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Alternatives for current net metering policy for solar PV in the Netherlands: A comparison of impacts on business case and purchasing behaviour of private homeowners, and on governmental costs

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ABSTRACT

To stimulate grid-connected solar PV systems on private dwellings, the Netherlands currently have a net metering policy, but questions have been raised on its continuation. In this study, several alternative policy options were assessed on the financial case for private homeowners investing in a PV system (simple payback time), on purchasing behaviour (using a technology adoption model), and on governmental costs. While continuation of net metering policy leads to ongoing improvement of the financial case up to levels that could be considered overstimulation, three policy alternatives can be set up so that they stabilise simple payback times of recent and future generations of PV systems. Under these alternative instruments, deployment of PV systems in this market segment is indicatively estimated to be 15–20% lower by the year 2030 than with continuation of net metering policy, while corresponding governmental cost reduction indications would be more than 50%. We conclude that from a cost effectiveness point of view there is reason to change to an alternative instrument. We did not find any decisive arguments pro or con either of the three alternative instruments, neither on the basis of the three main impacts analysed nor from other aspects reviewed more qualitatively.

1. Introduction

For the deployment of decentral grid-connected solar photovoltaic (PV) systems in conventional electricity grids, an effective and stable policy environment is pivotal [1,2]. Next to feed-in tariffs, net metering policy is generally considered a relevant instrument to improve the financial case for households investing in a PV system, thereby providing a strong incentive for the deployment of solar PV in this market segment [3,4]. Net metering policy allows households owning a PV system (‘prosumers’) to use the electricity they produce at any time, instead of only directly when it is generated. Effectively, it results in the value of the power produced by their PV system to be equal to the consumer tariff (including taxes), irrespective of the moment of production and consumption. Since 2004, the Netherlands have a net metering policy [5], for power consumers with a small capacity connection (3*80A and smaller) to the grid. It was first introduced with a maximum of 3000 kWh/year of electricity per household that could be net metered; in 2011 this limit was increased to 5000 kWh and in 2012 the limit was abolished [6]. This made household PV power production considerably more financially attractive than in a situation in which the power delivered to the grid is only worth a net feed-in price from the energy company. Together with the strong reduction of the costs of PV systems, net metering policy is considered to have been an important factor in the rapid reduction of simple payback times for PV systems on Dutch household rooftops, and

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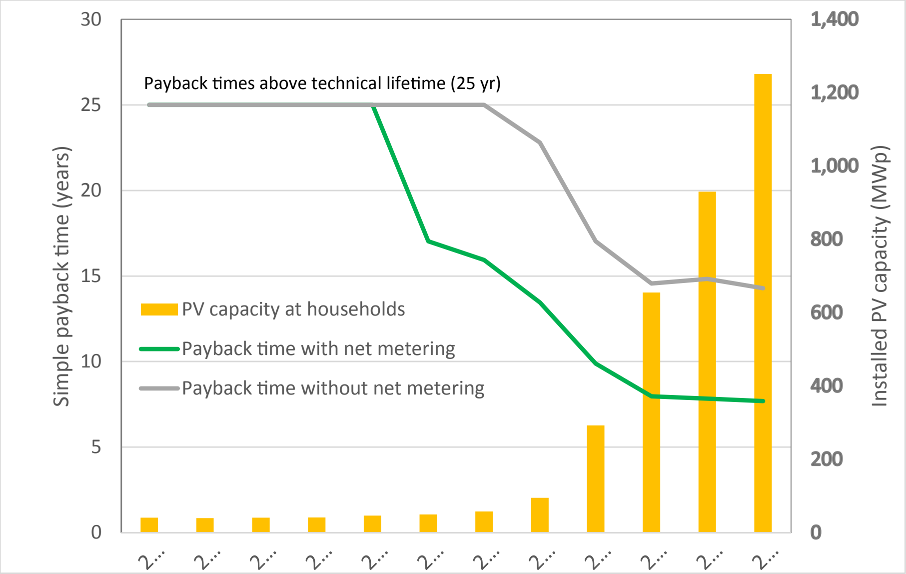

Fig. 1. Historic development of simple payback times with and without net metering for a reference household PV system, and of installed PV capacity at households in the Netherlands [6]. Due to small differences in the definition of the reference system, 2010–2015 payback times with net metering in this figure do not exactly match those in Fig. 4 for variant A.

corresponding capacity growth of these systems over the past years (Fig. 1) [6].

However, net metering policy has been under discussion in the Netherlands, mainly for four reasons. Firstly, the ongoing reductions in prices of domestic PV systems have raised the question to what extent the current net metering policy leads to overstimulation, viz. an overly profitable financial case.[3] Secondly, net metering policy leads to losses in governmental tax incomes, and with the expected ongoing growth in domestic PV systems, these losses can become significant. Thirdly, net metering policy also has practical drawbacks; for example, it strongly incentivises limiting the dimensions of a domestic PV system to the annual electricity consumption, not to the available rooftop area, leaving rooftop potential partly unused. Finally, net metering policy does not provide any incentive for PV system owners to increase their level of self-consumption (electricity produced and consumed behind the meter) and thereby reducing their use of power grid capacity. Such incentives will become increasingly important with the further roll-out of decentral PV systems as wide-spread feed-in of PV electricity can affect local power quality and increased grid capacity use [7,8]. These arguments can also be found in other studies on the pros and cons of net metering policy vis-à-vis other incentives, such as feed-in tariffs [9–11].

Because of these considerations, the Dutch Ministry of Economic Affairs requested us to explore several possible alternatives for current net metering policy, and assess these on three aspects:

- Impact on the financial case for realising a PV system (in this specific target group of small-scale connections);
- Impact on purchasing behaviour and resulting growth rate in PV systems (ditto);
- Impact on the governmental costs, c.q. losses of tax income.

During the study, we also identified several other relevant characteristics of the possible alternatives, which we discuss qualitatively in Section 3.5. This paper focusses on the analysis for private dwellings, which make up the lion's share of current and potential PV systems behind a small capacity power connection [12]. Net metering policy also covers rental dwellings and the services sector. While these make up a smaller (but possibly increasing) share of the decentral PV market, our analytical framework (particularly for the assessment of purchasing behaviour) is not suitable in its current form to address these sectors.

2. Approach

2.1. Possible alternative instruments

Based on some iteration with the client and an advisory board[4] to the project, six variants were defined (see Table 1):

- Variant A: Fully maintaining net metering is the baseline option, in which the current policy framework is kept intact.
- Variant A1: Fiscally maintaining net metering is an alternative in which net metering is kept intact for the fiscal part of the electricity tariff, viz. the energy tax, the tax for funding renewable energy (ODE), and VAT on these taxes; this is currently circa two thirds of the total consumer price, see Fig. 3. However, for the producer part of the energy tariff (currently one third), net metering is abolished: the energy company is allowed to reward electricity fed into the grid with a feed-in price lower than the consumer tariff.
- In variant B: Limiting net metering, net metering is abolished for the producer part (as in A1), and only a percentage of the

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[3] This means that the electricity production of these systems in the period after 2030 is not considered. Given technical lifetimes of PV systems, this production is considerable. This makes this indicator fit for a comparison between the policy options analysed in this study, but unfit for a comparison of governmental costs per kWh under these policy options with those under other instruments, such as the feed-in premium for large-scale PV as applicable in the Netherlands.

