lead to an increase in employment volume. The employment effects are particularly positive if the entry age for partial retirement is the same as the early retirement age of 63. This reduces the number of people entering early retirement with the corresponding pension deductions.

Furthermore, the partial retirement scheme presented here has a positive effect on government budgets. Here,

Table

Fiscal effects of partial retirement

Average in euros per person from age 55 until end of life

	Basic scenario: No partial retirement	Scenario 1: Partial retirement at age 60			Scenario 2: Partial retirement at age 63		
Fiscal effect	Sum in euros	Sum in euros	Difference to basic scenario (euros)	Difference to basic scenario (percent)	Sum in euros	Difference to basic scenario (euros)	Difference to basic scenario (percent)
Pension payouts	−350 170	−341 210	8 960	2.56	−350 160	10	0.00
Unemployment payments	−9 148	−6 447	2 701	29.53	−7 594	1 554	16.99
Social security contributions	115 200	112 920	−2 280	−1.98	118 010	2 810	2.44
Income tax	64 299	60 931	−3 368	−5.24	65 617	1 318	2.05
Net effect	−179 819	−173 806	6 013	3.34	−174 137	5 692	3.16

Source: Author's own calculations.

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too, there are important differences depending on the entry age. The simulations show that the positive effects of partial retirement starting at 60 are primarily achieved through reducing pension payouts. If it is first possible to enter partial retirement at the same age as it is possible to enter early retirement, the running costs for pensions hardly change. However, additional income comes from higher taxes and social security contributions which are achieved through higher employment. It must also be taken into account that this study is based on a random sample of West German men. Therefore, the results cannot be fully applied to the whole population.

With the introduction of flexible retirement in Germany in two phases on January 1 and July 1, 2017, the possibilities for a more flexible transition into retirement have improved. Since flexible retirement is only a possibility once the early retirement age has been reached, partial retirement's potentially negative effects on employment are reduced. The ability to enter into flexible retirement before the normal retirement age was first made possible in July 2017. Therefore, it is not yet possible to estimate how many people will actually make use of flexible retirement.

Our simulations show that there is presumably a large demand for partial retirement and that it can lead to positive effects on employment. However, it is important for

the realization of the positive effects on employment that the combination of pensions and part-time work does not become financially unattractive as a result of high reduction rates when receiving partial pension payouts. The abolition of rigid supplementary income limits was a step in the right direction with the introduction of flexible retirement, but the computation of supplementary income limits for flexible retirement is still very complex.

It is not yet clear to what degree companies will use flexible retirement. According to the current legislation, an application for a reduction in work hours must be approved by the employer. Moreover, the possibility to apply for reduced hours does not exist in companies with fewer than 15 employees.

An evaluation of the new, more flexible transition into retirement is important in order to find out how strongly these factors influence the decision for a flexible retirement. If flexible retirement proves itself to be too complex and financially too unattractive for employees, consideration should be given to simplifying and reducing the reduction rate to pension payouts in flexible retirement. If it turns out that few businesses agree to a flexible retirement, then a legal right to partial retirement should be considered. However, exceptions—especially for small companies—still need to be discussed.

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Nuclear power unnecessary for climate protection—there are more cost-efficient alternatives

By Claudia Kemfert, Thorsten Burandt, Karlo Hainsch, Konstantin Löffler, Pao-Yu Oei, and Christian von Hirschhausen

The world needs to continue working to protect the climate—this is generally undisputed. However, there is no agreement on which technologies should be used to decarbonize the energy sector. Many international scenarios still assume a relevant role for nuclear power in the future. However, a study by the German Institute for Economic Research shows that the Paris climate protection target—limiting global warming to below two degrees—can be achieved inexpensively without nuclear power. The results of a global energy system model indicate that no new nuclear power plants have to be built in order to meet the global climate target. It would be cheaper to use a combination of renewable energy and energy storage systems.

Upon signing the Treaty of Paris in 2015, virtually all nations worldwide committed to limiting global warming to below two degrees. In principle, each nation is free to choose specific technologies for achieving their national climate targets. For political reasons, some countries plan to keep using nuclear power because, among other reasons, it is closely connected to the development of nuclear weapons. For example, policy makers in the US are currently discussing a proposal to increase subsidies for nuclear power.¹ Existing direct and indirect support includes the costs for both the long-term storage of nuclear waste and possible accidents, such as the one in Fukushima in Japan.

Neither international organizations nor the scientific community can come to an agreement on nuclear power's role in climate protection. Some institutions, such as the International Atomic Energy Agency (IAEA) and EURATOM, the European Atomic Energy Community, have direct mandates to support nuclear power. The International Energy Agency (IEA) and the European Union typically see nuclear power as a relevant part of a future technology mix.² However, environmental and climate economists have strongly differing opinions on the future significance of nuclear power.³

On the other hand, the microeconomic perspective in the literature holds that nuclear power was not an economical form of electricity supply in the past. Analyses from

¹ See US Department of Energy, "Grid Resilience Pricing Rule 18 CFR Part 35," (PDF, Department of Energy, Washington D.C., 2017) (available online, accessed November 3, 2017. This also applies to all other online references in this report as long as not stated otherwise).

