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**TNO report**

## TNO 2022 P10368

# Barriers to demand response

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| Number of pages | 71 (incl. appendices) |
| Number of appendices | 2 |
| Sponsor | Ministry of Economic Affairs and Climate Policy of the Netherlands |
| Project name | Energy market modelling |
| Project number | 060.47628/01.04 |

# Summary

## Background and research question

Reduction of greenhouse gas emissions implies electrifying demand and decarbonising electricity production. Decarbonising electricity production is for the most part achieved by increasing the production from variable renewable energy (VRE) sources. The increasing share of VRE production increases demand for flexibility to balance supply and demand. This flexibility can be supplied by some combination of electricity storage, cross-border trade, dispatchable production, curtailment of VRE and demand response (DR). Of these flexibility sources DR is of increasing interest.[1]

To analyse the effect of an increasing share of VRE on the energy system, energy models are used to model the supply and demand of flexibility. TNO has worked on modelling the supply and demand for flexibility since the FLEXNET project and several follow-up projects (Sijm et al., 2017, 2020). An accurate representation of DR in energy models is important to draw valid conclusions on the supply and demand for flexibility. Therefore, TNO recently updated the COMPETES model by including four demand response technologies (Sijm et al., 2022) based on the theoretical framework described in (Morales-España et al., 2022). The included DR technologies are:

1 Power-to-hydrogen (P2H2);
2 Hybrid industrial boilers;
3 All-electric residential heat pumps; and
4 Electric vehicles (EVs).

The COMPETES modelling shows a substantial size and role for DR. The modelling results raise the question whether such a substantial size and role for DR is realistic. Although the model includes some constraints for DR, other barriers might be present that are excluded from the model. That could result in an overestimation of the potential supply of flexibility from DR.

To realistically estimate the potential supply of flexibility from DR, persistent barriers to DR should be included in the model. In addition, other barriers may be present that can be overcome or reduced by changing policies. Such barriers should not be included in the model, but addressed by implementing policies that unlock the DR potential. Thus, an analysis of barriers to DR can be used in follow-up research to (i) more realistically model persistent barriers to DR and (ii) suggest policies that unlock the DR potential. The goal of this report is to provide such an analysis of barriers to DR.

This leads to the following research question for this report:

- *Which barriers for DR that will impact the supply of flexibility from DR to balance supply and demand are present in the Netherlands?*

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[1] DR can supply flexibility that can be used either to balance supply and demand or to avoid grid congestion. This report focusses on the use of DR to balance supply and demand and excludes the use of DR for congestion management.

In this report we answer this question both in general and for the four technologies included in the COMPETES modelling in particular. We answer the research question by reviewing the literature. Both scientific and applied literature are included in the review. Given the wide scope of this report we do not claim to have exhaustively reviewed all available literature on the topic of barriers to DR. As a result, there might be other barriers than those presented in this report.

### Conclusions

In this report we discuss many different barriers for DR in general and for the four technologies specifically. The barriers are of a technical, economic or behavioural nature and are often interrelated. We structure the analysis of the barriers by discussing (i) barriers to electrification, (ii) preconditions for DR, (iii) costs and benefits of DR and (iv) deciding on participation in DR. We summarise the results here by using the same structure.

*Barriers to electrification*

To participate in DR there first needs to be a demand. Thus, barriers to electrification will need to be overcome for DR to play a relevant role. We conclude that there are still many general and technology specific barriers to electrification:

- In many cases the fossil-fuel alternative is still the cheapest option;
- There is competition from other, non-electric, options to reduce emissions;
- Electrification requires significant expansions of the electricity grid.

As a result, the market penetration of the technologies discussed in this report will depend on the extent to which these barriers are overcome.

*Preconditions for DR*

When there is a demand asset connected to the grid, then in principle it is possible to participate in DR when certain preconditions are met. These preconditions are:

- Ability to flexibly operate the asset(s)
- Sufficient grid capacity to flexibly operate asset(s)
- Proper incentives to reduce electricity costs by participating in DR
- No distorted incentives from grid tariffs and taxation
- Access to markets
- Accurate measurement and enforcement of DR

Several of these preconditions aren't met, resulting in barriers to DR. We conclude the following:

- <u>Ability to flexibly operate the asset(s):</u> For all the four technologies discussed in this report there is an ability to flexibly operate the assets. That flexibility can be constrained by (i) saturation and load recovery characteristics of DR, (ii) the ramping ability of the asset, (iii) the availability of the asset to provide DR and (iv) the reliability of the response as a result of the control mechanism for DR. It appears that there are more constraints to DR for the residential technologies (all-electric residential boilers and EVs) than for the large-scale technologies (hybrid industrial boilers and P2H2). For the residential technologies striking the right balance between enabling DR through automation without reducing the comfort of the end-user is a challenge.

- Grid capacity to flexibly operate asset(s): the deployment of DR for balancing purposes can both increase and decrease the required grid capacity. Although the effect of DR on the individual end-users grid capacity can sometimes be determined (i.e. load shifting can increase individual peak consumption whereas curtailment reduces the required grid capacity), the effect on the total grid capacity required for the electricity system is ambiguous because it depends on the flexibility source that would be used in the counterfactual situation without DR and the location of that flexibility source. In general we can conclude that DR has the potential to reduce the need for grid capacity when closely located with VRE. However, there is a lack of locational incentives in the current market design that incentivise the optimal location of DR assets.

- Proper incentives to reduce electricity costs by participating in DR: In principle the wholesale market design ensures that demand flexibility is valuable to balancing responsible parties (BRPs) and balancing service providers (BSPs) and, thus, incentivises DR. However, there are some important barriers. First, the incentives for DR need to be passed on to end-users via intermediaries (BRPs, BSPs, energy suppliers and independent aggregators). Incentives can be passed through via implicit or explicit contracts. Implicit DR incentivises DR by time-varying prices to which the end-user responds. Explicit DR incentivises DR by an explicit contract where the end-user promises to respond to an instruction to adjust the load. This pass-through of incentives via implicit or explicit DR often leads to diluted incentives, in part because the end-user may want to limit its exposure to risk. In addition, the net-metering of residential VRE production disincentivises simultaneous self-consumption.

- No distorted incentives from grid tariffs and taxation: Grid tariffs for large industrial end-users (i.e. hybrid industrial boilers and P2H2) distort incentives to provide DR, because (i) the tariff driver is the yearly and monthly individual peak consumption and (ii) the volumetric discount for large industrial end-users depends on the operating time (in Dutch: *bedrijfstijd*). This strongly incentivises baseload consumption even when the effect of DR on the required grid capacity is ambiguous. Abolishing the volumetric discount for large industrial end-users and reforming the tariff driver can enable DR. Furthermore, the electricity tax is levied on the basis of the annual consumption (kWh), which excludes the price of electricity. Although it is not always the case that this “distorts” the incentives for DR[2], it also doesn’t support DR. Reforming the electricity tax to a percentage on electricity costs ensures that a reduction of the electricity price as a result of DR also leads to lower electricity taxes, thus enabling DR. Furthermore, making the electricity taxes less regressive can limit distorted incentives to participate in DR in specific cases.

- Access to markets: Significant improvements have been made in recent years to improve the access to balancing markets. A minor remaining barrier is the symmetric procurement of FCR capacity by TenneT. Furthermore, the access to markets for residential end-users requires aggregation. Thus, barriers to aggregation are barriers to market access for residential end-users. There are important barriers for independent aggregators (i.e. aggregation by a third party

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[2] In case of load shifting, the annual consumption doesn’t change and so the electricity taxes aren’t affected by load shifting.

and not by the energy supplier) that are related to the measurement and enforcement of DR which we discuss next.

- Accurate measurement and enforcement of DR: To accurately incentivise DR it is important that the response can be measured and the contractual arrangements from both implicit and explicit DR can be settled. For implicit DR that requires that a smart meter is installed, which is currently not the case in the Netherlands for 15% of residential end-users. For explicit DR, in addition, the counterfactual consumption without DR, also called the baseline consumption, has to be determined. There are several issues with the baseline methods (Ziras et al., 2021) and the use of baselines leads to adverse selection and moral hazard problems (Chao, 2011). When energy supply and aggregation are split over different agents (i.e. independent aggregation), any load adjustment resulting from DR by an independent aggregator will result in an imbalance for the BRP (Vallés et al., 2016). This requires contractual arrangements between energy supplier, independent aggregator and their respective BRPs to determine the effect of DR relative to a baseline consumption level. Given the issues with the use of baselines, this leads to issues for the measurement and enforcement of DR incentivised by independent aggregators.

*Costs and benefits of DR*
When the preconditions for DR are met, the next question is whether for a specific technology and in a specific market context there is a positive business case for DR. The business case for DR depends on the costs and benefits of DR, which we discuss from both a private and social perspective.

- Benefit of DR: Participation in DR generally leads to lower energy costs, because the average electricity price is reduced (implicit DR) or additional revenues are obtained (explicit DR). From a social perspective DR reduces the need to curtail VRE, leads to a higher share of VRE in the system and reduces the need for dispatchable power plants as back-up. Thus, DR can reduce the overall costs and emissions of electricity production. These benefits to the electricity system are passed-through to end-users via implicit or explicit DR contracts, resulting in a reduction of the electricity costs.

- Costs of DR: There are several types of costs associated with participation in DR. We distinguish (i) costs of flexible operation of the asset, (ii) costs of grid tariffs, (iii) costs of taxation, (iv) costs of reduced value of outputs and (v) costs of unlocking DR. As discussed previously, the costs of grid capacity and taxation can have a large impact on the private business case even when there is a positive business case for DR from a social perspective (i.e. distorted incentives for DR resulting from grid tariffs and taxation). Furthermore, there is clear difference between the residential (all-electric residential heat pumps and EVs) and industrial technologies (hybrid industrial heat pumps and P2H2). For the industrial technologies there are clear monetary costs of flexible operation or reduced value of the outputs that can be quantified. In addition, these technologies require significant additional investments to be able to participate in DR (i.e. expansion of electrolyser capacity or combining a gas and E-boiler). The costs of unlocking DR appear to be of limited relevance for these technologies. In contrast, for the residential technologies the most relevant costs are related to the reduced value of outputs and costs related to unlocking DR. These are hard to quantify costs like a loss of comfort, a loss of control and a loss of privacy.

These “costs” are also not fixed, but can be influenced as we discuss in the next section. In addition, for the residential technologies the costs of participating in DR require limited additional investments (smart meter, ICT-systems) in addition to the investments in the assets (i.e. EV and heat pump).

*Deciding on participation in DR*

Even when there is a positive business case for DR (from both a private and social perspective), there can be barriers that prevent the end-user from participating in DR. These barriers are related to (i) financial constraints, (ii) inertia, (iii) consumer values and (iv) the form of information. These barriers are especially relevant for residential end-users and appear of limited relevance for industrial end-users.

- Financial constraints: When there is a positive business case for DR but DR requires investments, financial constraints can be a barrier to DR. The investments needed to enable DR for the residential end-users (i.e. all-electric heat pumps and EVs) appear to be limited but they are added to the high investments needed in the all-electric heat pump or EV. Many residential end-users will not be creditworthy enough to access capital markets and have limited savings, thus preventing them from participating in DR.

- Inertia: Inertia is another factor that will significantly limit the participation in DR from residential end-users, as many residential end-users simply won’t take any decision about participating in DR even when the benefits of doing so are obvious.

- Consumer values: The weight end-users place on hard to quantify costs like a loss of comfort or privacy but also on the wider benefits of DR (such as emission reduction) can be informed by consumer values (Good et al., 2017), such as autonomy, ownership, power and control. These consumer values can prevent end-users giving up control over some of their devices to participate in an automated response and sharing data that is required for the measurement of the response. Other consumer values such as environmental values could stimulate the participation in DR. This also suggests that it matters by whom the DR programme is sold to residential end-users and which values are signalled. Thus, these “costs” are probably not fixed, but they can be influenced by aligning DR with the consumers values. For example, trust between the aggregator or energy supplier and end-user is an important factor that will influence the end-users decision to participate in DR (Good et al., 2017).

- Form of information: The form of information that is exchanged between the end-user and the aggregator or energy supplier is another factor that can influence the decision to participate in DR. For example, implicit DR requires timely information about prices that the end-user can respond to. Explicit DR requires some instruction from the energy supplier or aggregator to adjust the load. Especially in case of a behavioural response poor design of the user interface can be a barrier to DR (Good et al., 2017), but also in case of an automated response it is important that the end-user is informed about the adjustment of the load in a proper way.

# Contents

**Appendices**

# 1 Introduction

Reduction of GHG-emissions implies electrifying demand and decarbonising electricity production. Decarbonising electricity production is for the most part achieved by increasing the production from variable renewable energy (VRE) sources. The increasing share of VRE production increases demand for flexibility to balance supply and demand. This flexibility can be supplied by some combination of electricity storage, cross-border trade, dispatchable production, curtailment of VRE and demand response (DR).

Of these flexibility sources DR is of increasing interest. The U.S. Department of Energy (2006) defines DR as “changes in electric use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.” In practice, demand response is just *curtailment* or *shifting* of consumption at times when it is valuable to the electricity system (Morales-España et al., 2022).[3]

To analyse the effect of an increasing share of VRE on the energy system, energy models are used to model the supply and demand of flexibility. TNO has worked on modelling the supply and demand for flexibility since the FLEXNET project and several follow-up projects (Sijm et al., 2017, 2020).

An accurate representation of DR in energy models is important to draw valid conclusions on the supply and demand for flexibility. Therefore, TNO recently updated the COMPETES model by including four demand response technologies (Sijm et al., 2022) based on the theoretical framework described in (Morales-España et al., 2022). The included DR technologies are:

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2 Hybrid industrial boilers;
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The COMPETES modelling shows a substantial size and role for DR. The modelling results raise the question whether such a substantial size and role for DR is realistic. Although the model includes some constraints for DR, other barriers might be present that are excluded from the model. That could result in an overestimation of the potential supply of flexibility from DR.

To realistically estimate the potential supply of flexibility from DR, persistent barriers to DR should be included in the model. In addition, other barriers may be present that can be overcome or reduced by changing policies. Such barriers should not be included in the model, but addressed by implementing policies that unlock the true DR potential. Thus, an analysis of barriers to DR can be used in follow-up research to (i) more realistically model persistent barriers to DR and (ii) suggest policies that unlock the DR potential. The goal of this report is to provide such an analysis of barriers to DR.

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[3] DR can supply flexibility that can be used either to balance supply and demand or to avoid grid congestion. This report focuses on the use of DR to balance supply and demand and excludes the use of DR for congestion management.