[4] For this project, an advisory board was set up with various representatives from the renewables sector (Holland Solar and NVDE, the association of companies working on renewables), the energy sector (Energie Nederland, the association of energy companies and Netbeheer Nederland, the association of grid operators) and the government. In three meetings, the advisory board discussed key assumptions, preliminary and final results of the study.

Table 1
Key characteristics of the six variants assessed.

	Net metering in:		New in this variant
	Producer part of power price	Fiscal part of power price	
A: Fully maintaining net metering	Yes	Yes	- (baseline)
A1: Fiscally maintaining net metering	No	Yes	Difference producer part: consumer price − feed-in price
B: Limiting net metering	No	Yes, but …	Maximum % on kWh net metered fiscally
C: Feed-in subsidy	No	No	Feed-in subsidy (€/kWh)
D: Investment subsidy	No	No	Investment subsidy (€/kW$_p$)
O: Abolishing net metering	No	No	No alternative policy

electricity that is fed into the grid and consumed on another moment is subject to fiscal net metering.

- In variant C: Feed-in subsidy, net metering is entirely abolished, and as an alternative, a feed-in subsidy is introduced for all electricity fed into the grid, next to the feed-in price the energy company already pays for it.
- In variant D: Investment subsidy, net metering is also abolished, and an alternative investment subsidy is introduced.
- Finally, Variant O: Abolishing net metering serves as the extreme reference in which net metering is abolished without introduction of any alternative support scheme.

In all variants, the value of self-consumption was kept unaffected on the full consumer price of electricity. Policy changes were assumed to take effect from 2020 onwards, and to affect all PV systems on small capacity connections, both existing and new ones. Net metering shares (in B) and subsidy levels (in C and D) can be varied over the years. In variant B and C, changes in net metering shares and feed-in subsidy levels apply to all systems producing in that year, regardless their year of purchase. This was chosen because differentiation over purchase years would lead to extensive additional administrative burden.

2.2. Financial case

The attractiveness for a household of investing in a PV system can be expressed in several ways from a simple payback time to sophisticated indicators like Internal Rate of Return or Net Present Value [13]. In practice, our impression is that consumers and salesmen of PV systems mostly communicate in terms of simple payback time (SPT), i.e. the amount of years it takes to earn back the original investment from cost savings on the power bill, not taking into account a discount rate; this was confirmed in the evaluation study of Dutch net metering policy [6]. Therefore, this indicator was used in this study.

A simple cash-flow model was set up to make the corresponding calculations. In this model four reference situations were defined:

- Large household versus smaller household;
- South versus East-West rooftop orientation.

These reference situations were assumed to differ from each other in terms of system size, annual power consumption, PV production and percentage of self-consumption (see Table 2). Capacity factors were set at 956 kWh/kW$_p$ for systems with South orientation, and 766 kWh/kW$_p$ for systems with North orientation.

Other key data inputs were:

- Cost development of the 4,5 kW$_p$ household PV system were set as in Fig. 3. This cost reduction pathway was proposed in two earlier projects and accepted as a probable estimates by stakeholders from the solar energy sector [14], by a broad set of representatives from the renewables sector [15] and in a meeting of the advisory board in this project[2]. For the 2,25 kW$_p$ reference system, the same cost pathway was used with a multiplication factor of 1,1, given the smaller scale.
- Developments in the full price of power for households (retail price and energy taxes) were taken from the 2016 National Energy Outlook [16]. The feed-in price paid by power companies for not net metered electricity fed into the grid was assumed to be 70% of the consumer tariff.

It should be noted that these outlooks of more than ten years are highly uncertain, both for the PV system costs (given the dynamic development of PV) and for power prices (given the strong changes that can be expected in the electricity system). Therefore, any source for these data will become outdated soon. This means that the conclusions of our analysis are indicative and merely useful for the analysis of the relative differences in impacts of policy instruments, not as a projection of absolute numbers.

In this analysis, we assume that the costs of PV systems in the Netherlands are independent from both the resulting simple payback time and their market development. This is a simplification we come back to in the discussion.

2.3. Purchasing behaviour and market development

From behavioural economics and social psychology, we know that a purchasing process is influenced by many other considerations beyond standard economic rationality. Various authors have analysed the adoption of PV systems by private households. These include qualitative review work of factors relevant in this adoption process, such as Karakaya and Sriwannawit (2015), statistical analyses identifying key factors affecting adoption, often based on surveys [18–24], and more qualitative studies on drivers and barriers, often using limited number of interviews [25–29]. Here we identify three categories of relevant factors: motivators, practical barriers and enablers, and factors related to awareness.

Most of these studies confirm the importance of several benefits that (potential) adopters attribute to PV systems, and act as *motivators* for the adoption process. The importance of financial profitability is found in all studies. Also the environmental benefit of solar-PV is regularly identified as a motivator [27,28]. Social status aspects (PV as a way of distinguishing oneself) are explicitly mentioned less often [18]. Finally, the impact of peers is relevant here [20,29]. Peer effects occur in two ways: by means of social comparison ('keeping up with the Joneses') but also as a source of practical experience [30].

Practical *barriers and enablers* form a second group of factors affecting the adoption process. Barriers mentioned relate to e.g. information required to make a choice [26], and trust in installers [25]. Very practical considerations in this category are available rooftop space [21] and home suitability [22].

Last but not least, *awareness* of PV plays a role in adoption, and the occurrence of a natural moment to consider purchase. On the basis of differences in awareness, Palm (2017) created a typology of

Table 2
Key dimensions of the four reference situations.

Reference situation	System size (kW_p)	Power consumption (kWh/y)	Power production (kWh/y)	Self-consumption (% of production)
Large South	4,5	4500	4300	25%
Large East-West	4,5	4500	3450	35%
Small South	2,25	3300	2150	30%
Small East-West	2,25	3300	1720	40%

adopters.

Obviously, the adoption process can also be quantitatively modelled. Islam and Meade (2013) and Islam (2014) provide curves for PV adoption probability over the years, for various classes of consumer preferences and PV system scales. However, the underlying model focuses on motivators for PV adoption and less explicitly on barriers and enablers and on awareness.

Building further on these insights, we therefore applied the CODEC-PV model to analyse PV system purchasing behaviour and corresponding (historic and future) market development. CODEC (COnsumer DEcisions Comprehended) is a quantitative simulation model on choice processes from a consumer's perspective. CODEC was developed to understand and predict the market uptake of technological innovations in the realm of sustainable energy consumption. Within CODEC, many of the non-economic considerations mentioned in the literature are explicitly incorporated in the adoption process for new technologies. CODEC was first developed for modelling of electric vehicle purchasing behaviour; for this study, CODEC-PV was specifically designed. A more comprehensive description of the model, its theoretical grounding and its applications so far can be found in a specific discussion paper [31].