² See International Energy Agency, World Energy Outlook 2016, Paris: International Energy Agency, 2016; Pantelis Capros et al., "EU Reference Scenario 2016 –Energy, transport and GHG emissions trends to 2050," (Publications Office of the European Union, Luxembourg, 2016) (available online).

³ See the controversial discussion initiated by Mark Z. Jacobson et al., "The United States can keep the grid stable at low cost with 100 % clean, renewable energy in all sectors despite inaccurate claims," *Proceedings of the National Academy of Sciences* 114 (26) (2017); and Christopher T. M. Clack et al., "Evaluation of a proposal for reliable low-cost grid power with 100 % wind, water, and solar," *Proceedings of the National Academy of Sciences* 114 (26) (2017): 6722–6727.

a range of research institutes that examined the competitiveness of nuclear power in detail, including calculations made by DIW Berlin, underline this assertion.⁴ Moreover, a comprehensive meta study determined that even more than 70 years after the first controlled nuclear chain reaction, the nuclear power industry has not been able to produce electricity under competitive conditions.⁵ A historical reappraisal of the birth of all nuclear power plants since the 1950s provides empirical substantiation of the model calculations: Not one of the more than 500 nuclear power plants around the world was constructed under general circumstances of market-based competition. In fact, the costs were so high that they were always centrally planned investment projects and were heavily subsidized by the state or electricity consumers.⁶

This economic bulletin discusses the role of nuclear power in climate protection based on an energy system model. The simulation of the cost-optimized development of the global energy mix shows that nuclear power as a mitigation technology is not a cheaper option. Instead, renewable energy could supply the world with energy sustainably and cost-efficiently until 2050.

Energy system model: structure and assumptions

To examine the role of nuclear power in climate protection scenarios, this report used the Global Energy System Model (GENESYS-MOD), derived from the established Open Source Energy Modelling System (OSeMOSYS), an open-source software for long-term energy system analyses (Box).⁷ OSeMOSYS is further developed decentrally by many researchers worldwide and is used in numerous scientific publications and policy white papers.⁸ For

the analysis at hand, OSeMOSYS was used as the basis for the GENESYS-MOD model.⁹ The model's objective function encompasses the total cost of the global power supply to the electricity, transportation, and heat sectors. The model yields a cost-minimized combination of technologies designed to cover the energy demand at any time. Climate protection targets, such as carbon emission budgets, can be explicitly specified as general conditions for the model calculations.

Since the supply of the variable renewable energy sources wind and solar power fluctuates as weather conditions change, temporal and spatial balancing is essential in meeting energy demand at all times. To do so, several technologies for storing energy or sector coupling were implemented in the model. Lithium-ion batteries, in particular, compensate for the temporal fluctuations in energy supply and demand. Furthermore, coupling the electricity sector with the heat and transportation sectors facilitates their decarbonization.

Spatially, the model aggregates various countries into a total of ten larger regions. This allows to abstract from energy transport within these regions. Among regions, it is possible to exchange fuel but not electricity or heat. To maintain tractability and computability of the complex model, we also aggregated on the temporal level. To do this, the hourly resolution was reduced to six periods ("time slices") representing the seasonal and diurnal fluctuations in demand and the supply of renewable energy. In total, we considered the period from 2020 to 2050 in five-year increments, assuming perfect foresight with regard to future trends in demand, cost, and supply of renewable energy.

Falling costs are a reasonable assumption for renewable energy and storage

The assumptions about the future costs of technologies central to the model results are key input variables. GENESYS-MOD contains default values for assumptions with regard to technology costs and energy consumption. We updated cost analyses performed at DIW Berlin for the present model calculations and refined them based on current trends and the international literature (Table).¹⁰

It is important to highlight the expected costs for photovoltaics, which are expected to fall significantly. This study is based on a number of established studies on

⁴ See Stephen Ansolabehere et al., "The Future of Nuclear Power," (Massachusetts Institute of Technology, Cambridge, 2003) (available online); Martin Castellano et al., "The Economic Future of Nuclear Power," (University of Chicago, Chicago, 2004) (available online); Paul L. Joskow and John E. Parsons, "The Future of Nuclear Power After Fukushima," *Economics of Energy & Environmental Policy* 1 (2) (2012): 99–113; and William D. D'haeseleer, "Final Report: Synthesis on the Economics of Nuclear Energy—Study for the European Commission," (European Commission, Leuven, 2013) (available online); and Claudia Kemfert et al., "European Climate Targets Achievable without Nuclear Power," *DIW Economic Bulletin* 47 (2015): 619–625 (available online).

⁵ See Lucas W. Davis, "Prospects for Nuclear Power," *Journal of Economic Perspectives* 26 (1) (2012): 49–66.

⁶ For an argument regarding the high historical construction costs of nuclear power plants, see Jonathan Koomey, Nathan E. Hultman, and Arnulf Grubler, "A reply to: Historical construction costs of global nuclear power reactors," *Energy Policy* 102 (2017): 640–643.