This leads to the following research question for this report:

- *Which barriers for DR are present in the Netherlands that will impact the supply of flexibility from DR to balance supply and demand?*

In this report we answer this question both in general and for the four technologies included in the COMPETES modelling in particular. We answer the research question by reviewing the literature. Both scientific and applied literature are included in the review. Given the wide scope of this report we do not claim to have exhaustively reviewed all available literature on the topic of barriers to DR. As a result, there might be other barriers than those presented in this report.

This report is structured as follows:
- In chapter 2 we discuss the framework for analysing barriers to DR as well as general (i.e. not technology specific) barriers to DR;
- In chapter 3 we discuss technology specific barriers to DR for power-to-hydrogen;
- In chapter 4 we discuss technology specific barriers to DR for hybrid industrial boilers;
- In chapter 5 we discuss technology specific barriers to DR for all-electric heat pumps;
- In chapter 6 we discuss technology specific barrier to DR for EVs; and
- In chapter 7 we present the conclusions of this report.

# 2 Framework for barriers to demand response

In this chapter we describe the framework for the analysis of barriers to DR as well as barriers that are not technology specific. Barriers to DR can be of technical, economic or behavioural nature (Good et al., 2017). The barriers are often interrelated. An enabling factor for one barrier can lead to another barrier. For example, the development of smart meters enables the measurement of DR (overcomes a technical barrier), but raises privacy concerns (raises a social/behavioural barrier).

To structure the discussion of barriers we make a distinction between:

- Barriers to electrification (section 2.1);
- Preconditions for DR (section 2.2);
- Costs and benefits of DR (section 2.3); and
- Deciding on participation in DR (section 2.4).

The idea behind this structure is as follows:

- Barriers to electrification: To provide DR, there first needs to be a demand for electricity. Therefore, we also discuss the barriers to electrification. The barriers to electrification are the barriers for the market penetration of the demand asset(s). In this report we make a distinction between barriers to electrification (i.e. barriers for the market penetration of the asset) and barriers to DR (i.e. barriers for electricity demand to respond flexibly, assuming a given market penetration of the asset). However, evidently, barriers for the market penetration of the asset(s) are barriers to provide DR with the asset(s).Technology specific barriers to electrification are discussed in the technology specific chapters.
- Preconditions for DR: When there is a demand asset connected to the grid it can provide DR if certain preconditions are met. These preconditions for DR relate to the flexibility of the demand asset(s), the grid capacity needed for DR and the (market) mechanisms required to unlock this flexibility. When the flexibility of the asset(s) is constrained or the required (market) mechanisms for DR are not in place, that implies there are barriers to DR. To the extent that these barriers are technology specific, they are discussed further in the technology specific chapters.
- Costs and benefits of DR: When there is a flexible demand asset connected to the system and the preconditions are met, the next question is whether for a specific technology and in a specific market context, the benefits of participating in DR outweigh the costs. We discuss the (types of) costs and benefits of DR that determine the business case for DR. From a private perspective any costs of DR can be seen as a barrier for DR, because lower costs will improve the business case for DR. From a social perspective, DR is desirable when the social benefits of DR from a social perspective outweigh the social costs of DR.[4] Any deviations between costs and benefits of DR from a social and private perspective will be highlighted in section 2.3.
- Deciding on participation in DR: Even when there is a positive business case for DR (from both a private and social perspective), there can be barriers that prevent the end-user from participating in DR. Especially for residential end-users

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[4] Ideally, the (market) mechanisms that enable and incentivise DR internalise all social costs and benefits. These (market) mechanisms to unlock DR are discussed in section 2.2.

deciding if and how to participate in DR is not merely a matter of maximizing utility based on costs and benefits. Financial constraints as well as behavioural aspects will influence the decision to participate in DR. We discuss these barriers in section 2.4.

## 2.1 Barriers to electrification

Electrification is the transition away from technologies that use fossil fuels to technologies that use electricity (Cleary, 2019). Electricity currently only accounts for 20% of the final energy consumption in industry, transport and buildings worldwide (IEA, 2021b). Electrification will play a particularly key role in decarbonizing the industrial and residential heating and transport sectors (IEA, 2021b).

Electrification requires investments in electric technologies such as heat pumps, E-boilers, electrolysers and EVs to replace their fossil fuel alternatives. A barrier to electrification is the fact that the fossil fuel alternative is often still the cheapest option. Pricing of emissions or setting emission standards are required to enable electrification. When the costs of electrifying the demand are lower than the costs of the fossil fuel alternative, there can still be a financial barrier when electrification requires higher initial investments and end-users are not capable to finance those investments.

Furthermore, to achieve emission reductions electrification competes with other non-electric emission free technologies. For example, an industry can electrify or store the emissions resulting from burning fossil fuels (CCS). This competition can be considered a barrier to electrification.

With electrification it is essential that the electricity sector itself is decarbonized to avoid that emissions shift to electricity production (Cruz et al., 2018). A lack of emission free power supply technologies such as from VRE sources, nuclear and bio-based fuels can be a barrier to electrification. Scaling up supply from VRE sources can lead to social challenges. Not in my backyard (NIMBY) is a term used to describe local opposition to VRE sources being built in their area (Batel, 2020). Nuclear and bio-based fuels are not uncontroversial as well. If there is insufficient supply of clean electricity, electrifying demand doesn’t reduce emissions which is a barrier to electrification.

In addition, electrification will require expansion of the power grid. Although flexibility sources can help reduce the strain on the grid, there is nevertheless a need to reinforce it. This not only requires investments from the grid operators but also requires large-scale structural and logistics planning. Insufficient grid capacity is a barrier to electrification.

## 2.2 Preconditions for demand response

We distinguish six preconditions for DR:

1. Ability to flexibly operate the asset(s)
2. Sufficient grid capacity for DR
3. Proper incentives to reduce electricity costs by participating in DR
4. No distorted incentives from grid tariffs and taxation
5. Access to markets

6 Accurate measurement and enforcement of DR

Preconditions 3 to 6 are based on the framework in a study by TenneT (2021).[5] We added preconditions 1 and 2, which are more technology specific.

### *2.2.1 Ability to flexibly operate the asset(s)*

DR is provided by some combination of load shifting and curtailment in response to a (price) signal (Morales-España et al., 2022). Therefore, a precondition for DR is that the asset(s) can be operated flexibly, to be able to respond to a signal by increasing or decreasing the load.

The ability to flexibly operate the asset(s) is constrained by a number of factors:

- Saturation and load recovery: Load shifting or curtailment can be constrained by saturation and load recovery (Morales-España et al., 2022). Saturation refers to the fact that at some level of load shifting or curtailment the maximum level is reached and it is not possible to further curtail or shift the load. Load recovery refers to the fact that after curtailment or load shifting, the load needs to recover to maintain on the same average level.
- Ramping ability: Assets differ with respect to their ramping ability. A very flexible asset can ramp up or down the load quickly in response to a signal. However, the rampingability of most assets is constrained by factors like the ramp rate and cold start-up times. These constraints can be a barrier to DR. Because the constraints are technology specific, they are discussed in the technology specific chapters.
- Availability: A factor that determines the ability to flexibly operate asset(s) is the availability of the asset. For example, EVs can only provide DR when they are plugged in to the grid, whereas an electrolyser can respond almost all the time. Where relevant (e.g. EVs) we discuss the availability of the asset(s) in the technology specific chapters.
- Reliability of the response: The reliability of the response is an important element. Here, a distinction between a behavioural and an automated response can be made (Parrish et al., 2019). A behavioural response will require the end-user to take action to increase or decrease the load in response to a signal. In case of an automated response, technology is installed that automatically adjusts the load of the asset(s) in response to the signal. Automated DR will result in a quicker and more reliable response, but requires investment in additional technology and reduces the end-users autonomy or control (Parrish et al., 2019). An automated response requires smart appliances and a control strategy that determines the response. Smart appliances include large household appliances such as washing machines, dishwashers and electric heating systems which can shift or curtail their loads. Currently, there is a lack of smart appliances available on the market, which is a barrier to DR.

Generally, the less constrained the response is by saturation and load recovery and the higher ramping ability, availability and reliability of the response, the higher the value of DR for the electricity system.

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[5] We excluded “awareness” of the value of DR which is included in the study by TenneT in the discussion of preconditions for DR in this report. We consider awareness of DR when we discuss decision making on participation in DR.

### 2.2.2 *Sufficient grid capacity for demand response*

A precondition for DR is that the required grid capacity to provide a response is available. For all technologies in this report, grid capacity in the electricity system is required for the market penetration of the asset(s). For some technologies (i.e. power-to-hydrogen and hybrid industrial boilers) also capacity in the gas or hydrogen system is required.

DR can potentially increase the required electricity grid capacity, which implies that congestion in the grid can be a barrier for DR or that the costs of grid expansion which can result in increased grid charges are a factor that should be taken into account. However, the relationship between DR and the required electricity grid capacity is rather complex. DR can both increase and decrease the required grid capacity, compared to the situation without DR.

Because DR is some combination of curtailment and load shifting, the overall effect of DR can be that the load is to some extent curtailed which generally reduces the required grid capacity as the demand is reduced. Load shifting, however, can both increase and decrease the peak load that needs to be transported. However, an increase of the end-users individual peak capacity doesn’t automatically imply that the grid costs increase. The effect of DR on the grid costs depends on the counterfactual situation without DR. Without DR the flexibility will have to be supplied by another flexibility source and the impact on the grid depends on the flexibility source and its location. A specific issue with load shifting, however, is that an automated response can reduce the load diversity, which does increase the required grid capacity (Hedegaard et al., 2019; Ramchurn et al., 2011; Salah et al., 2015). For example, when all EVs in a distribution grid simultaneously start charging in response to a (price) signal the resulting peak demand will be higher compared to the situation without DR.

Ambrosius et al. (2018) analyse investment incentives for industrial DR under different market designs. The authors conclude that industrial DR generally leads to increased welfare under different market designs, because industrial DR reduces the need for conventional generation capacity and transmission grid expansions. However, the authors note that under uniform pricing (i.e. one wholesale price per bidding zone) welfare is lower than under nodal pricing, because the latter incentivises flexible demand in optimal locations which further reduces the need for grid expansions. In the current market design in the Netherlands such locational incentives are absent from the market design, which may result in DR at sub-optimal locations from a grid perspective.

The lack of locational incentives is not by itself a barrier to DR, but the result underscores that the question whether there is sufficient grid capacity for DR also depends on the location of the DR asset(s). Generally DR assets that are closely located to the VRE production it responds to (i.e. solar-PV or offshore wind) limits the need for grid expansions. For example, building electrolysers close to shore or even offshore to consume offshore wind production reduces the need for transmission grid expansion compared to building the same electrolyser further inland.[6]

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[6] The P2H2 location also impacts the need for $H_2$-infrastructure.

### 2.2.3 *Incentives to reduce electricity costs by participating in DR*

Unlocking the DR potential requires that there are incentives to provide DR. Participating in DR will generally lead to reduced electricity costs (and in some cases energy costs). In this section we discuss how DR can lead to reduced electricity costs, by discussing (i) how the design of wholesale electricity markets values flexibility and (ii) how the value of the flexibility can be passed-through to end-users by intermediaries. The incentives to provide DR are also determined by the effect DR has on other components of the electricity bill: grid tariffs and taxation. We discuss whether and how grid tariff(s) and taxation distort incentives for DR in the next subsection (2.2.4).

The incentives to participate in DR to balance supply and demand stem from wholesale electricity and balancing markets. We first describe these markets and discuss how they incentivise DR. Then, we discuss how these incentives can be passed through to (residential) end-users through intermediaries, like balancing responsible parties (BRPs) and balancing service providers (BSPs), energy suppliers and independent aggregators.

Electricity markets are designed to keep the system in balance. For each connection to the grid a BRP has to be assigned. A BRP is responsible for managing the supply and demand for all the connections in its portfolio. BRPs need to submit the scheduled supply, demand and trade for every 15 minutes (the imbalance settlement period or ISP) of the day. The submitted schedule has to be in balance for every ISP. Deviations from the schedule are settled by the TSO with the imbalance price. In the Netherlands, the imbalance price is determined by TenneT for every ISP by requesting energy bids from contracted BSPs and free bids (i.e. energy bids from uncontracted providers) and determining the price based on the marginal bid.

To limit the risk of high imbalance charges, BRPs need to accurately estimate the supply and demand of the connections in their portfolio and trade in the wholesale electricity markets to balance their portfolio. In the day-ahead market electricity is typically traded for each hour of the next day. In the intraday market, electricity is also traded per ISP. A BRP can deviate from the schedule to help balance the system in real time, which results in negative imbalance charges (i.e. revenues) for the BRP.

To ensure that there are enough reserves to manage imbalances, TenneT procures balancing capacity (FCR, aFRR and mFRR) from BSPs.[7] Contracted BSPs receive a remuneration for the reservation of the capacity (all balancing capacity products). In addition to remuneration for the reservation of balancing capacity TenneT pays a balancing energy price based on the marginal bid for the activation of balancing capacity for all balancing capacity products except FCR.

In principle, this market design with market based wholesale and imbalance prices values flexibility, because prices for each ISP are determined by the scarcity of electricity in that ISP. In the day-ahead market prices will vary for each hour of the next day. In the intraday and balancing market, prices will vary for each ISP. These varying prices ensure that DR is valuable to BRPs. A BRP with the ability to activate demand response, can efficiently manage its own portfolio imbalances or sell the

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[7] TenneT doesn’t procure replacement reserves (RR).

flexibility to other BRPs. In addition, DR can participate in the balancing market by selling its capacity and/or submitting balancing energy bids. Thus, DR is also valuable to balancing service providers (BSPs) in the balancing market, for which both a remuneration for the reservation of the capacity and/or a remuneration for balancing energy are possible.

However, to incentivise DR from end-users the value of DR for BRPs and BSPs will have to be passed on to end-users through different actors like BRPs, BSPs, energy suppliers and independent aggregators. We discuss how these different market roles interact with one another and how they can incentivise DR from end-users.

BRPs and BSPs are market roles that can be carried out by companies. The market role of a BRP is to act as the counterpart for the TSO to settle imbalances. The market role of the BSP is to act as counterpart for the TSO for the supply of balancing capacity to the TSO. The energy supplier is a different role, that acts as the counterpart for end-users for the supply of energy. Sometimes, the BRP role and energy supplier role are carried out by the same company, but in other cases they are carried out by different companies. The BRP will then charge the energy supplier for the costs of managing the imbalances. In that case, it depends on the contractual arrangements how the value of demand flexibility in the wholesale and balancing market is passed on to the energy supplier. For simplicity, we'll assume these incentives are perfectly passed on to the energy supplier.[8] That implies that the energy supplier can reduce its energy sourcing cost (wholesale market, imbalance prices) or obtain additional revenues in the role of BSP (balancing capacity, balancing energy) by incentivising DR from its end-users.