2.3.1. Model setup

Central to the model is the decision-making process a consumer goes through while getting to the purchase of a PV system. This process is structured in three key phases (see Fig. 2): Attention, Enablers and Intention. These phases work as a funnel: in each phase, part of the consumers falls out, and only consumers that come through the filtering process purchase a PV system. The phases stand for the following:

- In the Attention phase, a consumer becomes aware that it is possible to produce one's own electricity by PV and develops an intention to invest in a (or replace their current) PV system. The result is the percentage of consumers that decides to orientate themselves further.
- In the Enablers phase, various practical barriers and enablers are considered that determine the feasibility and practical possibility of PV in their specific situation. Think of availability of budget for the investment and having sufficient knowledge to make an informed choice. The result is the percentage of consumers that feels able to purchase a PV system.
- Finally, the Intention phase mimics the consideration process on the attractiveness of purchasing a PV system, in which various motivators play a role: such as payback time and social comparison. The result is the percentage of consumers for whom a PV system purchase is sufficiently attractive.

Each phase has several considerations or steps that were considered, these are listed and explained some more in Table 4. Multiplication of the percentages from the three phases finally leads to the percentage of consumers that (in a given year) decides to purchase a PV system.

In the model, eight consumer groups were defined: the four reference types for the financial case analyses were taken into account (see Table 2), and each of them had two options for the current situation: with PV (possible replacement purchase) and without PV (possible new purchase).

2.3.2. Key input data

Several general datasets were used as input. The total stock of private dwellings and their distribution over the four reference situations was taken from Statistics Netherlands [32] and the WoON study [33], respectively. For the growth in the building stock in the period 2016–2030, its average historical growth of 0.94% per year in the period 2006–2015 was used [32]. Statistical data for installed capacities of PV systems were used for the period 1980–2015 [32]. For 1995–2004, these capacities were assumed to be entirely realised in the most attractive reference situation (Large South). From 2005 onwards, the model provided the distribution over the reference situations according to the decision process. For 2005–2015, the model outcomes were calibrated on the practical realisation of PV systems on private dwellings according to the background data for the Dutch National Energy Outlook [16].

Specific data for the various phases and steps in the model were derived from four sources: literature review, expert consultations, in-depth interviews with consumers and an online survey done by ECN specifically for this study.

Table 5 indicates the specific quantitative inputs that were taken in each phase and step, and Table 6 provides specific numbers for one of the steps in the Enablers phase. It should be remarked that data on behavioural aspects of a solar PV purchase process are still scarce, and as a result, the model parameterisation was not easy. As a consequence, the model provides indicative results, and is most appropriate for analysing differences between variants, not the absolute growth pathway.

2.4. Governmental costs

The assessment of governmental costs consisted of two parts:

- Avoided tax income in the cases in which net metering was (partly) maintained
- Specific costs for new policy instruments in cases in which these were introduced.

Avoided tax income due to self-consumption were not considered, nor was avoided VAT tax income.

With these assumptions, two indicators were calculated:

- Cumulative governmental costs 2010–2030 for the support of PV on private homes;
- Average governmental costs per kWh electricity produced by PV systems on private homes in the same period. [5]

The latter was calculated in two ways: with the total production of these PV systems in the denominator (so including self-consumption), and with only the power production fed into the

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[5] Although ‘overly profitable’ is usually not quantified in this context, the argument does play a role in the discussion.

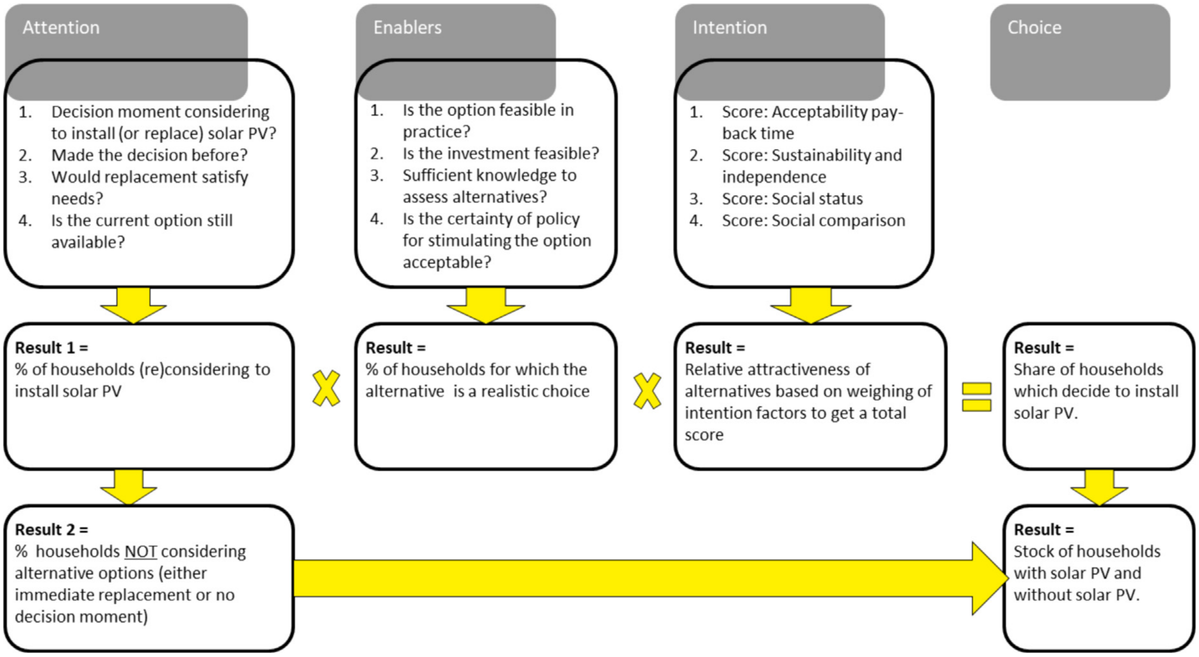

Fig. 2. Schematic representation of the key stages in CODEC-PV.