⁷ See the OSeMOSYS—Open Source Energy Modelling System project website (available online).

⁸ See for example Manuel Welsch et al., "Modelling elements of Smart Grids—Enhancing the OSeMOSYS (Open Source Energy Modelling System) code," *Energy* 46 (1) (2012): 337–350; Benjamin Lyseng et al., "Decarbonising the Alberta power system with carbon pricing," *Energy Strategy Reviews* 10 (2016): 40–52; and Constantinos Taliotis et al., "Natural gas in Cyprus: The need for consolidated planning," *Energy Policy* 107 (2017): 197–209.

⁹ This report is based on a technical article that contains a detailed model description. See Konstantin Löffler et al., "Designing a Model for the Global Energy System—GENESYS-MOD: An Application of the Open-Source Modeling System (OSeMOSYS)," *Energies* 10 (10) (2017): 1468 (available online).

¹⁰ See Andreas Schröder et al., "Current and Prospective Costs of Electricity Generation until 2050," *DIW Data Documentation* 68 (2013) (available online).

Table

Cost assumptions for selected technologies for the period 2015–2050

Costs in euros per kilowatt

Technology	2015	2020	2025	2030	2035	2040	2045	2050	Source
Photovoltaics	1,000	800	650	550	490	440	400	370	Gulagi et al. (2017)
Wind onshore	1,250	1,150	1,060	1,000	965	940	915	900	Gulagi et al. (2017)
Wind offshore	3,470	2,880	2,730	2,580	2,480	2,380	2,330	2,280	JRC (2014)
Biomass power plant	2,890	2,620	2,495	2,370	2,260	2,150	2,050	1,950	JRC (2014)
Nuclear power plant	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	Schröder et al. (2013)
Coal power plant	1,400	1,400	1,400	1,400	1,400	1,400	1,400	1,400	Schröder et al. (2013)
Natural gas power plant	675	675	675	675	675	675	675	675	Schröder et al. (2013)
Lithium-ion-battery	1,500	1,300	1,300	1,000	1,000	800	800	700	Wietschel et al. (2015)
Heat pump	1,300	1,286	1,271	1,257	1,243	1,229	1,214	1,200	DAE and Energinet.dk (2012); Fraunhofer ISE (2012); UBA (2016)

Authors' own compilation, based on International Energy Agency, "Technology Roadmap Solar Thermal Electricity," (OECD/IEA, Paris, 2014) (available online); Danish Energy Agency (DEA) and Energinet.dk, "Technology Data for Energy Plants—Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion," (Copenhagen, 2012) (available online); Fraunhofer ISE, "100% Erneuerbare Energien für Strom und Wärme in Deutschland," (Freiburg, 2012) (available online); Schröder et al., "Current and prospective costs," Joint Research Centre (JRC), "Energy Technology Reference Indicator (ETRI) projections for 2010–2050," (Luxembourg, 2014) (available online); Umweltbundesamt (UBA), "Klimaneutraler Gebäudebestand 2050," CLIMATE CHANGE 06/2016, (Dessau-Roßlau, 2016) (available online); Martin Wietschel et al., eds., *Energietechnologien der Zukunft* (Wiesbaden: Springer Fachmedien, 2015); and Ashish Gulagi et al., "Electricity system based on 100% renewable energy for India and SAARC," PLOS ONE 12 (7) (available online).

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Especially for renewable energy technologies, a strong cost-decline can be assumed.

observed and forecast learning curves.¹¹ Due to ongoing improvements in technology and production processes, it is assumed that the costs of materials and installations will fall by one-third of their current values by 2050. Observations in the past showed that even optimistic forecasts of cost trends were typically topped in reality.¹² It is also assumed that the costs of wind power plants will fall in both the onshore and offshore areas. The costs of offshore wind parks, in particular, are expected to fall sharply in the near future. The expected learning curves and technological developments in the systems themselves and construction of offshore wind parks will both play a role.¹³

The decreasing costs of storage technologies, in particular lithium-ion batteries, are an additional assumption. Cheaper production in a growing market and falling material costs are ensuring lower battery storage costs.¹⁴ In

conjunction with more affordable photovoltaic systems, they represent an inexpensive form of electricity supply.

Cost of fossil and nuclear power plants will remain at current level

While the forecasts assume that the cost of renewable energy will decrease over the years, the cost of fossil-fueled power plants will remain at approximately the current level. This will make them increasingly less competitive. The cost estimates for nuclear power also remain at the level presumed at present of around 6,000 euros per kilowatt, a seemingly realistic estimate in light of recent experience constructing new nuclear power plants.¹⁵ In the new calculations for the EU reference scenario, a long-term projection of the energy supply trend for Europe, the assumed costs of nuclear power are also of this magnitude.¹⁶

¹¹ See Johannes N. Mayer et al., "Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems," (Fraunhofer Institute for Solar Energy Systems, Freiburg, 2015) (available online); World Energy Council, "World Energy Resources," (World Energy Council, London, 2016) (available online); and Harry Wirth, "Aktuelle Fakten zur Photovoltaik in Deutschland," (Fraunhofer Institute for Solar Energy Systems, Freiburg, 2017) (available online).