A relatively new role in the electricity market is that of the independent aggregator. An aggregator pools the flexibility from different sources and sells it on the electricity markets (to BRPs and BSPs or the aggregator is also a BRP or BSP). Thus, the aggregator can obtain revenues by incentivising DR from the end-user. An aggregator will typically also need a BRP or be a BRP to manage the imbalances caused by its interventions. If the independent aggregator sells the flexibility to the TSO for balancing than the aggregator is also a BSP. Aggregation can also be performed by energy suppliers, but the term independent aggregator refers to the fact that the aggregator and the energy supplier are different companies.

In short, the design of wholesale and balancing markets ensures that flexibility is valuable to BRPs and BSPs, but the incentives for DR for end-users will have to be passed-through via energy suppliers or independent aggregators.

Energy suppliers or independent aggregators can incentivise DR from end-users in two way: (i) implicit or price-based DR and (ii) explicit or incentive-based DR (TenneT, 2021; U.S. Department of Energy, 2006).

Implicit DR refers to the situation where time-varying end-user energy prices incentivise DR. Examples of such contracts are static and dynamic time-of-use pricing, variable peak pricing, critical peak pricing and real time pricing (Parrish et al., 2019). For example, the energy supplier could offer the end-user a contract where the electricity prices are based on the day-ahead market prices for each hour of the

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[8] Or alternatively: that the energy supplier-role and BRP-role are carried out by the same company.

day. That incentivises the end-user to optimise the demand with respect to these time-varying electricity prices. The resulting DR is implicit, because the end-user determines the response to the price signal, and, as a result, the precise level of the response doesn't have to be determined and is implicit. The higher the extent to which the variability of electricity prices on wholesale and balancing markets is passed through to the end-user (i.e. real time pricing), the better the incentives for DR are from a system perspective. However, the price risk that is inherent to variable prices also significantly increases compared to a fixed energy price. Short-term price fluctuations will have a significant impact on the electricity costs, especially when for some reason the load can't be curtailed or shifted in a period with high prices. With a predetermined day- and night electricity price the price risk is much lower, but the incentives for DR are also diluted as the prices don't accurately reflect the scarcity of electricity in the ISP, which can be considered a barrier to efficient DR.

Explicit DR refers to a contracted response triggered by an explicit signal. For example, the end-user signs a contract with the energy supplier or independent aggregator to provide a response when the energy supplier or independent aggregator sends an explicit signal. In return, the energy supplier or aggregator could remunerate the end-user for its flexibility (e.g. discount on electricity bill or some combination of fixed reservation payments and variable activation payments). The resulting DR is explicit, because the level of the response is specified in advance and the response is triggered by an explicit signal. With an explicit response, there is a risk of a loss of load because the end-user has to curtail or shift the load in response to the signal.[9] The end-user may want to limit the risk of a loss of load and thus, participate in explicit DR only in pre-determined situations or with a limited frequency. This also dilutes incentives for efficient DR, which can be considered a barrier to efficient DR.

Another barrier for DR is the current practice in the Netherlands of net metering of residential VRE production (i.e. "salderingsregeling"). To stimulate production of renewable energy by households the Dutch government introduced net-metering (e.g. "saldering"). A household with VRE production is charged by its energy supplier for the net annual consumption. Thus, the annual supply from the energy supplier is reduced by the feed-in to the grid (net-metering). In case the feed-in to the grid exceeds the supply of the energy supplier, the energy supplier pays a feed-in tariff for the difference. The taxes are only levied on the net consumption. Net metering distorts incentives for the end-user to participate in DR, because the value of electricity at a specific point in time is not taken into account. Thus, there is no incentive for the end-user to increase its demand when there is a lot of residential VRE production. However, the net metering requirement forces the energy supplier to buy the electricity feed-in at the fixed price. That means that the electricity supplier still values DR and the electricity supplier could introduce incentives to increase self-consumption even when net metering is applied. For example, there is an energy supplier with time-varying electricity prices and the net metering is applied per hour instead of per year.[10]

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[9] The distinction between the price risk and the risk of a loss of load is not black and white. For example, in case of explicit DR there is typically a financial penalty when the contracted response is not provided, which is a price-based incentive. Vice versa, a very high electricity price in case of implicit DR might "force" an end-user to reduce its demand, resulting in a loss of load.

[10] Easy Energy uses hourly prices and any residential VRE production is settled with the same hourly price.

### 2.2.4 *No distorted incentives from grid tariffs and taxation*

Electricity grid tariffs and taxation can have a large impact on the incentives to provide DR.

For efficient DR it is desirable that the impact DR has on the costs of the electricity grid is reflected in the grid tariffs. If, for example, DR requires significant grid expansions, that should be reflected in higher grid charges for the end-user. In that case, the fact that DR requires significant grid expansions is a barrier to DR, but there is no distorted incentive from the grid tariff design. If however, DR doesn't impact the costs of the grid but the grid charges do significantly increase by participating in DR, that indicates that the grid tariffs distort incentives for DR as they don't accurately reflect the impact of DR on the grid costs.

A description of the tariff setting principles and process and the electricity grid tariff structure in the Netherlands is included in Appendix A. We conclude that the electricity grid tariffs distort incentives for DR for a number of reasons:

- The tariff driver of the variable transport tariff differs per voltage level (Overlegtafel energievoorziening, 2018). For the higher voltage levels the tariffs are charged for the annual (kW contract) and monthly (kW max) individual peak capacity. For lower voltage levels, the annual consumption (kWh) is used in addition to the kW contract and kW max. For connections with a capacity smaller or equal to 3x80 Ampère (i.e. *kleinverbruikers*), an assumed capacity (in Dutch: *rekencapaciteit*) is used as tariff driver. The different tariff drivers per voltage level distort the incentives for DR, because loads connected to different voltage levels are confronted with completely different incentives resulting from the grid tariffs.
- Specifically for end-users connected to high-voltage grids the grid tariffs are heavily capacity-based, because tariffs are charged for the yearly and monthly individual peak. This tariff structure incentivizes avoiding individual peak consumption (i.e. incentivises baseload consumption) and consequently disincentivizes DR in many cases, as load shifting and curtailment often reduce the capacity factor. Although the exact relationship between individual peak consumption and grid costs is hard to determine, it appears to be the case that the electricity grid tariffs are too heavily capacity-based, resulting in very high grid charges for small increases of the annual or monthly peak capacity.
- The incentive to limit individual peak consumption for large loads (per year and per month) is amplified by a discount for large industrial loads (in Dutch: *volumekorting energie-intensieve industrie*), because a discount on grid tariffs up to 90% is given to large loads with a high operating time (closely related to the capacity factor).
- For end-users connected to the low voltage grid with a connection of 3x80 Ampère or smaller, the actual use of the grid isn't taken into account as assumed capacity is used. This tariff structure doesn't provide any specific incentive for the use of the grid, apart from the incentive to limit capacity to stay within the capacity bracket for the assumed capacity. Requesting a larger connection capacity could increase the assumed capacity bracket, which significantly increases the grid costs. This tariff driver presumably incentivizes DR too much within a tariff bracket, because the effect of DR on grid costs is not accurately represented in the electricity grid charges.
- The tariff that covers the largest part of the grid costs (e.g. the variable transport tariff) is only charged to load and not to generation. That distorts the level playing

field between load and generation for the supply of flexibility. For example, when selling balancing capacity to the TSO demand assets will have to take into account the effect of activation of the balancing capacity on the grid tariffs, whereas supply assets don’t.

Taxes serve different purposes, such as redistributing welfare, generating government revenues and internalising external costs. With the exception of taxes that internalise external costs, taxes generally distort incentives as they influence production and consumption decisions. However, taxes can be more or less distortive depending on the tax design.

Taxation typically makes up a large part of the electricity bill. In the Netherlands, the energy tax, renewable energy and climate surcharge (ODE) and value added tax are the relevant taxes. A description of these taxes is included in Appendix B.

For the energy tax (including surcharge), the tax is levied on the electricity consumption (kWh per year). This incentivises reducing annual consumption. Thus, DR in the form of curtailment will lead to a reduction of these energy taxes. However, the overall tax system is regressive. That could imply that reducing the load increases the average tax per kWh consumed which distorts the incentives for load curtailment and could be a barrier for load curtailment. However, the tax brackets are quite large, so it is questionable whether load curtailment will lead to a significant increase of the average tax per kWh. Specifically for residential end-users the lump-sum tax deduction makes the energy tax progressive, which amplifies incentives for load curtailment.

For load shifting, however, the energy tax (including surcharge) doesn’t have any effect as they are charged per kWh of annual consumption. These taxes neither incentivise load shifting but it also doesn’t support load shifting, because the price of the electricity consumed doesn’t affect the taxes and annual consumption remains at the same level. In some specific cases (i.e. all-electric residential heat pumps) load shifting will lead to an increase of annual electricity consumption, because DR reduces the energy efficiency. In that specific example, the taxes disincentivise load shifting, because load shifting increases annual consumption. The value added tax does incentivise load shifting, because a reduction of the average electricity price reduces the value added tax.

To summarise, the energy tax (including surcharge) incentivises load curtailment but not load shifting. Electricity consumption is taxed, even at times when there is an excess of VRE production and electricity consumption needs to be incentivised. Although strictly speaking this might not be a distortion as load shifting has no effect of the energy taxes because annual electricity consumption doesn’t change, these taxes don’t support DR. The incentives for DR could be increased by changing the energy tax (including surcharge) from a tax on annual consumption (kWh) to a percentage tax on the electricity costs (like the VAT). With a percentage tax on electricity costs, a reduction of the average electricity price leads to lower taxes which increases the incentives for load shifting. Furthermore, the incentives for curtailment could be increased by making the energy taxes less regressive.

### 2.2.5 *Access to markets*

A precondition to participate in DR is that the end-user has access to the markets where flexibility is valued. As described in subsection 2.2.3, the value of flexibility stems from the wholesale and balancing markets. These markets provide incentives for DR to BRPs and BSPs, which are passed through to end-users through energy suppliers and independent aggregators.

However, there can be barriers to access the wholesale and balancing markets. The access could be limited if there are specific requirements to participate in those markets, such as minimum bid sizes, symmetric bid requirements (both upward and downward adjustment of the load required), high financial creditability requirements or requirements on the ramping ability of the asset (lead time, ramping-time, et cetera) that do not match the ramping ability of the asset.

In recent years, many improvements have been made or are being made to improve the access to markets. The access to balancing capacity markets has been improved by defining standard balancing capacity products and reducing minimum bid sizes for the procurement of balancing capacity products. Also, balancing capacity is procured for shorter durations based on day-ahead auctions. That allows VRE and DR to participate in these markets, because there is less uncertainty on the availability of the assets and more certainty on the opportunity costs (Schittekatte et al., 2020). The aFRR and mFRR products are procured asymmetrically, meaning that a demand asset can submit a bid for downward regulation or upward regulation only (asymmetric bids) and doesn’t have to bid downward and upward regulation combined (symmetric bids). As an exception, FCR is still procured by contracting symmetrical bids, which might limit participation of DR that can only increase or decrease the load (Sijm et al., 2021; TenneT, 2021).

A crucial enabler for the access to markets is the aggregation of flexibility by aggregators. Aggregation pools flexibility from different sources and sells the flexibility in the relevant markets (wholesale energy and balancing markets). By pooling flexibility from different (distributed) energy sources even the smallest flexible assets can get access to the relevant markets with minimum bid sizes. The aggregator business model is reviewed in Okur et al. (2021). In short, the aggregator can sell flexibility in different markets (day-ahead, intraday, balancing), with different incentives for the end-user (implicit, explicit) and different control mechanisms (behavioural or automated response). The introduction of the role of the independent aggregator, however, raises several new issues. Because the independent aggregator is crucial to ensure access to markets, the issues with the independent aggregator business model can be considered a barrier to DR. The issues with the independent aggregator business model are mostly related to the measurement of DR and the contractual relationships between energy supplier, independent aggregator and BRP which we discuss in the next subsection.

### 2.2.6 *Measurement and enforcement of demand response*

To accurately incentivise DR it is necessary that the actual response can be measured.

For implicit DR that implies that the load has to be metered with the same time-granularity as the variable electricity prices. For example, if an energy supplier charges day and night electricity prices, then the load has to be measured for every day and every night. In practice, there are hourly prices in the day-ahead market and prices per ISP in the intraday and balancing market. This generally requires the installation of smart meters (Strbac, 2008), that are able to measure the load per ISP. Thus, smart meters and ICT technologies are key to unlocking the true potential of DR. Without these, the communication between end-users and market parties is not possible. Smart meters provide the end-user instantaneous information on electricity consumption and smart ICT systems can give information on the price of electricity at a given moment.

Current estimates suggest that the smart meter rollout has reached 85% of end-users in the Netherlands (ACM, 2021). This indicates that 15% of households are still not equipped with smart meters and the reasoning behind this is thought to be due to the end-users feeling they don’t add value, they are unreliable, they are already equipped with PV panels and the loss of privacy (Statista, 2020). Given the high uptake of smart meters in the Netherlands, the share of end-users without a smart meter is only a minor barrier to DR.

For explicit DR the precise response to the signal has to be determined. To determine the level of the response, the level of the consumption without DR has to be determined (e.g. the baseline) and compared with the actual consumption. Because the actual consumption has to be measured, the need for smart meters is similar as for implicit DR. In addition, for explicit DR there are several issues with the determination of baselines, which is a barrier to DR.

There are several ways of calculating the baseline consumption, mentioned in Ziras et al. (2021) and they all come with their own assumptions and limitations. These calculation methods include averaging, regression, control groups and interpolation, among others. Averaging of the baseline works by taking the mean consumption from selected non-DR days to create an average baseline consumption profile. Regression works by selecting parameters based off historical data such as temperature, daylight hours as well as the consumption data to infer the baseline for future scenarios. The baseline for DR can also be calculated by comparing the demand from similar end-users (i.e. control groups) who are not enrolled in DR and can provide a database of baselines for different types of electricity end-users. Finally, interpolation determines the baseline consumption by measuring the demand before and after DR is implemented and fills the necessary gaps by means of interpolation, while also taking into account some external historical factors. Regression and control groups are the most complex and least transparent of all the calculation methods and require the greatest amount of estimation. Averaging and interpolation are the most simple, transparent and inclusive. However, these baseline calculations can be prone to manipulation and gaming.