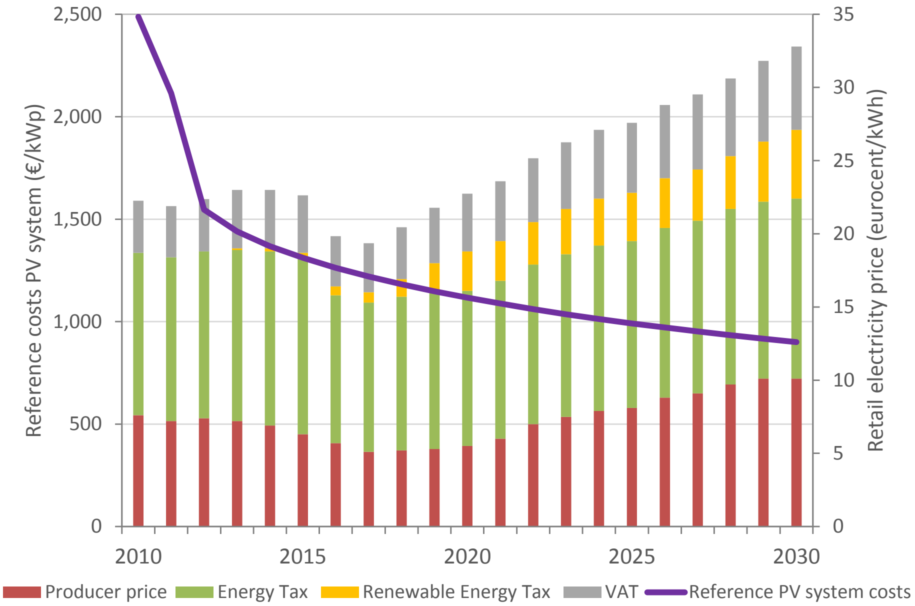

Fig. 3. Full installation cost development for the 4.5 kWp reference system, and retail electricity price with breakdown.

grid (and possibly consumed at a different stage). This because there was disagreement among stakeholders and experts which of these methods is most appropriate.

Given the uncertainties in the key inputs for the governmental cost calculations, these results are also indicative and primarily suitable for comparison of variants.

3. Results

3.1. Financial case

Fig. 4 shows the development of payback times for PV systems purchases in the years 2010–2030. In the first place, the Figure shows that simple payback times will gradually decrease to around 3 years for this reference system if net metering policy is maintained. The difference between Variant A and A1 (full maintenance of net metering vs. fiscal maintenance of it) is relatively minor, with differences in payback times of several months.

For the policy variants (B-D), our intention was to tune these instruments in such a way that simple payback times would stabilise around 7 years for all PV systems, regardless their year of purchase. Fig. 4 shows that this is technically possible, with settings of the policy variants as given in Table 3. For Variants B and C this may seem a bit counter-intuitive, as the respective policy instruments in these variants apply an annually decreasing financial incentive over all PV systems, regardless their year of purchase. But

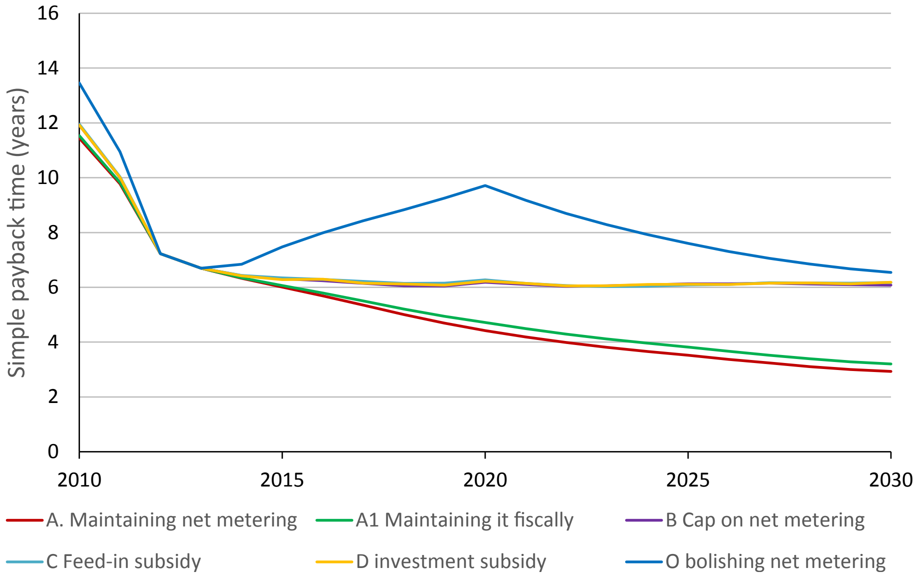

Fig. 4. Simple payback times for PV systems purchased in years 2010–2030, in case of continuation of net metering policy (A/A1), the policy alternatives (B–D) and simple abolishment of net metering policy (O). Data for the 4,5 kWp system with South orientation.

apparently this incentive can still be tuned to that it leads to relatively stable payback times. For variant D (the investment subsidy) this may seem more logical, as each annual 'generation' of PV systems receives a specific investment premium. For stabilising payback times in Variant D however, we also had to introduce investment subsidies for PV systems purchased in the years before introduction of the new instrument. In contrast to Variants B and C, investors in the years 2019 and earlier do not automatically profit from the new instrument. The extent to which it is practically possible to grant an investment subsidy to someone who purchased a PV system as early as the year 2010 is beyond the scope of this paper, although it is a clear practical drawback to this instrument.

Variant O in Fig. 4 indicates what happens if net metering policy is abolished and no alternative policy is introduced. In this variant, simple payback times go up significantly for almost the entire time horizon (2010–2030), with a peak in 2020, in which it peaks at almost 10 years. By 2030, by the time the financial incentives in Variants B-D have gradually decreased to almost zero, the difference in simple payback times between Variant O and B-D has almost disappeared.

Fig. 5 shows the differences in simple payback times between the four reference situations identified in Table 2, in this case for Variant C (feed-in subsidy). It shows that the assumed differences in system size, related investment costs, power consumption, system orientation and resulting level of self-consumption leads to differences in payback times of around two years in 2015–2020, to less than one year by 2030. Not surprisingly, large systems with south orientation show the shortest payback times, and small ones with east-west orientation the longest.

3.2. Purchasing behaviour and market development

Fig. 6 shows the annual electricity production (including self-consumption) of PV systems on private dwellings under the five variants. In reference Variant A (and A1), this production increases circa six-fold up to 2030, from slightly over 1 TWh by 2017 to more than 6 TWh in 2030. This illustrates the strong growth possibilities for PV given the improvement of the financial case (and partly limited by the non-financial factors considered in the model). In strongest contrast, the abolishment of net metering (Variant O) shows a strong stagnation of the growth path of this PV market segment, with very limited growth in 2019–2022 and a period in which growth recovers somewhat afterwards. This illustrates the importance of the financial case in purchasing behaviour: a sufficiently attractive payback time does matter.

For the Variants B-D, there is a much less strong decrease in growth rate, it is reduced by 6–9% by 2020 and 12–21% in 2030. This relatively modest growth decrease indicates that the less attractive payback times in these variants are still sufficient to mobilise a considerable number of new investors, also because there are other considerations in their purchase decision than purely financial ones.

Variant D (the investment subsidy) leads to less reduction of growth rate than Variants B and C. This is because this variant directly reduces the investment costs hurdle for private households, the fact that they have to mobilise several thousands of euros when buying a PV system (lease constructions were not part of our

Table 3
Specific annual settings for the alternative policy variants B, C and D.

Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Variant B (% met metering cap)	70%	60%	60%	55%	50%	40%	35%	25%	20%	15%	12%[a]
Variant C (feed-in subsidy €ct/kWh)	0,12	0,11	0,1	0,1	0,09	0,08	0,07	0,05	0,04	0,03	0,02[b]
Variant D (investment subsidy €/kW$_p$)	450	400	355	305	250	205	165	125	95	75	50
Variant D: Compensation for early investors (€/kW$_p$)	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	
	165	91	0	0	39	120	185	260	320	390	

[a] Decreasing to 0% in 2036.
[b] Decreasing to 0 ct/kWh in 2035.

Table 4
Considerations considered in each phase of the CODEC-PV model.

Phase, consideration	Explanation	
Attention phase	Current situation: no PV	Current situation: PV
1. Is there a decision moment?	Number of households which have the ownership of a single-family dwelling and consider installing solar PV.	Decision moment assumed to come at the end of the technical lifetime of the PV system.
2. Has the consumer made the decision before?	Assumed to be ‘no’	Assumed to be ‘yes’
3. Would repeated purchase solve the problem?	Not relevant	Percentage of households with solar PV and is (still) satisfied will replace their solar PV system when the time comes.
4. Is the current option still available?	Not relevant	If consumers replace their current solar panel, we assume there is an equivalent product available on the market.
Enablers phase		
1. Is it practically possible to install a PV system?	Typical reasons for perceived non-possibility: rooftop construction not strong enough, monumental building with additional requirements, north orientation, extensive shading	
2. Are the investment costs acceptable?	Households fall out if financial savings are actually insufficient, perceived to be insufficient, or if the household is not willing to bring in the required share of savings	
3. Sufficient knowledge of PV systems to purchase successfully?	Typical examples are basic knowledge of: • The financial aspects (system prices, current and future policy, payback time) • Maintaining the system in practice • Finding reliable installers and comparing offers	
4. Is the perceived certainty on current and future support schemes acceptable?	Relevant elements: • To what extent does policy uncertainty lead to uncertainty in the simple payback time? • To what extent can unexpected changes in the total retail price be corrected by policy changes? • Transition effects: if an alternative support scheme is introduced, how strongly will the new scheme differ from current net metering?	
Intention phase		
1. How attractive is the purchase financially?	This was related to the simple payback time	
2. How attractive is the purchase as a contribution to sustainability and reduced energy dependence?	These elements (sustainability and reduced energy dependence) are typically considerations pro purchase that can make a not very attractive payback time still acceptable.	
3. How attractive is the purchase as a means of reaching social status?	This relates to the point that people can distinguish themselves with a new technology and an interesting app. Particularly innovators and early adopters are sensitive to this consideration.	
4. How attractive is the purchase in terms of social comparison?	This consideration becomes more important by the time PV systems become more wide-spread. ‘Keeping up with the neighbours’ is more important to late majority and laggards.	

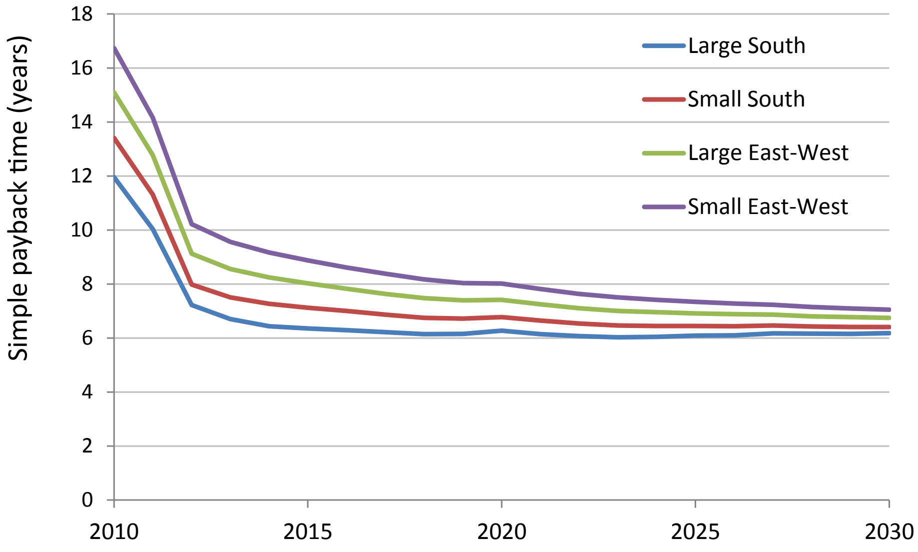

Fig. 5. Simple payback times for Variant C (feed-in subsidy) for the four reference situations identified in Table 2.

analysis). Besides, variants D and B/C differ slightly from each other in the perceived policy risks: in Variant D, these uncertainties merely relate to the moment of purchase (how high will the investment subsidy be); while in variants B and C, policy uncertainties play a role in later years (how reliable will the government be in setting the net metering ceiling and the feed-in subsidy, respectively).

Another relevant indicator is the development of the PV market: how many new systems are sold annually? This is shown in Fig. 7. Key insights from this graph are (see also the numbers in the Figure):

- The historical development can be well observed: around 2010. The market is still very small (1), because of simple payback times well over 10 years (see Fig. 4). Between 2010 and 2012, the payback time decreases strongly to levels below 10 years, inducing significant market growth (2).
- This market growth stagnates somewhat in 2016/2017, because in the model, uncertainties about the future of net metering policy starts to compensate for the effect of a still improving financial case (3). In 2017, the model assumes that the government announces which policy instrument for PV on private dwellings will be in place after 2020.

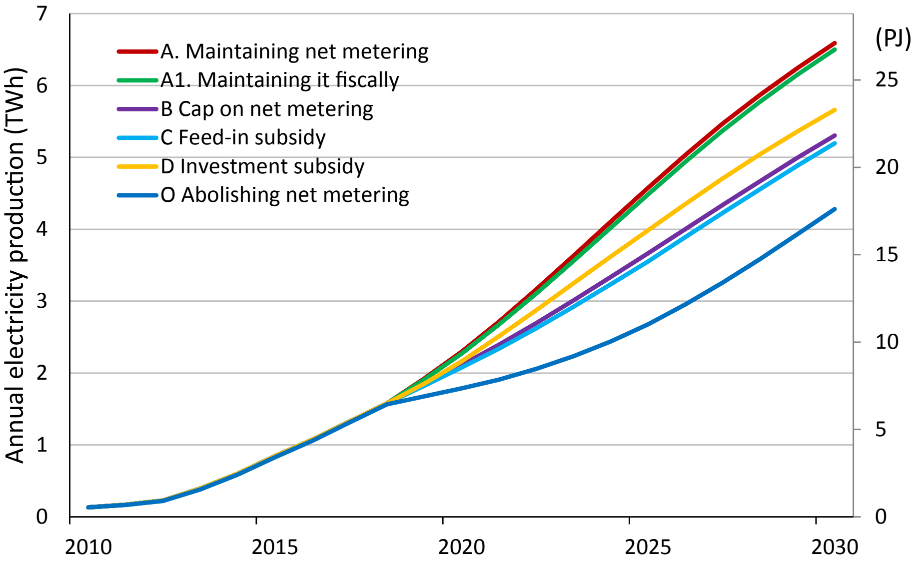

Fig. 6. Annual electricity production for PV systems on homes of private dwellings (in TWh and PJ) up to 2030, under the various policy options.