¹² See Christian Breyer et al., "On the role of solar photovoltaics in global energy transition scenarios," *Progress in Photovoltaics Research and Applications* 25 (8) (2017): 727–745.

¹³ See David E. H. J. Gernaat et al., "Global long-term cost dynamics of offshore wind electricity generation," *Energy* 76 (2014): 663–672; and Bruce Valpy and Philip English, "Future renewable energy costs: offshore wind," (KIC InnoEnergy and BVG Associates, Eindhoven, 2014) (available online).

¹⁴ See Bloomberg New Energy Finance, "Lithium-ion Battery Costs and Market," (Bloomberg New Energy Finance, New York City, 2017) (available online); and Gert Berckmans et al., "Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030," *Energies* 10 (10) (2017): 1314 (available online).

¹⁵ For a detailed analysis of various cost data, see Schröder et al., "Current and Prospective Costs." The value for nuclear power at present equals the average expected value of the nuclear power plants under construction for which reproducible cost estimates are available—Olkiluoto (Finland), Flamanville (France), Hinkley Point C (UK), Vogtle and Virgil C. Summer (US)—offset by a 15 percent cost degression for economies of scale. The concrete amounts can be derived from the participating companies' annual reports. For the dismantling of decommissioned nuclear power plants and long-term storage of radioactive waste, 900 euros per kilowatt must be added. Also see the literature on systematic cost overruns in nuclear power plants, including Arnulf Grubler, "The cost of the French nuclear scale-up: A case of negative learning by doing," *Energy Policy* 38 (2010): 5174–5188; Lina E. Rangel and Francois Lévêque, "Revisiting the cost escalation curse of nuclear power: New lessons from the French experience," *Economics of Energy & Environmental Policy* 4 (2) (2015): 103–125; and the summary of the literature in Christian von Hirschhausen et al., "Europäische Stromerzeugung nach 2020: Beitrag erneuerbarer Energien nicht unterschätzen," *DIW Wochenbericht* 29 (2012): 3–13 (available online).

¹⁶ See Capros et al., "EU Reference Scenario 2016."

Energy demand and remaining carbon budget

For the electricity, heat, and transportation sectors in the ten regions of the world, we assumed different growth in demand to be met with technologies available now and in the future. The assumptions are based on established literature, including IEA scenarios. They involve several factors. For example, India was assumed to have a sharply rising population, while it was assumed to remain constant or fall in other regions. The further industrialization of developing countries would drive an increase in demand for both electricity and process heat for the industry in their regions. At the same time, the demand for residential space heating was assumed to be falling. This assumption is primarily based on increases in the efficiency of buildings. In heavily industrialized regions such as Europe and North America, the demand for electricity and heat was assumed to decrease in the long term due to continued improvements in energy efficiency, among other reasons.

The quantity of carbon that can still be emitted into the atmosphere is extremely limited if we want to achieve sane climate protection targets. According to different calculations, a carbon budget in the range of 550 to 1,000 billion tons of CO₂ equivalents remains to limit the rise in the average temperature of the Earth to below two degrees.¹⁷ For example, extrapolating from the global carbon emissions of 36 billion tons in 2015, this budget would be used up within 16 to 27 years. In order to meet the targets of the Paris climate protection treaty, this study is based on a scenario in which the temperature rise remains below two degrees. As a result, the scenario assumes a remaining CO₂ budget of 650 billion tons—a figure that accommodates the emissions from agriculture and industrial processes that are not considered in the model.

Most international climate protection models make meeting a challenging target dependent on negative emissions. They assume it will be achieved using technologies that remove carbon from the atmosphere and store it permanently, such as bioenergy carbon capture and storage (BECCS) or climate engineering (for example, the distribution of particles in the atmosphere). However, these technologies are not tested on an industrial scale; nor is it possible to plausibly estimate their long-term cost development. For these reasons, they are not included in the following section.

¹⁷ CO₂ equivalents as a unit of measure makes the capacity of other greenhouse gases (such as methane or nitrous oxide) to damage the climate comparable to that of CO₂. As a result, the remaining emissions budget is listed in CO₂ equivalents in many analyses. See John Christensen et al., "The Emissions Gap Report 2015," (United Nations Environment Program, Nairobi, 2015) (available online). This report refers to carbon emissions only.

Results: Nuclear power not part of the cost-efficient energy mix

The model results showed that at a CO₂ budget of 650 billion tons, the cost-optimized, cross-sector energy mix shifts from fossil energy sources (coal, natural gas, and oil) to more affordable renewable energy sources (Figure 1). The results indicate that a "fuel switch" from coal to natural gas will not occur among fossil energy sources. Instead, coal will remain part of the energy mix longer than natural gas, which will lose its significance by the end of the time horizon. Of the renewable energy sources, photovoltaics, wind, and biomass are of approximately equally crucial importance. In order to realize a sustainable energy supply with optimal costs, the total capacity of renewable energy must be increased. For example, in 2030 photovoltaic systems with a capacity of just below 1,000 gigawatts will be installed throughout Europe, a figure projected to rise to 1,700 gigawatts by 2050.¹⁸

Starting in 2025, photovoltaics will play a dominant role in supplying electricity. Natural gas will continue to supply heat for industry over a longer period of time, but biomass will take on a greater role. When it comes to interior heating, heat pumps operated with (renewable) electricity will gain greatly in importance. In the transportation sector, oil will continue to play a starring role, but by 2050 it should be replaced by a mix of biofuel with hydrogen and electric drives.