Chao (2011) mentions two issues regarding baseline manipulation: the adverse selection problem and the moral hazard problem. The adverse selection problem is where the end-user has an advantage over the market administrator with regards to their baseline knowledge. This means that the end-user will understand their baseline and energy consumption patterns better than a market administrator who will have limited knowledge of the end-user’s baseline prior to enrolling in DR and therefore has a market advantage. The moral hazard problem occurs when the market administrator is calculating the end-user’s baseline, and the end-user can manipulate or increase its consumption (prior to enrolling in DR) above its regular baseline to achieve a greater financial gain from a reduction of electricity when enrolled in a DR program. The frequency with which baselines need to be updated can also be a relevant consideration, as DR will alter the end-users consumption (Shoreh et al., 2016).

The issue with baselines becomes more complicated when independent aggregators are involved. When energy supply and DR are split over different agents, any load adjustment resulting from DR by a third party aggregator will result in an imbalance for the BRP (Vallés et al., 2016). The easiest solution to this discrepancy is that the supplier assumes the role of the DR operator and manages the flexibility and imbalances together and, hence, eliminates the independent aggregator from the market. However in markets which allow independent aggregation of assets, it is necessary for the independent aggregator, energy supplier and their respective BRPs to have a contractual agreement clearly outlining the financial remuneration that the aggregator will pay the energy supplier for the load adjustment and that the imbalance can be correctly neutralised (Vallés et al., 2016). Furthermore, it requires contractual arrangements between the BRPs to distinguish the settlement of imbalances resulting from the “normal” baseline consumption and imbalance resulting from deviations from the contracted the load adjustment (Schittekatte et al., 2021). These contracts, which aim to relieve the conflict of interest between energy supplier, independent aggregator and BRPs  increase the administration and complexity of explicit DR and perhaps reduce the benefits to the end-user when remuneration is paid to BRPs from the aggregator. Moreover, the contracts between aggregators and BRPs potentially stand upon false or inaccurate baseline measurements.

## 2.3 Costs and benefits of demand response

In section 2.2 we discussed the preconditions for DR. When these preconditions are met there is:

- An asset that can be operated flexibly;
- With sufficient grid capacity for the response;
- Where the response is accurately incentivised by the electricity market design;
- And not unduly disincentivised by grid tariffs and taxation;
- And has access to the relevant markets to monetise this value;
- And the response can be accurately measured and enforced.

Then, the next question is whether for a specific technology and in a specific market context the benefits of DR are higher than the costs. In this section we discuss the different types of costs and benefits that need to be considered. The actual costs and benefits are technology specific and are discussed in the technology specific chapters.

When we discuss the costs and benefits of DR, two perspectives are relevant: a private (i.e. end-user) perspective and a social perspective. Ideally, these perspectives don’t deviate. That is the case when the market design provides the right incentivises and grid tariffs and taxes don’t unduly distort incentives. However, as discussed in sections 2.2.3 and 2.2.4, that is not always the case. That indicates that DR is either incentivised too much or unduly disincentivised. Where that is the case we discuss the difference between the costs and benefits from a private and social perspective.

In this section we discuss the following types of costs and benefits:

- Costs of flexible operation of the asset;
- Costs of grid capacity;
- Costs of taxation;
- Costs of reduced value of outputs;
- Costs of unlocking DR; and
- Benefits of DR.

### *2.3.1 Costs of flexible operation of the asset*

Flexible operation of the asset(s) can lead to increased costs compared with the inflexible operation. For example, for load shifting there is often the need to increase the capacity of the asset. The increased capacity (MW) leads to additional investment costs and results in higher costs per MWh of output. Flexible operation can also lead to additional non-linear costs compared to inflexible operation, such as ramping and cold start costs. As these are costs of the operation of the end-users asset, there is no difference between the costs from a private and social perspective.

### *2.3.2 Costs of grid capacity*

As previously discussed in subsections 2.2.2 and 2.2.4 DR can have an effect on the required grid capacity and on the grid tariffs to be paid. Ideally, the effect DR has on the grid costs would be accurately reflected in the grid tariffs. However, the current electricity grid tariffs in the Netherlands distort incentives for DR for a number of reasons described in 2.2.4. Thus, when determining the relationship between costs and benefits of DR there will generally be a difference between the private costs and benefits (grid tariffs) and the social costs and benefits (grid costs).

Because the tariff drivers for the electricity grid tariffs (i.e. the price for grid capacity) differ per voltage level, the effect of DR on the grid charges (i.e. the private costs resulting from the grid tariffs) depends on the specific technology. Therefore, the effect of DR on the grid charges is discussed in the technology specific chapters.

For technologies that use capacity in the gas or hydrogen grid also grid tariffs for the use of these grids might be a relevant cost item. For the gas transmission system, the grid tariff structure is described in Appendix A. A hydrogen transmission grid doesn’t exist yet and therefore the grid tariffs are unknown.

### *2.3.3 Costs of taxation*

Taxation will impact the business case for DR. An explanation of the relevant taxes is given in Appendix B. There is inherently some distortion due to taxation. As described in section 2.2.4 the energy tax (including surcharge) is a regressive tax on annual consumption, with a progressive element for small end-users due to the lump-sum tax reduction. These taxes incentivise reducing annual consumption. Thus, load curtailment is incentivized by the taxes, whereas load shifting is neither incentivized nor disincentivized. The VAT incentivizes load shifting because the VAT is charged over all electricity costs, which means that the price of electricity is also taken into account.

### 2.3.4 *Costs of reduced value of outputs*

Flexible operation of the asset(s) can lead to a reduced value of the output of the assets. For example:

- Flexible operation of an electrolyser can reduce the quality of the produced hydrogen compared to inflexible operation (see section 3.4.4);
- Flexible operation of an electrolyser leads to varying hydrogen production resulting in time-varying hydrogen prices and a reduced hydrogen capture price[11] (see section 3.4.4); and
- Flexible operation of a residential heat pump can lead to a loss of comfort (see section 5.4.4).

The reduced value of the output can be considered a cost from both a social and a private perspective.

### 2.3.5 *Costs of unlocking demand response*

Unlocking the DR potential will lead to additional costs. These include costs of smart meters required for the measurement and enforcement, costs of installed technology for an automated response and costs of the effort/time and communication technology for a behavioural response. The sharing of data that this requires also leads to costs in the form of a loss of privacy.

Furthermore, aggregators or energy suppliers will enable the participation in DR, especially for residential end-users, but their costs will need to be covered as well. These costs involve collecting and processing the correct metrics, while complying with privacy regulations. The sheer amount of data from smart metering and smart appliances is a challenge to implementing DR and comes at an added cost (Good et al., 2017). Another type of costs are the costs to raise awareness of the value of DR, such as marketing costs to enrol participants in a DR programme. Thus, the aggregator or energy supplier has to appropriate part of the value of DR to cover its costs.

For implicit DR the price risk for the end-user will increase as a result of time-varying electricity prices. Although the average electricity price is expected to decrease, the exposure to sudden price increases will be higher. This could lead to additional costs in the form of a risk premium that the end-users will take into account when deciding whether to participate in DR.

For explicit DR, the exposure to the price risk can be much lower but the risk of a loss value of the output (e.g. comfort) is higher as the response will have to be provided to avoid penalties.

In the end, these are two sides of the same coin.[12] Thus, also for explicit DR a risk premium can be relevant.

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[11] Hydrogen storage can be used to supply a baseload hydrogen demand with variable hydrogen production, but a positive business case for storage requires varying hydrogen prices.

[12] With implicit DR prices could be so high that they practically force DR resulting in a loss of load and with explicit DR not providing a response will result in a financial penalty.

### 2.3.6 *Benefit of demand response*

From a social perspective DR has the potential to increase VRE penetration, reduce VRE curtailment and reduce the need for dispatchable generation. Thus, DR has the potential to reduce emissions and reduce the costs of electricity production.

In subsection 2.2.3 we discussed how the wholesale and balancing market design ensures that these benefits are allocated to the end-user that provides DR. This is possible through either implicit or explicit DR. In case of implicit DR, the cost reduction will be realised by responding to variable electricity prices. In case of explicit DR, the terms and conditions can be determined in the contract. There could be some combination of a fixed payment for the reservation of flexible capacity and variable payments for the actual activation of the response.

## 2.4 Deciding on participation in demand response

Even when there is a positive business case for DR (from both a private and social point of view) end-users might decide not to participate in DR for various reasons. In this section we discuss several factors that can influence the decision to participate in DR for different types of end-users (i.e. industries and residential end-users) even when there is a positive business case for DR.

### 2.4.1 *Financial constraints*

When there is a positive business case for DR but significant investment is required to participate in DR, there can be financial barriers that prevent end-users to participate in DR. Some end-users may simply not be credit worthy enough to finance the investments and have insufficient savings. This is especially the case for lower income residential end-users.

### 2.4.2 *Inertia*

End-users can be inert, which means they simply won’t take a decision to join a DR programme, even when the benefits of doing so are obvious (Good et al., 2017). End-users may also simply be unaware of the value of DR and the potential it has to reduce electricity costs. This is even the case for large industrial end-users (TenneT, 2021).

According to Parrish et al., (2019) automatic enrolment with an opt-out option will generally increase the enrolment in a DR programme. However, the enrolment in a programme (for example: time-of-use tariffs) doesn’t imply the end-user will actively participate in DR. In opt-out systems the active participation is generally lower than in opt-in systems.

### 2.4.3 *Consumer values*

The costs and benefits discussed in subsection 2.3 of participating in DR include several hard to quantify “costs” that are especially relevant for residential end-users, such as a loss of comfort or privacy. These costs will be weighed differently by different residential end-users and will probably not be constant over time. The weight end-users place on these types of costs - but also on the wider benefits of DR such as increased VRE consumption - can be informed by consumer values (Good et al., 2017), such as autonomy, ownership, power and control. These consumer values can prevent end-users giving up control over some of their devices to participate in an automated response and sharing data that is required for the measurement of the response. Other consumer values such as environmental values could stimulate the participation in DR.

This suggests that it matters by whom the DR programme is sold to residential end-users and which values are signalled. Thus, these “costs” are probably not fixed, but they can be influenced by aligning DR with the consumers values. For example, trust between the aggregator or energy supplier and end-user is an important factor that will influence the end-users decision to participate in DR (Good et al., 2017). Especially in case of an automated response, the user discomfort is a key consideration. An end-user’s experiencing inconvenience because of a loss of heating, a delayed washing cycle or other household hindrances will impact its willingness to participate in DR in the future. Finding a balance between the financial gains and the discomfort or loss of control as a result of DR is challenging. If the program loses the trust from the end-user through poor planning or timing of DR then it will lead to end-user dissatisfaction. The onboarding process for a DR program is very important, as failure to explain the system and how it works will lead to customer dissatisfaction. It is therefore imperative that the smart system is set up by an aggregator or the instructions are simple and easy to follow. It is equally important that aggregators play a role in offloading the participation time burden from the end-user to ensure that engagement in the program remains long-term (Shoreh et al., 2016).

### *2.4.4 Form of information*

The form of information that is exchanged between the end-user and the aggregator or energy supplier is another factor that can influence the decision to participate in DR. For example, implicit DR requires timely information about prices that the end-user can respond to. Explicit DR requires some instruction from the energy supplier or aggregator to adjust the load. Especially in case of a behavioural response poor design of the user interface can be a barrier to DR (Good et al., 2017). But also in case of an automated response it is important that the end-user is informed about the adjustment of the load in a proper way.

# 3 Power-to-hydrogen

## 3.1 Technology description

Hydrogen has been used as an important feedstock for industrial processes for many years (Baykara, 2018). The hydrogen industry is well established and, in the past, hydrogen has been primarily produced via steam methane reforming (SMR) and coal gasification (IRENA, 2019). These two processes, however, are carbon intensive, meaning, there is a need to find renewable and environmentally friendly methods of producing hydrogen (Sinigaglia et al., 2017).

Power-to-hydrogen (P2H2) is the production of hydrogen through electrolysis. Electrolysis is the process of splitting water into hydrogen and oxygen with the use of electricity. An electrolyser is needed for the production of hydrogen through electrolysis. There are three main electrolyser types, these include; proton exchange membrane (PEM), alkaline electrolysers (AEL) and solid oxide electrolysers (SOE). These electrolysers all operate slightly differently and have their individual pros and cons but these will not be discussed here as it falls outside the scope of the report.

When carbon free electricity is used for electrolysis, electrolysis has the potential to provide clean energy and feedstock (Staffell et al., 2019; van Renssen, 2020; Wang et al., 2020). The hydrogen can then be stored or transported to be used as energy or feedstock for industry and clean energy for other sectors. Hydrogen can also be converted back to electricity using a fuel cell or gas turbine.

P2H2 can provide DR through load shifting. Thus, hydrogen production is increased when electricity prices are low and decreased when electricity prices are high. We discuss the barriers to DR by comparing (i) P2H2 with DR with (ii) P2H2 without DR. For the latter, we assume P2H2 with a baseload electricity consumption and baseload hydrogen production.

## 3.2 Barriers to electrification

Although P2H2 is generally considered an interesting option in combination with DR, in this section we discuss barriers for the electrification of hydrogen production without DR. Thus, we assume a baseload electricity demand to produce baseload hydrogen. In the next section we discuss barriers to P2H2 by DR.

For P2H2 the barriers to electrification are not the only barriers for the market penetration of P2H2. The market penetration of P2H2 will depend on (i) the development of the hydrogen demand and (ii) the extent to which the hydrogen demand is electrified. Therefore, we discuss barriers for hydrogen demand in subsection 3.2.1 and barriers for electrifying the hydrogen demand in subsection 3.2.2.

### *3.2.1 Barriers to hydrogen demand*

Currently, the largest user of hydrogen is the oil refinery sector (33%), and its future growth depends on the demand for its downstream products (IEA, 2019a). Hydrogen’s role in oil refinery is primarily to remove impurities such as sulphur and to upgrade crude oil to wider used fuels. This demand is set to increase 7% by 2030 as stricter pollutant policies on sulphur are set to increase. However, this demand could decrease drastically with stricter climate policies enabling electrification of transport (IEA, 2019a).

Other large industrial sectors using hydrogen such as ammonia (27%), methanol (11%) and steel production (3%) are all set to increase their hydrogen demand through 2030 and 2050 (IEA, 2019a).