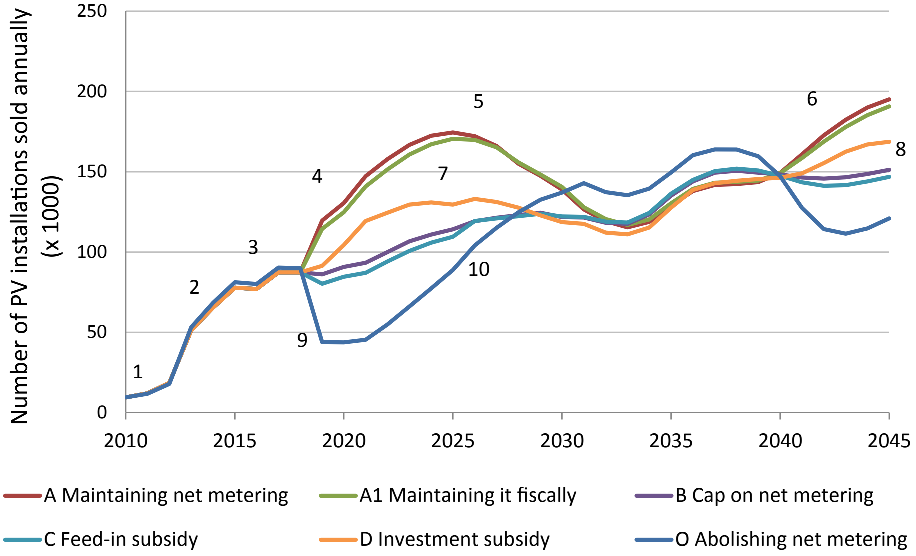

Fig. 7. Annual sales of PV systems 2010–2045 under the various policy variants.

- Due to this announcement, Variants A and A1 show a strong increase shortly after 2017, because the financial case still improves, and policy uncertainty has been reduced (4). Between 2020 and 2025, saturation effects start to occur: most home owners for whom PV is a viable option have purchased a system by then (5). From 2035 onwards, the market recovers somewhat, mainly because of replacement investments as the model assumes a lifetime of 20 years for PV systems (6).
- Variants B-D lead to a steadier market development: the peak in 2020–2025 is considerably lower than in Variants A/A1, with Variants B and C slightly more stable than Variant D (7). Also, the replacement market from 2035 is more stable (8).
- Finally, Variant O (in which net metering is abolished without a successor) leads to a strong decrease in market size, directly after its announcement (9); market size recovers to 2016 levels only by 2025 (10).

3.3. Governmental costs

Table 7 shows the cumulative cost savings for the different variants (with Variant A as the reference), and the resulting average governmental cost per kWh of electricity produced between 2020 and 2030. It indicates that the reform variants B-D reduce both cumulative governmental costs and governmental costs per kWh by more than 50%, compared to reference Variant A in which net metering is maintained. Combined with the results of the market development (section 3.2) this leads to the following: compared with the reform variants B-D, maintaining net metering (Variant A) leads to 15–25% more PV production on private dwellings by 2030, but against a more than doubling of governmental costs. The fact that annual governmental expenditures in case of net metering maintenance would rise of up 7 billion euro by 2030 (or circa 2% of total State Budget in the Netherlands by then) indicates that this would become a significant issue in public spending.

3.4. Key sensitivities

Obviously, our results are dependent on the input data, of which several are uncertain (see the discussion on the data limitations in section 4). However, the focus of our analysis is on the relative differences between the variants. On these differences, most assumptions have limited or no impact. For example, a faster than assumed reduction of PV system costs will further reduce simple payback times in Fig. 4 but will not affect the order between the variants. Besides, with changing assumptions, variants B-D can still be tuned so that they provide a stable payback time over the years of investment. Also in CODEC-PV, most assumptions affect the growth pathway of PV systems in all variants. Assumptions that do have a direct impact on the difference between Variant A on the one hand and B-D on the other are prosumers' sensitivity to changes in the simple payback time (Table 5, intention phase, consideration 1), and its relative weight vis-à-vis other considerations in the Intention phase. Furthermore, the assumed degree towards which investment costs are a barrier (Table 5 Enablers phase, consideration 2) and the effect of perceived policy stability (Enablers phase, consideration 4 and Table 6) have an impact on relative differences between all variants. These assumptions were partly based on primary survey data, partly on expert guesses, and would be a priority for further empirical grounding.

3.5. Other considerations relevant for the alternative policy options

During this study, we also identified several other characteristics of the different reform variants (B-D) worth considering, which we discuss qualitatively here.

3.5.1. Incentivising purchase or production

A key difference between Variants B/C and D is that variants B and C provide an ongoing incentive for producing electricity with PV, while the investment subsidy only reduces investment costs. Although an attractive payback time in Variant D still requires proper functioning of the PV system over its entire lifetime, there is general agreement that for technically mature options like small-scale PV, policies that incentivise production are more appropriate than investment subsidies [34,35].

3.5.2. Responsiveness to uncertainties

This difference between Variants B/C and D also has impacts on their responsiveness to uncertain future developments. Two key uncertainties affect the financial case for decentral PV: the investment costs for new PV systems, and the value of the electricity produced, the latter being affected by both market circumstances (the retail price) and by governmental influences (the electricity taxation regime, in the Netherlands mainly the energy tax, the renewable energy tax and the general VAT). Unforeseen developments in the investment costs can be well dealt with in Variant D, by monitoring investment costs developments and adapting the investment subsidy accordingly. However, this variant has limited means for dealing with unforeseen developments in the prices of electricity. Variants B and C have opposite characteristics: they can easily accommodate unforeseen changes in retail price and/or fiscal regime but can less well respond to radical changes in investment costs, because a change in net metering cap (variant B) or feed-in subsidy (variant C) also affects investors from earlier years.