In the case of nuclear power, the results show that electricity production will gradually decline over the coming decades from its 2015 level of 2,640 terawatt hours (Figure 2). Geographically, the distribution of nuclear power plants will mirror that of today's major nuclear electricity producers: China, the US, and France. Due to their high costs, new nuclear power plants will not be built, and production will fall as actively producing nuclear power plants are decommissioned.

Due to variations in climate conditions and potential for new construction, the proportions of photovoltaic, wind, and hydro power vary worldwide (Figure 3). For example, the model results indicate that the proportion of electricity production via photovoltaics in India will be over 50 percent in 2050. In Europe and North America, on the other hand, wind power will have a higher proportion. Even countries and regions for which particularly

¹⁸ These figures are essentially the same as those in similar studies that also examine the decarbonization of the global energy system. See Mark Z. Jacobson et al., "100 % Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World," *Joule* 1 (2017): 108–121 (available online); Breyer et al., "On the role of solar photovoltaics"; and Manish Ram et al., "Global Energy System based on 100 % Renewable Energy—Power Sector," (Lappeenranta University of Technology & Energy Watch Group, Lappeenranta, 2017) (available online).

Box

GENeSYS-MOD

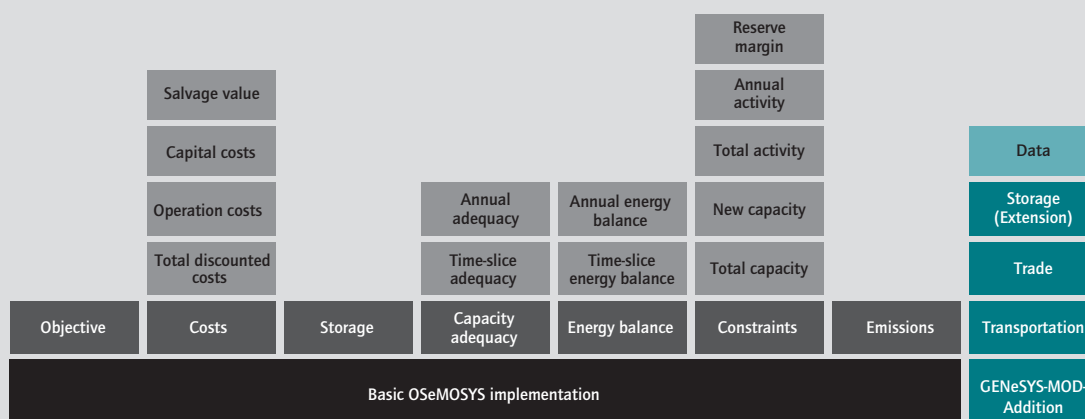
The global energy system model GENE SYS-MOD¹ is based on the open-source model family OSeMOSYS (Open-Source Energy Modelling System).² The OSeMOSYS model family is characterized by a high level of transparency and low access barriers. All programming code and input data are made available under open license in order to facilitate reproducibility and critical discussion of the results.

1 For a detailed model description, see Konstantin Löffler et al., "Designing a Model for the Global Energy System – GENE SYS-MOD: An Application of the Open-Source Modeling System (OSeMOSYS)," *Energies* 10 (10) (2017): 1468 (available online).

2 See the OSeMOSYS project website (available online). For a basic introduction, see Mark Howells et al., "OSeMOSYS: The Open Source Energy Modeling System. An introduction to its ethos, structure and development," *Energy Policy* 39 (10) (2017): 5850–5870.

GENeSYS-MOD has a modular structure (Figure 1). Mathematically, the model is a linear optimization program that takes into account a number of technological and economic constraints and determines a cost-optimized technology mix for the energy system. The basic model consists of a target function that accounts for the various cost components. The discounted total costs for production plants, storage, and other flexibility options consist of capital and operating costs plus a residual book value at the end of the period of analysis. The model is divided into various time slices, and the energy demand from various sectors must be met constantly (capacity and energy balances). By defining additional requirements, such as on reserve capacities or emissions, regulatory or political conditions, such as climate policy targets, can be taken into consideration. GENE SYS-MOD expands upon the basic model with additional modules for international exchange and an improved representation of energy

Figure 1

GENeSYS-MOD: The functional blocks of the energy system model

Source: Löffler et al., "GENeSYS-MOD," adapted from Howells et al., "OSeMOSYS."

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GENeSYS-MOD adds new modules to the established energy modeling system OSeMOSYS.

storage capacity. Moreover, an up-to-date database accommodates assumptions on the costs and availability of various technologies.