The future hydrogen demand from other sectors than industry will probably increase, because hydrogen has the potential to decarbonise transport, the built environment and electricity generation. For example (IEA, 2019):

- Hydrogen fuelled vehicles become competitive with electric vehicles in ranges greater than 400 km and is an opportunity for the decarbonisation of trucks and busses.
- Shipping and aviation also have a potential for hydrogen based fuels. However, the cost of producing the fuels required are not competitive with oil-based fuels, and compete with advanced biofuels and ammonia.
- There is potential demand for hydrogen for heating in large and commercial buildings. This is a particularly attractive option when the installation of heat pumps is challenging. The potential for heating using hydrogen, however, requires the blending of hydrogen into the gas network or repurposing gas networks which provides challenges discussed later.
- Hydrogen also offers a potential to fuel flexible electricity generators if the price of hydrogen is under $2.5/kg, however this also competes with CCS technologies and biogas as a fuel source.

In these sectors, hydrogen can replace fossil fuel alternatives. However, without climate policies to address emissions the fossil fuel alternatives are often still the cheaper option. Furthermore, P2H2 only reduces emissions if the carbon intensity of hydrogen is lower than the fossil-fuel alternative (i.e. P2H2 with clean electricity or SMR with CCS). Thus, the future demand for hydrogen in these sectors depends on (i) the climate policies to address emissions and (ii) the costs of producing hydrogen with a low carbon intensity.

Specifically for the electricity sector, the option to combine P2H2 with $H_2$2P requires (long term) energy storage. Saccani et al., (2020) outline the challenges for power-to-hydrogen-to-power compared to other storage technologies. Currently the round trip efficiency and levelized cost of storage (LCOS) stand as a barrier to power-to-hydrogen-to-power's competitiveness.

In addition, hydrogen transport infrastructure is needed to facilitate the demand for hydrogen. Due to hydrogen's lower volumetric density, storing $H_2$ and mixing $H_2$ into natural gas pipelines can be a barrier. Storing $H_2$ requires more volume to meet the same demand as methane (Hu et al., 2020). Similarly, in order to blend $H_2$ in the natural gas network, the volumetric flow rate of that natural gas network would need to increase in order to meet the same energy demand (Saccani et al., 2020). Despite this, in order to create a greater future demand for hydrogen it will be necessary to blend hydrogen into the gas network or repurpose gas pipes to hydrogen pipes to ensure that hydrogen production hubs meet the demand hubs.

Schlund et al. (2022) discusses the barriers to P2H2 demand by calling it the “three-sided chicken-and-egg” problem by summarising it as without supply, there is no demand, and with no demand there is no supply, without the transport infrastructure there is not the possibility of trade. The problem is heightened by the economic disparity between different types of hydrogen production (green, blue, grey) and the uncertainty surrounding hydrogen demand in oil refinery, currently the largest hydrogen user. This “three-sided chicken-and-egg” problem is a barrier to hydrogen demand.

### *3.2.2 Barriers to electrification*

The costs of P2H2 are still high when comparing it to SMR with and without CCS. The high costs of P2H2 present a barrier to P2H2. P2H2 production costs are 2.5-6.4 (€/kg) compared to 1.3-2.5 and 0.8-2.7 (€/kg) for SMR with and without CCS respectively (Saccani et al., 2020). The relatively high P2H2 costs are largely associated with the high CAPEX of the electrolyser, but OPEX costs tend to also be higher than other hydrogen production pathways (Saccani et al., 2020).

The efficiency of P2H2 is less than that of other hydrogen production pathways, it currently stands at 60-70% compared to SMR, for example, which currently has an efficiency of 70-85%. This will ensure that unless the power supply to P2H2 is from VRE sources (which are statistically 100% efficient compared to gas turbines which are around 40-50%) the entire conversion process is too inefficient and it will financially make sense to use other hydrogen production pathways. Proost (2020) predicts that state of the art electrolysers need a CAPEX of 500 €/kW, an efficiency of 70% and an electricity price of 30 €/MWh to be competitive with SMR if the capacity factor is 50%.

Of course, these costs comparisons depend on the relative gas and electricity prices as well as $CO_2$ prices. In countries such as Chile, China and Morocco where the cost of renewable energy is cheap, the cost competitiveness of P2H2 is close to that of natural gas. However, these areas are far from the worlds hydrogen demand centres (IEA, 2019a). This underscores that the demand for hydrogen in other parts of the world will depend on climate policies that make P2H2 more competitive compared with the fossil fuel alternatives.

As discussed in section 2.1 decarbonising the electricity sector is important to ensure that the emissions do not shift to the electricity sector itself. Although, in theory DR is not necessary to produce hydrogen from emission free power (i.e. nuclear to hydrogen or VRE with electricity storage), producing hydrogen from VRE sources with DR is generally considered a relevant option for P2H2.

P2H2 will require capacity in both the electricity and gas or hydrogen grid. This will require expansions of the electricity grid and the need to develop hydrogen grid. These expansions are a barrier to P2H2. The choice of the location of electrolysers will determine the need for grid expansions in both grids. Choosing the optimal location from a grid perspective can limit the costs of grid expansions, which enables P2H2.

## 3.3 Preconditions for demand response

### *3.3.1 Ability to flexibly operate the asset*

P2H2 can provide DR by shifting the load from high to low electricity prices. Low electricity prices will occur when there is an excess of electricity from VRE sources, which would otherwise be curtailed or when demand is low, typically at night time. The load shifting is constrained by load recovery, because the hydrogen demand has to be met. Thus, when the load is reduced during hours with low electricity prices, the load has to be increased during high electricity prices. In principle, the load can be shifted between zero and the maximum capacity of the electrolysers. Thus, saturation is not a relevant constraint.

The ramping ability of electrolysers is high and, as a result, there are limited constraints to quickly ramp the load. Electrolysers can begin from a warm or a cold start. A warm start is when the electrolyser was kept at operating temperature and pressure prior to the start and is then started from an idle state (Buttler & Spliethoff, 2018). A cold start occurs when the electrolyser is at ambient temperature and pressure after a prolonged shut-down and is then started (Buttler & Spliethoff, 2018). The temperature and pressure at which the electrolyser starts to operate is highly important as these factors determine how quickly the electrolyser can be ramped from 0 to 100% of its capacity. These start up times are also specific to the electrolyser type with polymer electrolyte membrane (PEM) electrolyser cold starting at 5-10 minutes and warm starting <10s. Alkaline electrolysers (AEL) cold start in 1-2 hours and warm start <5m mins. Solid Oxide Electrolysers (SOEL) cold start in hours and warm start at 15 minutes (Buttler & Spliethoff, 2018).

Tuinema et al. (2020) have further explored the ramp rates of electrolysers from warm starts in Figure 1. It can be shown that the generic electrolyser can be ramped from 0-100% within 4 seconds, furthermore the start time can be more than halved if the electrolyser starts at 10% and ramps to 100%. These high ramp rates imply that P2H2 can monetize its flexibility in all markets, including in balancing capacity markets. Specifically for the AEL the minimum load required to avoid cold starts is 20-25% which is higher than for the generic electrolyser.

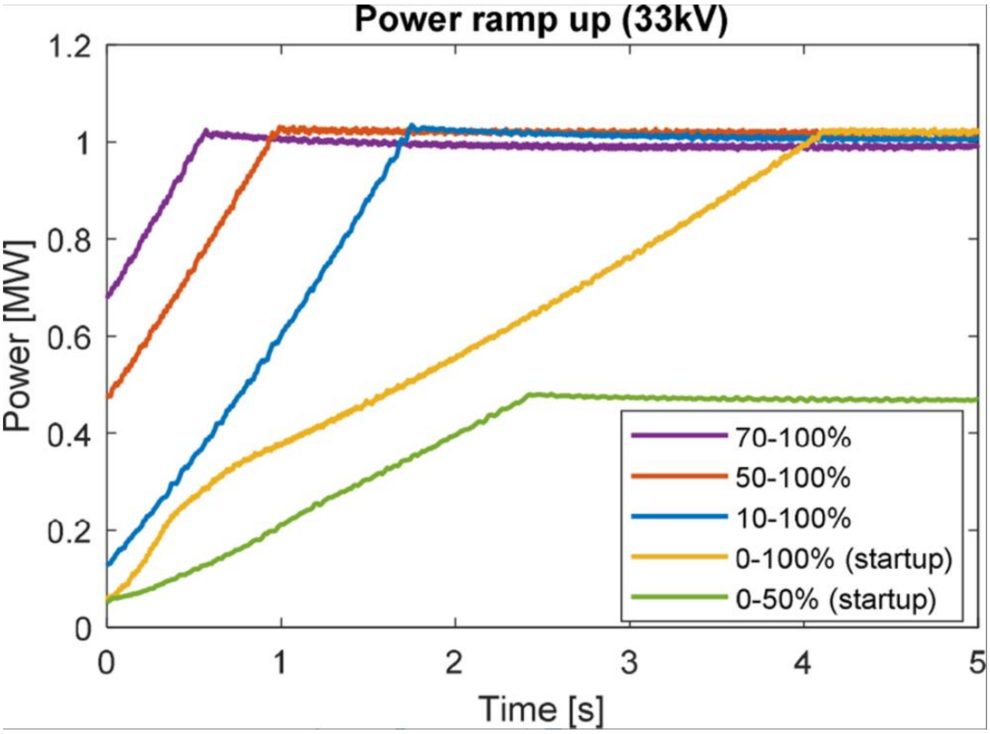

Figure 1: The ramp rates of a 1 MW generic electrolyser

Source: Tuinema et al. (2020)

Furthermore, P2H2 is available for DR almost permanently, because the electrolysers will be available 24/7 to maximize profits. Only in case of maintenance or a contingency the electrolysers is unavailable for a response. Because the electrolyser is available 24/7 for a response (either behaviourally by an operator or automated), the response will generally be reliable.

### 3.3.2 *Sufficient grid capacity for demand response*

P2H2 will require capacity in both the electricity and gas or hydrogen grid. This will require expansions of the electricity grid, the need to develop hydrogen grid or investments to enable blending hydrogen into the gas grid. These expansions are a barrier to P2H2. The choice of the location of electrolysers will determine the need for grid expansions in both grids. Choosing the optimal location from a grid perspective can limit the costs of grid expansions, which enables P2H2.

The effect of DR on the required grid capacity for these grids is ambiguous. Generally, load shifting will lead to higher individual peak load and higher peak hydrogen production compared to baseload operation which need to be transported. However, the higher load might also reduce the need for electricity grid expansions when the electrolyser is closely located to VRE production (e.g. offshore wind). But that might also require more significant expansions of the hydrogen or gas grid (offshore pipelines).

### *3.3.3 Incentives to reduce electricity costs by participating in DR*

There appear to be proper incentives to reduce electricity costs by participating in DR, as the operator of the electrolyser and its energy supplier or BRP will trade on the wholesale and balancing market where the flexibility is valued. The operator of the electrolyser could also offer its flexibility to a BSP (or become a BSP).

### *3.3.4 No distorted incentives from grid tariffs or taxes*

The electricity grid tariffs are an important barrier for P2H2 DR. Electrolysers will typically have a large capacity and will be connected to the transmission grid. Thus, the tariff driver is the individual peak capacity per year and month.

As explained in section 2.2.4, the electricity grid tariffs for large industrial end-users incentivise baseload consumption because (i) the tariff driver is the yearly and monthly individual peak consumption and (ii) the volumetric discount for large industrial end-users depends on the operating time. This implies that the electricity grid tariffs per MWh of hydrogen produced increase significantly compared to baseload operation of an electrolyser.

As discussed previously, the choice of location will significantly impact the need for grid expansions. The effect of DR on the overall grid costs will depend to a large extent on the choice of location. However, the choice of location doesn’t impact the grid charges. This could result in high electricity grid charges, even when the impact on electricity grid costs is small. The electricity grid charges might incentivise not using the electricity grid at all (co-locating VRE sources and P2H2 “behind the meter”) and using only the hydrogen grid, even when this is not necessarily optimal from a societal perspective.

Energy taxation in the Netherlands doesn’t disincentivise DR from P2H2 but it also doesn’t support DR. The electricity tax (including surcharge) is based on total electricity consumption (kWh), which ignores the electricity price. Load shifting will not impact the electricity tax as the overall consumption doesn’t change. Reforming the electricity tax to a percentage on the electricity costs (like the VAT) would incentivise DR because consuming electricity with a lower average price would result in lower taxes.

### *3.3.5 Access to markets*

We are unaware of any other technology specific barriers related to the access to markets for DR in addition to the general barriers discussed in chapter 2.

### *3.3.6 Measurement and enforcement of demand response*

We are unaware of any other technology specific barriers related to the measurement and enforcement of DR in addition to the general barriers discussed in chapter 2.

## 3.4 Costs and benefits of demand response

### *3.4.1 Costs of flexible operation of the asset*

There are additional costs associated with flexible operation of the electrolyser because (i) the electrolyser capacity will need to be expanded and (ii) flexible operation leads to degradation of the electrolyser.

For an electrolyser to provide DR through load shifting the capacity of the electrolyser will have to increase to be able to supply the same annual hydrogen demand as an inflexible electrolyser operating in baseload. Naturally the capacity factor of the electrolyser will then be reduced. This will increase the CAPEX of the electrolyser per MWh of hydrogen produced compared to an electrolyser operating in baseload. In fact, the CAPEX of the electrolyser becomes the key cost component of a flexible electrolyser, whereas for an inflexible electrolyser operating in baseload, the CAPEX of the electrolyser is less important and instead the costs of electricity are the key cost driver (IEA, 2019a). This difference is shown in Figure 2. The figure on the left shows relationship between hydrogen production costs and electrolyser full load hours with a fixed electricity price and varying electrolyser CAPEX. At low full load hours, the CAPEX of the electrolyser becomes a key determinant of the production costs. At high full load hours, the relevance of the CAPEX of the electrolyser for the hydrogen production costs is much less relevant. The figure on the right shows the same relationship between hydrogen production costs and electrolyser full load hours, but with varying electricity price and fixed CAPEX of the electrolyser. This shows that the electricity price becomes a key determinant of the costs at high full load hours.