3.5.3. Options for accompanying measures stimulating adoption of PV systems

Particularly the work with CODEC indicates where there are options to increase the adoption rate of PV systems with policy measures other that purely financial ones. Key options are:

- In the Attention phase (A), almost a quarter of all households is open to improving their dwelling with a PV system, which also means that three quarter is not. People may vary in the reasons why they are not open to buying PV, but this percentage can possibly be improved by general and positive communication on PV, its financial attractiveness and its relevance for the climate. To provoke attention, such communication need not be very substantive.
- In the Enablers phase (B), underlying data indicates that the actual financial investment costs are a barrier for almost half of all households. This percentage is slightly reduced in Variant B and will generally decrease with investment costs for PV going down. But it can also be reduced by the further deployment of lease constructions, or by making it easier to make the investment part of a mortgage. Such alternatives will also have an impact on the financial case.
- In the Enablers phase, a lack of knowledge and information necessary to judge an offer of a PV installer is a bottleneck to more than 20% of all households. A PV installer quality label, including e.g. standardisation of financial offers to potential clients may help reduce this percentage.
- For another 20% of all households in the Enablers phase, rooftop construction and shading effects from e.g. trees prohibit installation of PV. This cannot be solved easily but building criteria for (re)construction of new and existing rooftops can reduce this percentage in the long term.
- Finally, in the Intention phase (C), the final decision does not only depend on financial considerations but also on social status and social comparison. While this is not easily directly influenceable, generic governmental communication on PV as something that should just be part of any normal household could mobilise the social comparison factor, and thereby help tilting the balance for some of them.

4. Discussion

4.1. On the financial case analysis

The indicative financial case analysis under the different Variants confirms the drawbacks of the two extremes. Maintaining net metering leads to future simple payback times so short that questions on overstimulation and windfall profits can be reasonably expected. On the other hand, abolishing net metering policy without the introduction of an alternative leads to a sharp increase in simple payback times. This illustrates that on the short-to mid-term, additional policy is essential if simple payback times are to be made sufficiently attractive to provoke ongoing new investments [36].

The results also show that the financial case for PV on private dwellings can be stabilised over the years by the introduction of alternative instruments. By carefully tuning the exact levels of the stimuli in either of the three reform variants analysed, simple payback times can seamlessly land around 7 years. This confirms what can be found in literature: proper introduction and tuning of the chosen instrument is at least equally important as the choice for the instrument itself [37]. As such, the three instruments have also proven that they can be effective in practice in other studies [10,38,39].

4.2. On market development

The analysis of purchasing behaviour indicates that the changes in financial case correspondingly affect market development, but also that the financial case is not the only factor affecting this. In the

Table 5
Specific data inputs for each consideration/step and their motivation.

Attention phase	Percentage of households	Motivation
1. Decision moment?	• Households without PV: 23% intends to install PV within three years. • Households with PV: a 20-year lifetime defines when there is a decision moment.	• In a survey, 23% of private dwelling owners indicates to be (possibly) willing to realise a solar-PV system on their house [44] • Standard assumption.
2. Made before?	• Households without PV: No. • Households with PV: Yes.	• Standard assumption • Standard assumption
3. Repeated purchase?	Households with PV: 92% directly replaces the system after 20 years; 8% re-enters the process as 'currently no PV'	ECN survey: 92% of private dwelling owners with PV indicates to be willing to replace them after technical lifetime (n = 1394)
4. Still available?	Households with PV: 100% availability current option.	Basic assumption
Enablers phase	**Percentage of households (currently no PV)**	**Motivation**
1. Practically possible?	80%	In a sample for a Dutch region, 20% of all rooftops appeared to be unfit for PV systems [45]. Difference between actual and perceived fitness not considered
2. Investment cost acceptable?	2005: 26% 2015: 53% 2030: 62%	Investment costs: as in Fig. 3, possible investment subsidy considered Saving accounts private home owners: Statistics Netherlands [46] Acceptable share for investment: in consultation with several bank experts
3. Sufficient knowledge of PV systems?	2005: 50% 2017: 77% 2030: 95%	ECN survey: for 23% of the respondent, lack of sufficient knowledge on solar PV is currently a decisive barrier for a potential purchase (n = 793) Numbers for 2005 and 2030 are assumptions, interpolation by an S-curve
4. Certainty on policy acceptable?	Differentiated between the variants	See Table 6
Intention phase	**Input and relative weight in the overall consideration**[a]	**Motivation**
1. Financial attractiveness	Simple payback time of 6.7 years sufficiently attractive for 50% of population Relative weight: 75%	Actual payback times dependent on year, reference situation and Variant (see section 3.1) ECN survey (n = 922); average and shape of the curve taken into the model. ECN survey (n = 2520)
2. Attractiveness for sustainability and energy independence	Having PV gets a score of 1, not having it gets a score of 0. Relative weight: 6%	Standard assumption. ECN survey (n = 2520),
3. Social status	Up to 2012, almost 100% of households with PV obtain social stats from it; this decreases to roughly half by 2016.By 2020 this effect is 10%, fading out to zero by 2024. Relative weight: 5%	Innovation diffusion theory [47], quantification through expert judgment by the authors ECN survey (n = 2520)
4. Social comparison	In 2016, roughly 12% of the households experience an incentive for PV by comparing themselves with neighbours, increasing to 60% in 2020 and 100% in 2030. Relative weight: 14%	Innovation diffusion theory [47], quantification through expert judgment by the authors ECN survey (n = 2520),

[a] In the Intention phase, the percentage for whom the purchase is sufficiently attractive is calculated by a weighted average of all four considerations. The relative weights of the arguments were based on the ECN survey (n = 2520).

reform variants in which simple payback times are stabilised around 7 years, market development is only reduced by maximally 20% compared to maintaining net metering. The differences between the three reform variants are relatively small.

Quantitative models on the adoption process for PV purchasers are still relatively rare, and the ones that do exist often take the financial dimension of the purchase as the central point, such as the SolarDC model [40–42], while other empirical material indicates that several other factors also influence the purchase process [17,19–22,30,43]. However, no quantitative models that estimate future market development with a comparable level of quantitative and behavioural detail as in CODEC-PV were found in the literature.

4.3. On governmental costs

The indicative analysis of governmental costs confirms one of the key starting assumptions of the study, viz. that there are better alternatives for current net metering policy, which still lead to robust growth of decentral PV but against significantly lower costs and with a smaller risk of overstimulation.

4.4. On the approach as a whole

In total, the study illustrates the relevance of combining techno-economic and social-scientific approaches in addressing questions related to consumer behaviour. With the increasing decentralisation of energy options, both supply-side (e.g. solar PV) and demand-side (electric vehicles, low-carbon home heating technologies), such analyses will become more and more relevant, also from a policy perspective.

4.5. Methodical limitations

Several methodical simplifications to this study are worth explicit mentioning. Firstly, we have assumed retail prices of PV systems for households not to be dependent on the policy instrument applied and resulting payback time and market volume. In practice, there will certainly be feedbacks between these factors and retail prices, both positive (e.g. market growth leads to scale leads to lower prices) and negative (e.g. a very attractive financial case reduces the pressure on suppliers to provide a very competitive offer). It was beyond the scope of this paper to go into more detail on this matter.

Secondly, the wide range of financial cases for different households was reduced into four reference cases. We consider this a defendable simplification.