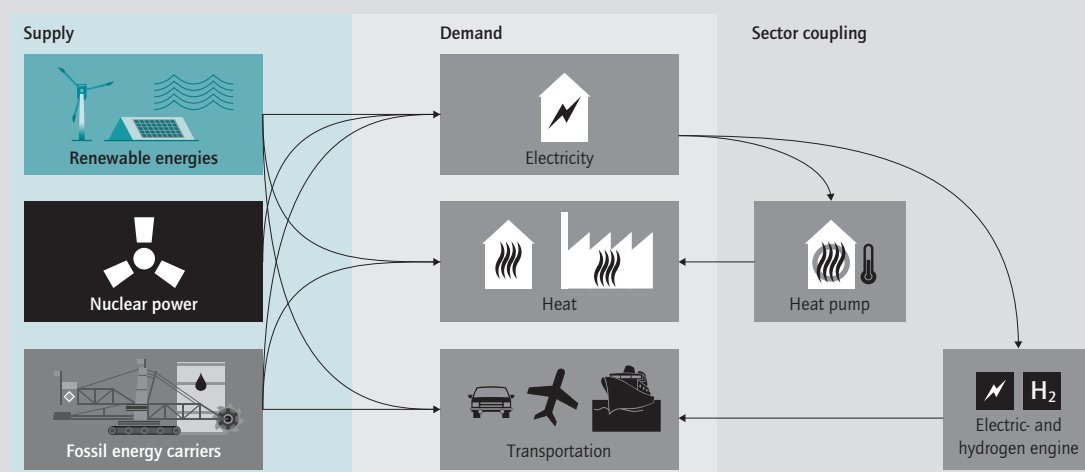
The model maps various conventional and renewable energy sources to be used in the electricity, transportation, and heat sectors (Figure 2). The respective energy demand is given exogenously. It is also possible to map the couplings of energy sectors by using electricity for heat and transportation, as well as the option of transforming electricity into other sources of energy, such as hydrogen.³

3 In principle, the model can factor in interfaces to other models such as sector-specific bottom-up models or climate system models. And the degree of spatial detail is scalable. For example, the company, city, country, continent, or—as in the present study—the global level can be examined.

Depending on the subject of study, regions and time-slices are aggregated. In order to make the best of the limited computing capacity available, users must trade off detail and scope. For example, aggregation makes it possible to capture broad spatial and temporal relationships. On the other hand, some specific requirements for integrating renewable energy into the energy system can only be considered in stylized form.

Figure 2

Technologies and sectors in the energy system model GENeSYS-MOD



Source: Authors' own depiction, based on Löffler et al., "GENeSYS-MOD."

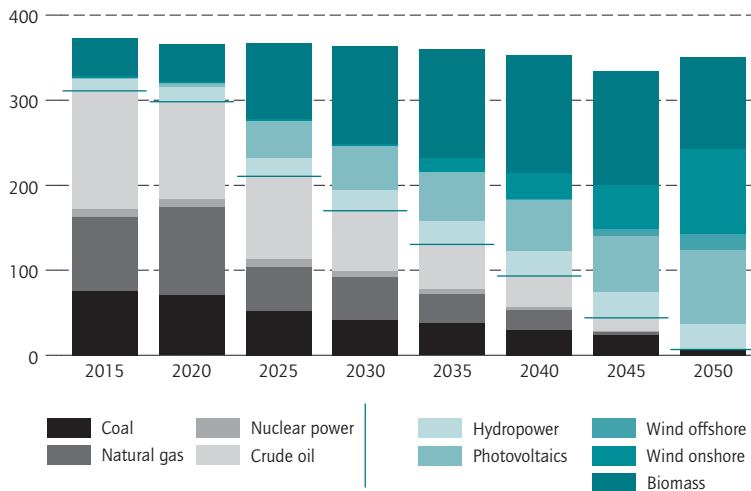
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Various technologies generate energy to meet the demand in the sectors electricity, heat, and transportation.

Figure 1

Development of the global energy mix with a CO₂ budget of 650 billion tons

Energy supply in exajoule



Sources: GENeSYS-MOD v1.0, see Löffler et al., "GENeSYS-MOD," authors' own calculations.

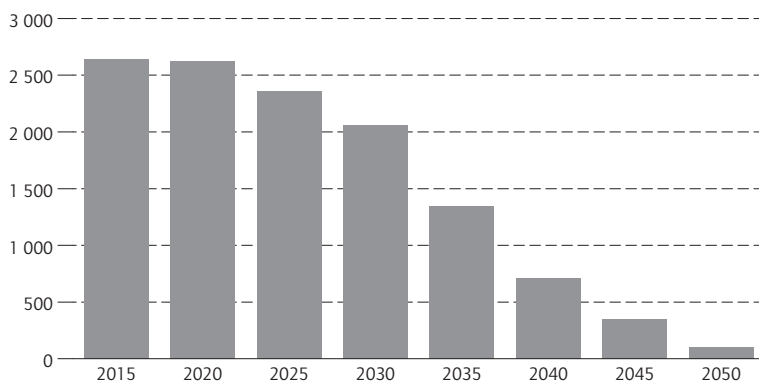
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In 2050, a decarbonized energy system will be achieved with renewable energies, not with nuclear power.