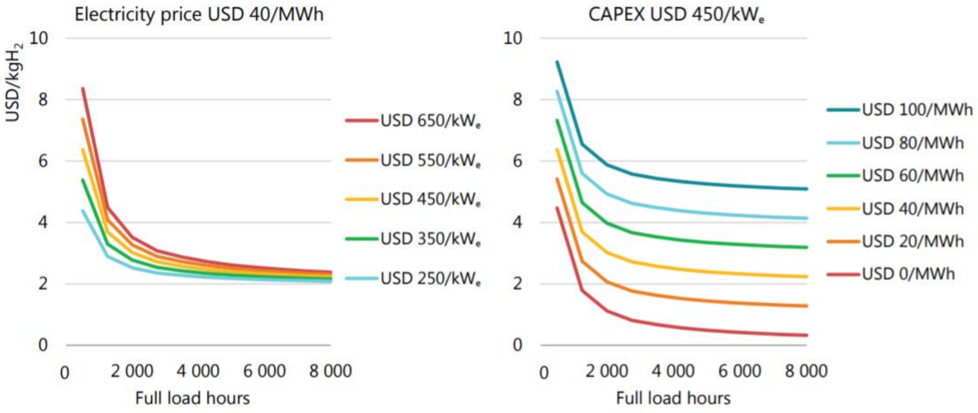

Figure 2 The relationship between hydrogen production costs and electrolyser full load hours Source: IEA (2019)

The development of the CAPEX of electrolysers will thus be a key determinant for the business case for P2H2 DR. So the question is: what determines the CAPEX of the electrolyser and what can be expected in term of cost development?

An electrolyser is composed of many stacks, which convert electricity to hydrogen. While it is true that the electrolyser capacity can be expanded slightly by increasing the stack size (making the stacks area larger), the electrolyser capacity is primarily expanded through increasing the number of stacks. IEA (2019) studied the stacking of electrolyser cells (i.e. the expansion of an electrolyser by adding additional electrolyser components) and shows that electrolysers can benefit from economies of scale, particularly in low MW electrolysers, shown in Figure 3. However, at some point the economies of scale from increasing the capacity of the electrolyser decrease.

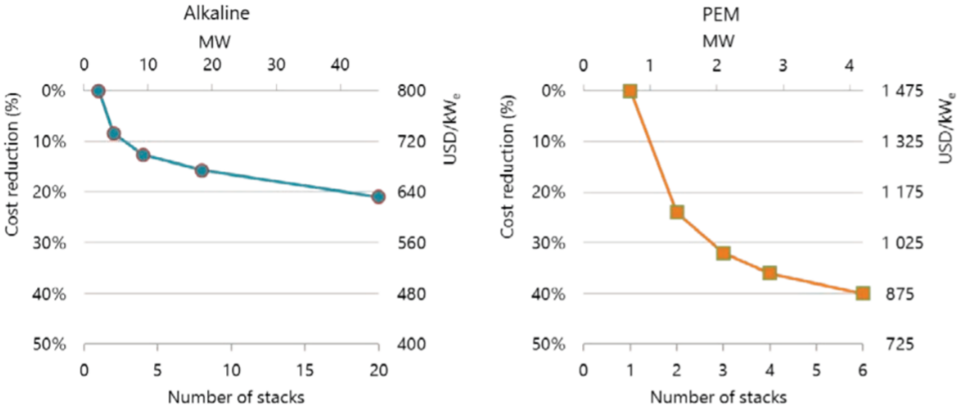

Figure 3 Economies of scale of stacking an electrolyser
Source: IEA (2019)

Economies of scale can also be expected from increasing the annual production of electrolysers. As shown in Figure 4, with increased annual production of electrolysers, there can be a great reduction in electrolyser costs. This will have a positive impact on the business case of DR P2H2. These cost reductions mostly come with a reduction in stack costs, where naturally, the mark-up and installation costs remain relatively unchanged. The Balance of Plant (BOP) includes the costs associated with the equipment for hydrogen processing, deionised water circulation, power supplies, cooling and miscellaneous.

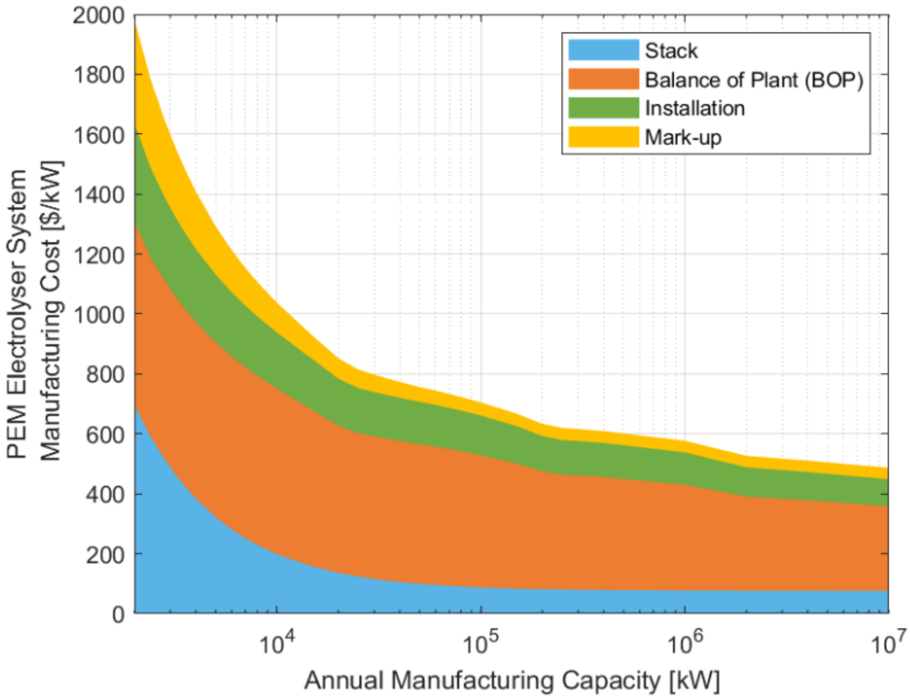

Figure 4 The estimated relationship between the annual manufacturing capacity (kW) of electrolysers and the CAPEX costs of an electrolyser ($/kW)
Source: Bristowe & Smallbone (2021)

In addition to costs associated with the increase of the CAPEX of the electrolyser, flexible P2H2 will also lead to additional costs of degradation. Increasing and decreasing the load will lead to wear and tear leading to degradation of the electrolytic membrane (Gusain et al., 2020). As a result of this, the ohmic overpotential, the increase in resistance, increases over time. This has been reported by Buttler & Spliethoff (2018) as a degradation of 1–2 µV/h or an efficiency degradation of 0.25-1.5 % per year. This leads to the requirement to replace all or some of the cell stack every 8-15 years (Buttler & Spliethoff, 2018) even though a plant life can be 20-40 years (TNO, 2018a, 2019b, 2020), thus, increasing the variable OPEX of the electrolyser. These replacement costs are said to be 50% of the total initial capital costs (Brynolf et al., 2018) and, therefore, a significant barrier to DR.

The replacement costs are said to be 50% because as shown in Figure 4, the stack costs are currently 50% of the total CAPEX. However, when global production of electrolysers is scaled up, the stack costs are expected to decrease significantly. This reduces the additional costs of having to replace a large share of the stacks every 8-15 years.

### *3.4.2 Costs of grid capacity*

As discussed in subsection 3.3.4 the grid tariffs disincentivise flexible production because (i) the tariff driver is the yearly and monthly individual peak capacity and (ii) there is a volumetric discount for large industrial end-users with a high operating time. These grid tariffs incentivise baseload consumption even though the effect on the grid costs of individual peak capacity is ambiguous and will depend to a large extent on the location of the electrolyser. Thus, the costs of DR resulting from the grid charges (i.e. costs from a private perspective) could deviate significantly from the costs of the grid (i.e. costs from a social perspective).

### *3.4.3 Costs of taxation*

The energy tax (including surcharge) isn’t impacted by DR as the tax is levied per kWh of electricity consumption and annual electricity consumption isn’t changed by DR through load shifting. A reduced average electricity price does lead to a reduced VAT.

### *3.4.4 Costs of reduced value of outputs*

Flexible hydrogen production can lead to a reduced value of the output in two ways. First, varying hydrogen production to supply baseload hydrogen demand requires flexibility in the hydrogen system. Second, flexible hydrogen production reduces the hydrogen quality.

Flexible hydrogen production requires flexibility in the hydrogen system. Hydrogen storage is an effective option to supply this flexibility. However, the need to store hydrogen impacts the business case for P2H2 as this comes at an added cost. In the Netherlands the expected storage method for hydrogen is in salt caverns. The cost of hydrogen storage in salt caverns is predicted to be $0.21/kg for hydrogen and covers the cost of compression and storage (Ahluwalia et al., 2019). Because there has to be a business case for storage as well, hydrogen prices will have to vary. This implies that hydrogen prices will be low (high) when the supply of hydrogen from P2H2 is high (low). Thus, flexible hydrogen production might reduce the hydrogen capture price.

Zhang et al. (2021) report that with a reduction in power load of the electrolyser, the percentage of hydrogen in the oxygen content and vice versa the percentage of oxygen in the hydrogen content increases. Thus, the quality of the hydrogen produced decreases. These diluting impurities occur as a result of the need to adjust the pressure in the electrolyser when the power load is less than 100%. This was explored under a range of different pressures, from 0.5-1.6 megapascal (MPa) in an AEL. Although the purity of H2 can be increased slightly with pressure adjustments, the power load of the electrolyser has an influence on the purity of hydrogen produced. This is relevant for DR, where load factors vary rapidly and stands as a minor quality barrier to P2H2 production by DR as it can be expected that with a poorer quality of H2, or a diluted quality, the price of the hydrogen produced will be reduced, and hence, the benefits of DR by P2H2 are lower (and/or the costs are higher).

These impurities also present a safety hazard as higher impurities of H2 in O2 output brings the electrolyser system closer to the lower flammability limit (LFL), the lower end of concentration in which a percentage of the gas can ignite at normal temperature and pressure (Zhang et al., 2021). This is a safety concern as hydrogen is a flammable gas, particularly when in the presence of a high concentration of oxygen. This presents a potential safety barrier if not managed correctly and may lead to an increase in insurance prices, posing an added cost or a reduction in the benefits from DR by P2H2.

### *3.4.5 Costs of unlocking demand response*

The costs of unlocking P2H2 DR appear to be limited, because the control mechanisms (smart meters, ICT, automation, operators) are generally already in place and the costs are limited compared to other costs (i.e. expansion of electrolysers capacity).

### *3.4.6 Benefit of demand response*

From a private perspective P2H2 DR has the potential to reduce the costs of electricity needed for the production of hydrogen because the average electricity price is reduced (implicit DR) and/or additional revenues are obtained by explicitly selling the flexibility in the market (explicit DR). This benefit from a private perspective reflects the fact that P2H2 DR has the potential to reduce the costs of electricity generation, by reducing VRE curtailment and reducing the need for dispatchable power plants.

## 3.5 Deciding on participation in demand response

As discussed in 2.4 there can be barriers that prevent participation in DR even when there is a positive business case for DR. Those barriers can, for example, be related to financial constraints, inertia, consumer values and the form of information.
However, for P2H2 those barriers seem less relevant as we can assume that a company investing in P2H2 will maximize profits and has access to capital.

For P2H2 the key question is whether investing in excess P2H2 capacity to participate in DR increases profits. The benefits of such an investment depend on the volatility of electricity prices and the costs of alternative forms of hydrogen production (SMR with and without CCS), which are uncertain. Furthermore, the grid tariff structure hampers the business case DR. The grid tariff structure might be changed, but whether, when and how such a change will impact the grid tariffs is uncertain, resulting in regulatory risk. Thus, a key element for the decision making on the participation in DR is the uncertainty. This uncertainty on the future benefits of DR will be taken into account in a higher discount factor for those benefits, which means the net present value of those benefits reduces. Thus, these risks can be a barrier for DR.

# 4 Hybrid industrial boilers

## 4.1 Technology description

Power-to-heat in industry refers to the use of electricity to generate useful heat for industrial processes. There are many different power-to-heat technologies. An overview of power-to-heat technologies is presented in Maruf et al. (2021). In this chapter we discuss the electric or electrode boiler to produce industrial process heat. Electric boilers use a an electric heating element, whereas electrode boilers use the conductive and resistive properties of water (Maruf et al., 2021). Hereafter, we'll use the term E-boiler to refer to both the electric and electrode boiler.

The E- boiler is an interesting option for demand response because it is an existing technology with low investment costs, high efficiency (95-99,9%) and that is very flexible. Because industries typically require baseload heat demand, an E-boiler can only be operated flexibly by some combination of (i) heat storage and (ii) heat production from another energy source. In this chapter we discuss only the latter type of a hybrid industrial boiler. With a hybrid industrial boiler heat can be supplied by either the E-boiler or the gas boiler depending on the relative gas and electricity prices. That results in electrical load when heat is provided by E-boilers, that is when the variable costs of producing heat from electricity are lower than that from gas. Otherwise, the electrical load is curtailed and the heat load is supplied by the gas boiler.

We analyse the barriers for DR for hybrid industrial boilers by comparing (i) flexible operation of a hybrid boiler with (ii) baseload operation of an E-boiler. This is a somewhat stylized comparison, because the industrial heat demand is currently supplied by gas boilers and the addition of the E-boiler to the gas boiler to form a hybrid boiler is an interesting option precisely because it can participate in DR.

## 4.2 Barriers to electrification

E-boilers and gas boilers are an established technology with technology readiness level 9 (TNO, 2018b, 2019a). Currently industrial process heat is primarily produced in gas boilers, simply because it is cheaper to produce heat from gas than from electricity. As further emission reductions are required over time, switching to (renewable) electricity is expected to become more attractive over time.

A hybrid industrial boiler can be an attractive option during the transition, primarily because of its DR potential. The value of the hybrid boiler is that it gives the option to switch between gas and electricity consumption, enabling price arbitrage. Therefore the market penetration of the E-boiler will primarily be determined by the relative gas-, electricity- and $CO_2$ prices. If, however, producing heat from electricity is cheaper all the time, then other electrification options (e.g. industrial high temperature heat pumps) might become more attractive than E-boilers. If producing heat from gas is cheaper almost all of the time, electrifying part of the demand is not attractive. Furthermore, hybrid industrial boilers reduce emissions but do not lead to zero emissions. Thus, hybrid industrial boilers might only be attractive during the transition.

In addition, insufficient availability of zero-emission electricity and transmission grid capacity can be a barrier for electrifying (part of) the industrial heat demand (TKI Energie en industrie et al., 2019).

## 4.3 Preconditions for demand response

### *4.3.1 Ability to flexibly operate the asset(s)*

The hybrid industrial boiler can participate in DR by curtailing the load when switching to gas (compared to inflexible baseload operation of an E-boiler). There are limited constraints for DR as (i) the flexibility is not constrained by saturation or load recovery, (ii) the assets have a high ramping ability, (iii) are available almost all of the time and (iv) with a reliable response.