Thirdly, the technical performance of PV systems will further develop over time, and more and more building integrated PV

Table 6
Percentage of households for whom the uncertainty in policy is a decisive barrier for a PV system purchase[a].

Variant	% of households for whom the uncertainty in policy is a decisive barrier for a PV system purchase							
Year	2005	2010	2015	2017	2018	2020	2025	2030
A: Fully maintaining net met.	5%	10%	20%	30%	10%	5%	5%	5%
A1: Fiscally maintaining n.m.	5%	10%	20%	30%	10%	5%	5%	5%
B: Limiting net metering	5%	10%	20%	30%	15%	15%	12%	10%
C: Feed-in subsidy	5%	10%	20%	30%	20%	20%	13%	10%
D: Investment subsidy	5%	10%	20%	30%	20%	16%	12%	8%
O: Abolishing net metering	5%	10%	20%	30%	30%	20%	15%	10%

[a] Key underlying considerations to this table.

- In 2005–2015, there was no political discussion on the future of net metering, policy certainty was high.
- In 2014, the minister announces an evaluation of net metering policy by 2017, and that it might be abolished by 2020. Therefore, we assume an increasing public perception of uncertainty in 2015–2017.
- We assume that by 2018, a decision on net metering and its potential alternatives is announced, which generally reduces uncertainty. This reduction is strongest in Variants in which changes are smaller (A, A1, partly B) and smaller in C and D, where policy changes are stronger.
- Finally, we made some variant-specific uncertainties explicit:
  - o Variant A and A1: Relatively high certainty from 2018 onwards, quickly coming back to 2005 level
  - o Variant B: As net metering is not abolished but gradually phased out, more uncertainty than A/A1, particularly in initial years after 2018. Also, by 2030 uncertainty is higher than in these variants.
  - o Variant C: As net metering is abolished and replaced by another instrument, more uncertainty than B in initial years after 2018. In the long term, policy uncertainty is comparable with B.
  - o Variant D: An investment subsidy for household PV has a bad reputation in the Netherlands because of ill-conceived application in 2012–13, therefore comparable initial uncertainty in 2018 as variant C. However, as the instrument provides a one-off subsidy in the investment stage and changes later on do not affect existing systems (in contrast to Variants B and C, in which existing systems can also be affected by policy changes later on), long-term uncertainty is assumed to be in-between B/C and A/A1.
  - o Variant O: Full abolishment of net metering policy will lead to a stronger dip in policy confidence by 2018 compared to variants B-D. This difference is assumed out to fade out towards 2030.

Table 7
Cumulative cost savings (up to 2030) compared to continuation of net metering policy of the various alternatives, and corresponding governmental costs for renewables.

	Cumulative cost savings (2020−2030) compared to variant A		Average governmental costs (2020–2030) in €/kWh[b]	
	Billion €	%	Incl. self-consumption	Excl. self-consumption
A Maintaining net metering	(ref)[a]	(ref)	0.11	0.15
A1 Maintaining it fiscally	0,1	1,5%	0.11	0.15
B Cap on net metering	4,5	62%	0.04	0.06
C Feed-in subsidy	4,3	59%	0.05	0.07
D Investment subsidy	4,6	67%	0.04	0.06
O Abolishing net metering	6,6	89%	0,01	0,06

[a] Cumulative costs for Variant A were 7 billion euros.

[b] Indicator only suitable for comparison of instruments within this study, not for comparison with other instruments; see text footnote 3.

options are expected to come into the market. While we have assumed gradual performance improvement of current systems over time, we have not considered entirely new concepts.

Fourthly, the practical issues related to a reform from net metering policy into an alternative have not been assessed in full detail. Most pregnant issue found is that all proposed policy alternatives require households owning a PV set to use a ‘smart meter’, or more specifically a meter that separately registers consumption from and feed-in into the grid. Distribution system operators in the Netherlands are in the roll-out process of these meters, and we have assumed here that this will not be a limitation to policy change.

Fifthly, impacts or policy reforms were reviewed on their impact on financial case, market development and governmental costs. Various other aspects, often part of ex-ante impact assessments of policy changes, were not studied. Think of practicability and steerability (for the government), administrative burden for other stakeholders (such as energy companies and grid operators), understandability for the target group, and minimal market disturbance.

Sixthly, while the CODEC model applies a relatively sophisticated approach to consumer behaviour, this remains a matter that is very hard to model in a quantitative way, given the wide variety of aspects that influence consumer behaviour. Therefore, the results should be considered indicative, and differences between variants more relevant than their absolute outcomes.

Seventhly, as mentioned in the introduction, our analysis is focused on private dwellings, currently the main market segment for decentral PV systems. Particularly the assessment of impacts on purchasing behaviour in rental dwellings and the services sector requires a different method.

Finally, the model takes a consumer perspective. The fact that this will also be strongly influenced by what a potential installer of PV systems will convey in the offer he or she provides was not part of the analysis.

4.6. Data limitations

In terms of the data applied, we'd like to stress the following limitations. Firstly, for several key data in the financial calculation, surprisingly little information could be found. Clearest example for this is the average percentage of self-consumption of PV electricity. It may be that privacy and data protection issues seem to make it difficult to make such figures public. Our estimate on this point should be considered indicative.

Secondly, with the dynamic developments in the power sector, it is extremely difficult to estimate future electricity prices, prices of PV systems, and the future fiscal regime as well.

Thirdly, the parameterisation of a behavioural model is never without its difficulties, and that also applied for CODEC. While we are convinced that we have used a state-of-the-art dataset, we must remain careful in drawing too far-reaching conclusions from the outcomes.

However, the relative differences in outcomes between the variants are much less dependent on our full data set than the absolute results. Therefore, while updates of data inputs will certainly show differences with our assumptions, we are convinced that our key conclusions are relatively robust, as they focus on the differences between the variants. Key data inputs that affect the differences between the variants are indicated in section 3.4.

5. Conclusions

Taking the limitations mentioned in section 4 into consideration, our key conclusions are as follows. Several alternative policy instruments can be conceived and introduced in such a way that the financial case for household investors in decentral PV stabilises over the future years of investment, here expressed as simple payback time stabilisation between 6 and 7 years for the four reference situations. Under these alternative instruments, deployment of PV systems in this market segment is estimated to be 15–20% lower by the year 2030 than with continuation of net metering policy, with relatively small differences between the three different instruments (limiting net metering, a feed-in subsidy and an investment subsidy). Corresponding governmental cost reductions in the alternative cases would be more than 50%. From a cost effectiveness point of view, we conclude that there is reason to change to an alternative instrument, also when we take into account the limitations of approach and data.

We did not find any decisive arguments pro or con either of the three alternative instruments, neither based on the three main impacts analysed nor from other aspects reviewed more qualitatively. From the analysis of consumer behaviour, we also identified various options for accompanying policies stimulating market development of PV systems, such as general communication efforts, unburdening of the consumer in the purchase process, and reduction of the investment barrier through specific loans and lease constructions.

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