Figure 2

Global development of nuclear power until 2050

Electricity generation by nuclear power in terawatt hours



Sources: GENeSYS-MOD v1.0, see Löffler et al., "GENeSYS-MOD," authors' own calculations.

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When considering the cost-optimal energy supply, nuclear power is being phased out until 2050.

rapid growth of nuclear power has been forecast will be able to meet their electricity demand in a climate-friendly manner without nuclear power.

Nuclear power not a factor also when assuming other cost estimates

The cost estimates this report is based on are a key factor in interpreting the findings. In some studies, the IEA assumes lower investment costs than the most recent literature. They are around 3,000 U.S. dollars per kilowatt, for example, in China.¹⁹ However, the empirical database these estimates are based on is unclear. In any case, nuclear power does not even play a role in the model results at these low costs.²⁰ For example, a global cost of 2,800 euros per kilowatt was assumed for nuclear power for a sensitivity calculation. The model results show that the lower assumed cost is not enough to make nuclear power competitive against renewable energy.²¹ The findings remain quantitatively unchanged: no new nuclear power plants were required in the model calculation.

Further, the amount of the investment is less relevant from an economic perspective because it only represents a small portion of the total cost. Alongside investment costs, the following are all relevant: operating costs, the costs of decommissioning and long-term storage, system costs such as research and development, and the external costs of nuclear power in case of accidents, for example. From a welfare economics perspective, therefore, it is obvious that new nuclear power plants should not be built or used—not even as a technology that supposedly protects the climate.²²

¹⁹ See International Energy Agency, "Power generation assumptions in the New Policies and 450 Scenarios in the World Energy Outlook 2016," (OECD/IEA, Paris, 2016) (available online).

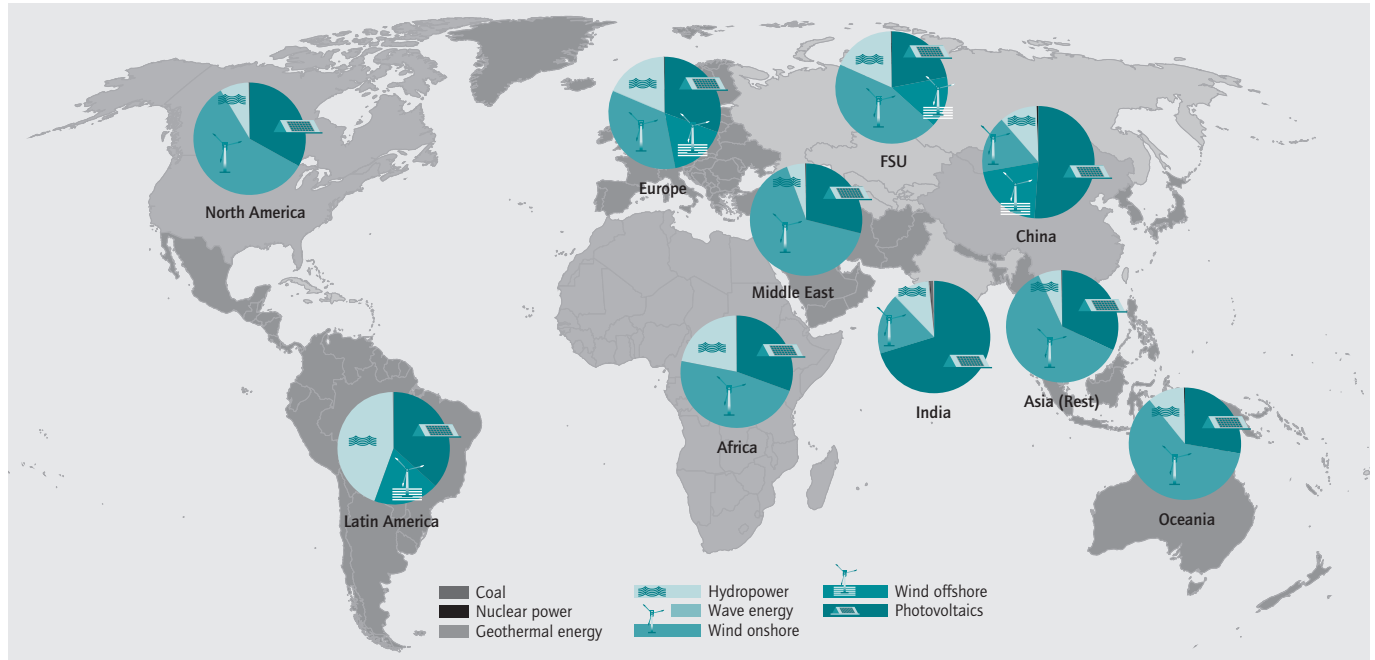
²⁰ Actually, the high proportion of nuclear power in the IEA scenarios can be explained by a substantial exaggeration of the cost of renewable energy. This artifact has been criticized by the scientific community. See Mathieu Metayer, Christian Breyer, and Hans-Josef Fell, "The projections for the future and quality in the past of the world energy outlook for solar PV and other renewable energy technologies," *Proceedings of the 31st European Photovoltaic Solar Energy Conference* (2015): 3112–3238; and Felix Creutzig et al., "The underestimated potential of solar energy to mitigate climate change," *Nature Energy* 2 (9) (2017): 17140.