Both the gas and E-boiler are very flexible, but the E-boiler is more flexible than the gas boiler. According to the Danish Energy Agency & Energinet (2021), the E-boiler has a minimum load of 2%, compared to 15% for the gas boiler. The warm start-up time is 0.03 hours for the E-boiler and 0.1 hours for the gas boiler. The cold start-up time is 0.17 hours for the E-boiler and 0.4 hours for the gas boiler. The minimum load of 15% for the gas boiler seems to be a relevant operational constraint (Chikri, 2020). But given the short cold start-up time seems to be an insignificant constraint for very flexible operation.

The industrial hybrid boiler is available for DR almost permanently, because industrial processes require 24/7 heat supply. Only in case of maintenance or a contingency of either the gas- or E-boiler, the hybrid boiler is unavailable for a response.

Because the asset(s) are operated 24/7 a response (either behaviourally by an operator or automated) will generally be reliable.

### *4.3.2 Sufficient grid capacity for demand response*

The required grid capacity is available by definition, as the hybrid industrial boiler provides DR through curtailment of the load. The availability of sufficient grid capacity is a barrier for electrification (the adoption of an E-boiler to produce heat), but once installed, the grid capacity is not a barrier for DR because the load is curtailed.

### *4.3.3 Incentives to reduce electricity costs by participating in DR*

There appear to be proper incentives to reduce electricity costs by participating in DR, as the industry and its energy supplier or BRP will trade on the wholesale and balancing market where the flexibility is valued. The industry could also offer its flexibility to a BSP (or become a BSP).

### *4.3.4 No distorted incentives from grid tariffs or taxes*

The electricity grid tariffs are a key barrier for flexible operation. Thus, the preconditions that there should be no distorted incentives from grid tariffs isn’t met.
As explained in section 2.2.4 the electricity grid tariffs for large industrial end-users incentivise baseload consumption because (i) the tariff driver is the yearly and monthly individual peak consumption and (ii) the volumetric discount for large

industrial end-users depends on the operating time. This implies that the grid tariffs per MWh of heat produced increase significantly compared to baseload operation of an E-boiler.

To some extent the increased grid charges make sense from a social point of view, because the hybrid industrial boiler requires grid capacity in both the gas and electricity system. The effect on the grid tariffs, however, appears to be larger than the effect on the actual grid costs. The gas grid tariffs are also to some extent capacity-based, but there the tariff driver differs substantially from the tariff driver for the electricity grid. For example: a peak consumption on one day for the gas grid can be covered by contracting a daily capacity product at a price that is (on average) 75% higher than 1/365th of the price of a yearly capacity product. For the electricity grid, a peak consumption on one day can lead to an increase of both kW-max and kW-contract, which implies a significant increase of yearly grid charges. In addition, the daily increase can result in the volumetric discount that can go up to 90% being lost entirely. Reforming the electricity grid tariffs to a system more similar to the gas grid tariffs appears to be necessary to avoid distorting incentives for DR.

The regressive energy taxes in the Netherlands for both gas and electricity can also distort incentives to participate in DR for hybrid industrial boilers. By switching between gas and electricity the annual consumption of both gas and electricity is lower, compared with heat production with either a gas or an E-boiler. If that implies the annual consumption level drops to a lower tax bracket, the average tax per MWh of heat production increases as a result of DR.

### *4.3.5 Access to markets*

We are unaware of any other technology specific barriers related to the access to markets for DR in addition to the general barriers discussed in chapter 2.

### *4.3.6 Measurement and enforcement of demand response*

We are unaware of any other technology specific barriers related to the measurement and enforcement of DR in addition to the general barriers discussed in chapter 2.

## 4.4 Costs and benefits of demand response

### *4.4.1 Costs of flexible operation of the asset*

The fixed costs will increase because in addition to the E-boiler a gas boiler is required. The fixed costs of a gas steam boiler are equal to the sum of annualised investment costs and the fixed operation and maintenance (O&M) costs. Assuming a nominal investment of 0,055 million €/MW (Danish Energy Agency & Energinet, 2021b), a discount rate of 7% and an economic lifetime of 25 years the annualised investment costs are 4.681 €/MW. The fixed O&M costs are 2000 €/MW/year (Danish Energy Agency & Energinet, 2021b). The total fixed costs of a gas boiler are thus 6.681 €/MW/year.

There seem to be no significant start-up or ramping costs (Danish Energy Agency & Energinet, 2021b)

### 4.4.2 *Costs of grid capacity*

Because the hybrid E-boiler requires capacity in both the gas and electricity grid, it is likely that the costs of grid capacity from a social perspective are higher than compared to baseload operation of an E-boiler. Thus, an accurate reflection of grid costs in the grid tariffs will likely result in higher grid tariff charges per MWh of heat produced.

However, as noted in 4.3.4 the electricity grid tariffs disproportionately increase for flexible operation compared with baseload operation. As a result, DR can be unprofitable from a private perspective when there is a positive business case from a social perspective.

### 4.4.3 *Costs of taxation*

The energy tax (including surcharge) for gas and electricity and the VAT impact the business case for DR. As discussed in 4.3.4 there can be a distortion due to the regressive taxes for gas and electricity.

### 4.4.4 *Costs of reduced value of outputs*

There appear to be no costs of reduced value of the output, because the quantity and quality of heat produced doesn’t change.

### 4.4.5 *Costs of unlocking demand response*

The costs of unlocking DR appear to be limited, because the control mechanisms (smart meters, ICT, automation, operators) are generally already in place. There could be costs of intermediaries, like energy suppliers or independent aggregators.

### 4.4.6 *Benefit of demand response*

From a private perspective, DR by hybrid industrial E-boilers can reduce the variable costs (energy, emission, variable O&M and taxation) from the heat supply, because the source with lowest variable costs is used for heat production. This reflects the fact from a social perspective the costs of both electricity and gas production are reduced. For example, the electric load is reduced when there is shortage of electricity supply.

## 4.5 Deciding on participation in demand response

As discussed in 2.4 there can be barriers that prevent participation in DR even when there is a positive business case for DR. Those barriers can, for example, be related to financial constraints, inertia, consumer values and the form of information.
However, for hybrid industrial boilers those barriers seem less relevant as we can assume that industries will maximize profits and have access to capital.

For hybrid boilers the key question is whether investing in E-boilers to complement to current use of gas boilers increases profits. The benefits of such an investment depend on the volatility of relative gas (including $CO_2$) and electricity prices, which are uncertain. Furthermore, the grid tariff structure hampers the business case for DR by E-boilers. The grid tariff structure might be changed, but whether, when and how such a change will impact the grid tariffs is uncertain, resulting in regulatory risk. Thus, a key element for the decision making on the participation in DR is the uncertainty. This uncertainty on the future benefits of DR will be taken into account in a higher discount factor for those future benefits, which means the net present value of those benefits reduces. Thus, these risks can be a barrier for DR.

# 5 All-electric residential heat pumps

## 5.1 Technology description

Residential power-to-heat refers to the use of electricity to generate useful heat for residential heating. Many different technologies exist for residential power-to-heat. A distinction between centralized and decentralized power-to-heat is generally made (Bloess et al., 2018; Maruf et al., 2021). Centralized power-to-heat refers to heat produced from electricity and supplied to residential end-users through district heating systems. Decentralized power-to-heat refers to the production of heat right at or close to the heat demand. In this chapter we discuss only decentralized residential power-to-heat. Several decentralized residential power-to-heat technologies exist (Maruf et al., 2021).[13] Of these, we discuss only all-electric heat pumps (hereafter simply: heat pumps) in this chapter.

Heat pumps use heat from a source (input heat), such as the outside air or ground water, and convert the heat to a higher temperature (output heat). A heat pump supplies low temperature heat, which requires a well-insulated home with a suitable heating system (e.g. underfloor heating).

For space heating with a heat pump there is inherently some flexibility due to the thermal inertia of the building. For example, it is possible to heat homes at night or during the day before the resident of the house gets up in the morning or gets home from work. Basically, the building is used as heat storage. Therefore, residential heat pumps can provide DR by load shifting. Especially in well-insulated homes it is possible to shift the load to high VRE periods, without significantly reducing impacting the comfort (Patteeuw et al., 2015). This load shifting will lead to a loss of efficiency because some of the heat is lost. Thus, the load shifting is combined with an increase of overall electricity consumption.

## 5.2 Barriers to electrification

Heat pumps currently meet only 7% of the global residential heat demand, while fossil-fuel alternatives still supply around half of the global residential heat demand (IEA, 2021a).

High upfront costs and high electricity prices are a barrier to the adoption of heat pumps (IEA, 2021a). The IEA notes that in many markets the adoption of a heat pump is only marginally less expensive than a gas boiler over a period of 10 to 12 years. According to the IEA, globally, fossil fuel subsidies and electricity taxes cause high electricity prices relative to gas prices.

Another barrier for the adoption of heat pumps is the need to renovate existing buildings to make them suitable for a heat pump. The current uptake of heat pumps is mostly limited to new buildings (IEA, 2021a). In existing homes, a hybrid heating system (combining a heat pump with a gas boiler) can reduce the need to renovate buildings. Moreover, the all-electric residential heat pump also faces competition from centralised heating systems.

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[13] All-electric heat pumps, electric boilers, electric resistance heaters and hybrid heating systems.

Furthermore, widespread adoption of heat pumps will require significant grid expansions of lower and medium voltage grids. Insufficient grid capacity stands as a barrier for the adoption of heat pumps for residential heat.

## 5.3 Preconditions for demand response

### *5.3.1 Ability to flexibly operate the asset(s)*

Providing DR through load shifting requires the ability to flexibly operate the heat pump. The ability to flexibly operate the heat pump is constrained by (i) saturation and load recovery, (ii) the ramping ability of the heat pump, (iii) the availability of the heat pump to provide DR and (iv) the control mechanism for an automated response.

To avoid a significant impact on the comfort, the load can only be increased or decreased up to a certain indoor temperature level (saturation). When that temperature level is reached, the temperature has to be brought back to the target temperature (load recovery). Therefore, saturation and load recovery constraint the potential for DR. The extent to which saturation and load recovery constrain DR depends on the loss of comfort an end-user is willing to accept.

All heat pumps have on/off regulation ability and most modern heat pumps can regulate the capacity between 20-30% of the capacity and the full capacity of the heat pump (Danish Energy Agency & Energinet, 2021a). Because frequent starts and stops decrease the efficiency and lifetime of the heat pump, the ability to regulate the capacity is an important enabler for DR. But even with the ability to regulate the capacity, frequent starts and stops need to be avoided. This means that the minimum load of 20-30% is a constraint to the flexibility.

Because heat pumps are primarily used for heating in the heating season, their availability for DR could also be limited to the heating season. However, some heat pumps can also be used for cooling in the summer, which implies some availability to participate in DR in the summer as well.

An automated response will be required because it is unlikely that residential end-users will monitor short-term developments on the electricity market and adjust the thermostat manually, given the fact that those adjustments will have to be made while the resident is asleep or at work. The installation of smart thermostats allows for the automated control of the heat pump, which enables the participation in DR.

A key issue is the control strategy for the heat pump, that determines the automated response. There is a body of literature on the control strategy for heat pumps that is reviewed by Péan et al. (2019). The control strategy aims to maximize the value of DR given the constraints, such as the comfort level. According to Péan et al. (2019) a distinction between rule-based controls (RBCs) and model predictive controls (MPCs) can be made. RBCs determine the control based on a set statements that take the form: “if (condition is verified), then (action is triggered)”. MPCs rely on a model of the building to project its future behaviour and determine the response based on optimization. MPCs determine the heat pump operation over a certain time horizon to achieve an objective within certain constraints. Péan et al. (2019) conclude that MPCs outperform RBC’s, but that there are still some challenges before MPCs can be widely implemented. The technology requires further development before it can be implemented on a large scale, which is a barrier to DR.

According to Péan et al. (2019) MPCs differ with respect to their objective function and the inputs that determine the response. In most cases, MPCs include the comfort level and the energy costs in the objective function. Alternatively, the comfort level is included in the model as a constraint. The power of the heat pump is also included as a constraint. Inputs for the optimization are generally the weather conditions (outside temperature, wind speed, solar irradiation), predictions of energy prices (peak and off-peak prices or hourly day-ahead prices) and internal gains (fixed schedule, occupancy sensor, electricity consumption from other devices).

To further complicate matters, the level of the DR should also take into account the overall DR provided by different technologies. When there is a large scale deployment of residential heat pumps with MPCs, the individual optimization with respect to a given price profile (e.g. day-ahead prices) will lead to an exaggerated response compared to the optimal level (Patteeuw et al., 2016).

### *5.3.2 Sufficient grid capacity for demand response*

A precondition for DR is that there is sufficient grid capacity available for the response. As mentioned in 5.2, large-scale adoption of heat pumps will require significant grid expansions, which is a barrier to electrification. Because we separate barriers to electrification from barriers to DR the question is whether DR further increases or decreases the required grid capacity relative to the adoption of heat pumps without DR.

The overall effect of DR on grid congestion is ambiguous. Adding DR could both lead to a reduction and an increase of local grid congestion, compared with heat pumps without DR. DR increases the electricity demand because of the loss of efficiency and thus could increase congestion. DR could also relieve congestion in the transmission grid, because it reduces the demand for interconnection to export offshore wind production. DR could also relieve congestion, when load is shifted to off-peak moments. However, the load shift could also cause new (shifted) peaks to emerge. As noted in 2.2.2 simultaneous automated response of several heat pumps in a street could lead to a loss of load diversity, impeding grid stability.

### *5.3.3 Incentives to reduce the electricity costs by participating in DR*

Although MPCs often take (a prediction of) variable energy prices as an input for the optimization, that doesn’t imply that MPCs are only possible with implicit DR. In case of explicit DR, the energy supplier or aggregator could offer the residential end-user a contract with some fixed remuneration or discount on the electricity costs under the condition that the residential customer installs the heat pump with the MPC. The MPC then controls the heat pump, which provides flexibility to the aggregator or energy supplier.

In case of implicit DR, the residential customer would install the MPC and sign up for a dynamic price contract. That increases the electricity price risk for the residential customer. On average electricity costs would be expected to decrease, but a short-term price spike on wholesale markets could lead to high electricity costs. As discussed in 2.2.3 the risk can be mitigated by reducing the variability of electricity prices (e.g. static time-of-use tariffs), but this dilutes incentives for efficient DR.