²¹ These model calculations do not imply that no countries will ever build new nuclear power plants. For example, India and China are currently planning to increase their capacity significantly in the near future. The results actually indicate that nuclear power is not an inexpensive option in these countries either and would not be considered if the decision were based on cost alone.

²² For a differentiated view of the cost concept and a review of the literature, see Christian von Hirschhausen, "Nuclear Power in the 21st Century—An Assessment (Part I)," *DIW Discussion Paper* 1700 (2017).

Figure 3

Regional electricity generation in the year 2050



Source: Authors' own depiction, based on Löffler et al., "GENESYS-MOD."

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The regional mix of renewable energy reflects the climatic and geographic potentials.

On temporal and spatial aggregation

When using a global model with a time horizon far in the future, as is the case in this study, it is necessary to make simplifying assumptions. Specifically, this report used a simplified representation of the temporal and spatial dimensions involved in integrating renewable energy into the electricity system.

For example, the model used six time-slices per year—for three seasons, one day and one night each—in order to approach the temporal variability of energy demand and the availability of renewable energy. A major portion of the variability is thus not explicitly considered, and it is possible that the model overestimated the contributions of wind power and photovoltaics. While in reality the fluctuation in supply could lead to longer phases with very low production, a reduction in the time slices implies an optimistic view of their availability. We assumed that within a time slice and a region, the production of renewable energy would equal a specific proportion of the installed capacity. This generally involves an underestimation of the demand for supplementary temporal flexibility for the system integration of renewable energy, such

as using energy storage systems. According to the calculations at hand, there will be approximately 5,000 gigawatts of energy storage worldwide by 2050. Lithium-ion batteries could shift power from day to night, and pump storage and power-to-gas systems could compensate for seasonal variation. A detailed examination of temporal fluctuations in the supply of renewable energy would likely indicate higher demand—for renewable energy plants and storage capacity—and therefore higher costs as well. At present, it is not clear how this will explicitly affect the optimal technology mix.

The spatial aggregation of countries into regions also abstracts from possible regional bottlenecks. In reality, locations with a reliable supply of renewable energy must not necessarily coincide with the locations where demand is concentrated. We also assumed unlimited transmission capacity within the ten model regions. To the extent that the model abstracts from a concrete representation of spatial balancing, technological issues regarding optimal grid dimensioning and management were not explicitly considered either. A spatially differentiated representation could involve higher expansion rates for renewable energy or downstream infrastructure—and therefore

higher costs. However, nuclear and fossil technologies would also require a certain level of infrastructure for the spatial distribution of the energy they produce. As a result of spatial aggregation, we used a simplified map of the quality of locations for wind power and photovoltaics.

Conclusions

International studies are not in agreement on their estimates of the importance of nuclear power as a technology for climate protection. There is still a discrepancy among the perspectives of a number of studies that examine the future development of the global energy system, including those of international organizations, and a microeconomic viewpoint that attributes virtually no importance to nuclear power in a competitive environment. In order to map climate protection scenarios in a global environment, this report further developed and applied an established open-source energy system model. The model optimizes the expansion pathways for different technologies by minimizing the global costs of supplying energy for electricity, heat, and transportation. In the process, it includes a remaining CO₂ budget of 650 billion tons in accordance with the target of limiting global warming to a maximum of two degrees. However, this broad spatial and temporal scope goes hand in hand with a simplified map of system integration for renewable energy.

The model results indicate that nuclear power is unnecessary for achieving future climate protection targets. In view of the high cost of nuclear power and the cost degression of renewable energy and energy storage, in purely economic terms nuclear power will be entirely phased out within the next two to three decades. It does not pay to build new nuclear power plants. Depending on the region, the cost-optimized energy mix consists of solar, wind, and hydro power, plus bioenergy supported by energy storage technologies and coupling the electricity, heat, and transportation sectors. Above and beyond the direct costs of investment and operation, the environmental costs and risks of nuclear power are highly relevant. The risks include accidents and proliferation, as well as the undetermined long-term strategy of storing nuclear waste. The present study does not address these aspects, but they must be kept in mind when abandoning an argument based exclusively on costs in favor of a comprehensive economic assessment.

Accordingly, promoting nuclear power can be viewed as counterproductive because it can hinder the development of other, less expensive sources of energy. Resources for research and development and international funding should be diverted to renewable energy, storage technologies, and the opportunities inherent in sector coupling.

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JEL: L91, L95, Q4

Keywords: Nuclear power, renewable energy, energy system model, climate policy, decarbonization