### *5.3.4 No distorted incentives from grid tariffs or taxation*

It appears that with the current grid tariffs in the Netherlands for end-users with a connection up to 3 x 80 Ampère (i.e. *kleinverbruikers*), participating in DR does not impact the grid charges. That is because grid charges are based on an assumed capacity (in Dutch: *rekencapaciteit)* - per connection type and not on the actual capacity used. The grid charges only increase when, to enable DR, the size of the connection has to increase such that it leads to a higher assumed capacity. However, it is likely that in the near future instead of the assumed capacity some measure of the actual capacity will be used. Even then, the effect of DR on the capacity is ambiguous. Thus, it is unlikely that the grid tariffs unduly disincentivise DR.

Energy taxation in the Netherlands does disincentivise DR from heat pumps. The electricity tax (including surcharge) is based on total electricity consumption (kWh), which ignores the electricity price. Since DR will lead to an increase of the consumption due to an energy loss and a reduction of the average electricity price, overall, the energy tax will increase as a result of DR. Reforming the energy tax to a percentage on the electricity costs (like the VAT) would avoid such a distortion.

### *5.3.5 Access to markets*

As discussed in 2.2.5 residential loads can only monetise flexibility through aggregation. That means that DR from residential heat pumps relies on energy suppliers and independent aggregators. The issues with the aggregator business model discussed in 2.2.6 are relevant for DR from residential heat pumps.

### *5.3.6 Measurement and enforcement of demand response*

There is an issue with the measurement and enforcement of explicit DR from residential heat pumps. The difficulty is that the MPC needs to function in such a way that the comfort of the residential customer is hardly affected. To keep the temperature on the right level, the behaviour of the residential customer and the weather needs to be taken into account. Uncertainty on the behaviour of the residential customer, will lead to uncertainty for the aggregator or energy supplier on the value of the DR. That is a specific case of the problems with the establishment of baselines for explicit DR: the electricity consumption without DR is unknown and as a result the level of the response is unknown as well.

## 5.4 Costs and benefits of demand response

### *5.4.1 Costs of flexible operation of the asset*

There can be costs of flexible operation of the asset when frequent starts and stops are caused by DR. Furthermore, DR will reduce the energy efficiency leading to higher costs of electricity consumption.

### *5.4.2 Costs of grid capacity*

As discussed in 5.3.4 the effect of DR on the required grid capacity is ambiguous. Thus, it is not possible to determine this effect. Based on the current grid tariffs, no additional costs from grid charges can be expected.

### *5.4.3 Costs of taxation*

Energy taxation disincentives DR. The energy tax is based on total electricity consumption (kWh), which ignores the electricity price. Since DR will lead to an increase in consumption and a reduction of the average electricity price, overall the energy tax will increase as a result of DR. Reforming the energy tax to a percentage on the electricity costs (like the VAT) would avoid such a distortion.

### *5.4.4 Costs of reduced value of the outputs*

Participating in DR can potentially lead to a loss of comfort because the indoor temperature deviates from the target temperature.

### *5.4.5 Costs of unlocking demand response*

The residential end-user will have to incur costs to be able to participate in DR. The MPC, smart meter and sensors are required, which requires (small) investments. Furthermore, the collecting and sharing of data that is necessary for DR implies costs in the form of a loss of privacy, which different end-users will weigh differently.

### *5.4.6 Benefit of demand response*

From a private perspective the main benefit of DR by residential heat pumps is the reduction of electricity costs. Residential heat pump DR has the potential to reduce the costs of electricity needed for the heat production because the average electricity price is reduced (implicit DR) and/or revenues are obtained by explicitly selling its flexibility in the market (explicit DR). This benefit from a private perspective reflects the fact that DR by residential heat pumps has the potential to reduce the costs of electricity generation, by reducing VRE curtailment and reducing the need for dispatchable power plants.

## 5.5 Deciding on participation in demand response

As discussed in 2.4 there can be barriers that prevent participation in DR even when there is a positive business case for DR. Those barriers can, for example, be related to financial constraints, inertia, consumer values and the form of information. These barriers are all, to some extent, relevant for DR by residential heat pumps.

### *5.5.1 Financial constraints*

Unlocking DR from residential heat pumps requires additional investments in smart meters, smart thermostats and sensors. Although these investments are limited compared to the investments in the heat pump and insulation of the house, they are added to those investments. Furthermore, smart meters are already installed in a majority of households. Thus, only for some residential end-users there might be financial constraints, which is a barrier for DR.

### *5.5.2 Inertia*

It can be expected that many residential end-users will simply not take any decision about participation in DR, simply because residential end-users are inert. Furthermore, end-users might simply be unaware of the value of DR. Advertising might be needed to inform end-users of this value, but at the expense of advertising costs. Parrish et al. (2019) note that in many residential DR trials and programmes enrolment varies widely between trials and programmes but is typically much lower than assumed in many electricity market models.

### *5.5.3 Consumer values*

For the residential end-users that do consider participating in a DR program, their values and the trust they have in the aggregator/supplier/technology will likely determine whether they will join. Given the fact that participation in DR basically requires to hand over the control of the thermostat, high trust combined with environmental and economic values will be needed. Low trust or “anti DR” values (such a privacy) will be a significant barrier for DR. Furthermore, bounded rationality could mean that end-users over- or underestimate the risks of DR. They could, for example, overestimate the effect of participating in DR on the comfort level.

### *5.5.4 Form of information*

When end-users do enrol in a DR programme, the actual response and the persistence of those responses will, among other things, depend on the user experience. The form of information will be an important element that can influence the user experience.

# 6 Electric vehicles

## 6.1 Technology description

The transport sector in the Netherlands is currently the second largest emitter of CO2, emitting 30 Mt, second only to the electricity and heat production sector. The need to electrify the transport sector is evident and this can be achieved by using an Electric Vehicle (EV), a vehicle that exclusively runs on electricity and produces zero exhaust emissions (Miele et al., 2020).[14] In this chapter we discuss only passenger EVs.[15] EV growth has continued each year and the 2019 climate agreement has called for 1.9 million vehicles in the Netherlands to be EVs by 2030 (IEA, 2020).

EVs can be charged at a charging station located at the end-users home, at work or at public charging stations. Public charging stations also differ in charging speeds, with high speed charging being available as well as the regular low speed charging stations. The range at which an EV can travel depends on the model type and battery size, and this driving range is currently between 275 and 450 km.

An EV connected to the grid can provide DR in two ways: grid to vehicle (G2V) and vehicle to grid (V2G). For G2V the charging speed can be adjusted according to the (price) signal. The charging speed will increase or start when the price is low and decrease or stop when the price is high. V2G also allows discharging the EV battery to supply electricity to the grid. For example, the EV can discharge when the electricity price is high, as long as there is sufficient range in the battery for the next scheduled trip. Thus, V2G uses the EV battery as a storage option. In this chapter we focus on G2V DR. V2G is only mentioned briefly in some cases.

## 6.2 Barriers to electrification

The market penetration of EVs depends on the consumers interest in purchasing an EV. Currently, the main barrier to this choice is the high capital cost of purchasing an EV. The excess upfront cost for an EV is roughly € 7,500 compared to a fossil fuel car of similar specifications (Liu et al., 2021). These higher upfront cost pose a significant financial burden on the consumer and excludes many potential consumers due to this excess financial strain. The total cost of ownership (TCO) of an EV can, however, be less than that of a petrol car through reduced maintenance and operational costs, reduced tax or full tax breaks and government subsidies. Despite these benefits, the upfront costs still stand as a barrier to the electrification of the transport sector as it is the end-user who takes the financial burden which requires people to make long term financial decisions where they will not be rewarded with the benefits for several years.

There will also be a bracket of consumers who will wait for the EV to be the same price as its comparable petrol or diesel model, this holds back the electrification of vehicles in the short term, even if these consumers will purchase an EV in the future.

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[14] Thus, we exclude plug-in hybrids with a battery and a reserve fuel tank and hybrid electrics with a fuel tank and a battery that charges of regenerative braking.

[15] Thus, we exclude electric busses and other types of electric vehicles.

In addition, the supply of different types and qualities of EVs is still limited and excludes various consumers from the market.

Furthermore, the number of cars to be replaced each year is limited, the average age of cars in the Netherlands is 11 years (ACEA, 2021) and there will be consumers who feel they haven't yet got their value worth of their current car and will wait until they have got their value worth before upgrading to an EV. This means that the market penetration of EVs will simply take time.

The current range of EVs holds back some customers, particularly those who need to drive large distances. The term 'range anxiety' refers to users worrying about not having enough range in their EV to complete a journey. This is not a major issue to those who live in cities and do not have to commute far each day. However, those to commute long distances in their car may choose a traditional petrol or diesel car to cover this range and reduce re-fuelling times if required. This issue is highlighted further by the limited charging infrastructure available to EVs, in particular, high speed charging stations along motor ways.

A lack of grid capacity for low voltage charging is a significant barrier to the development of EVs. Using DR from EVs to reduce the need for grid expansions is therefore seen as an enabler for the electrification (Hu et al., 2015). Another enabler to reduce the strain on the low voltage grid is to move charging away from the vulnerable low voltage grid to the robust medium voltage grid. This can be achieved at public charging stations, although typically outside cities and offers fast charging of EVs. This solution can also be optimal from a charging station perspective, with less additional grid connections required.

## 6.3 Preconditions for demand response

### *6.3.1 Ability to flexibly operate the asset(s)*

EVs can provide DR through load shifting. The load shifting is constrained by (i) load recovery, (ii) the unavailability of EVs to participate in DR and (iii) the control mechanisms needed to provide an accurate response to a signal. The ramping ability is not a relevant constraint.

Load shifting for EV DR is constrained by the fact that the EV battery has to be charged in time for the next trip. Therefore, when the battery is charged slower or not at all at some point in time, that requires the load to recover later on to make sure the battery is charged before the next trip. When there is uncertainty about the time and range of the next trip, there is a risk the battery is not sufficiently charged. Thus, the extent to which end-users fear that their battery will not be charged in time is an important factor that determines the potential for DR. We discuss this further in section 6.5.

The modern EV, which uses lithium-ion batteries has negligible ramping constraints (U.S. Department of Energy, 2019). This allows EVs to respond instantaneously to (price) signals and adjust their charging pattern immediately.

EVs can only participate in DR when they are available. This availability refers to the EV being plugged into a charging station that allows ramping up or down the charging speed. Evidently, EVs that are in transit or parked but not plugged into the grid are unavailable for DR. Furthermore, EVs that are charged at high speed charging ports are unavailable for DR as well, as the goal of this charging pattern is to reach full battery capacity in as little time as possible. The end-user is presumably not interested in DR when this charging method is desired. Therefore, DR is only possible when the EV is connected to a low speed charging station for a longer period than strictly necessary to charge the battery.

However, there is a trade-off between maximizing the availability of EVs for DR and limiting the costs and spatial impact of charging stations. Maximizing the availability of EVs for DR requires the EV to be plugged into the grid each time it is parked and, thus, every parking spot needs to have a charging port. Minimizing the cost and spatial impact of EV charging requires that the charging ports are optimised in a manor where the cost of implementing the ports is minimised, the usage of the ports is maximised, and the spatial location of the ports is widespread (Mashhoodi & van der Blij, 2021). Thus, the availability of EVs for DR will likely be constrained by the lack of suitable charging points.

EV DR can be done by means of behavioural or automated response. A behavioural response requires the end-user to respond to price signals and adjust their charging pattern accordingly, which takes time and effort. An automated response requires soft and hardware to be installed to monitor (price) signals and communicate with market parties to adjust the charging automatically. An automated response seems to be a more likely model for EV DR.

Automation is a particularly important model for overnight household charging as it allows the most accurate match of supply and demand and the greatest reduction in electricity bills. Automation requires information on the vehicles state of charge, the amount of charge needed and the time at which the vehicle is next required. The automation system then optimises when the EV will be charged within the constraints to maximise electricity savings (Dayem et al., 2020).

Dayem et al. (2020) also studied controlling workplace charging, stating that it is also possible due to the EV being parked for a full workday. The same constraints as household charging is required to achieve the most beneficial charging pattern. The charging at a workplace becomes more complicated if there is more than one EV per charging station. In this case the focus shifts to meeting the demand for all EVs rather than DR.

While automation can successfully eliminate or partially eliminate human behaviour and effort from charging decisions, reduce the end-user response time, increase monetary benefits and reduce energy peaks there are some barriers to this. There is some human effort in supplying information to an automation system, this information can include next time of use, journey type and distance or the knowledge of driving from previous and similar days (Chen et al., 2017). The failure of this scheduling is also an issue and can leave the end-user frustrated and unhappy with the DR program and more likely to drop out or discontinue with it.

### 6.3.2 *Sufficient grid capacity for demand response*

A precondition for DR is that there is sufficient grid capacity available for the response. As mentioned in 6.2, large scale adoption of EVs will require significant grid expansions, which is a barrier to electrification. Because we separate barriers to electrification from barriers to DR the question is whether DR further increases or decreases the required grid capacity relative to the adoption of EVs without DR. As discussed in 6.2 using the flexibility of EV-charging to charge in a “grid friendly” manner can be seen as an enabler for the electrification of transport, as it reduces the need for grid expansion. However, “grid friendly” charging could lead to different charging patterns compared to the normal charging pattern (i.e. slow charging overnight versus charging as fast as possible when plugged in). For the discussion of the effect of DR (to maintain the system balance) on the grid capacity we consider the normal charging pattern (i.e. charging as fast as possible when plugged in) and not the charging pattern where the flexibility is used to minimise the strain on the grid.

The overall effect of DR on grid congestion is ambiguous. Adding DR could both lead to a reduction and an increase of local grid congestion, compared with EVs without DR. DR could relieve congestion, because distributed solar PV production is used to charge the battery which limits the need for expansion of higher voltage grids. DR could also relieve congestion, when load is shifted to off-peak moments. DR could also increase congestion as the demand in lower voltage grids might increase significantly when there is a lot of VRE production from offshore wind. Furthermore, the load shift could also cause new (shifted) peaks to emerge. As noted in 2.2.2 simultaneous automated response of several EVs in a street could lead to a loss of load diversity, impeding grid stability.

### 6.3.3 *Incentives to reduce electricity consumption by participating in DR*

As discussed in section 2.2.3 demand flexibility is valuable to BRPs and BSPs but the incentives to participate in DR will have to be passed on to end-users through energy suppliers or independent aggregators. For public charging points those incentives will also have to be passed through via the charging point operator. In any case, the energy supplier, independent aggregator or charging point operator can incentivise DR through an implicit or an explicit DR contract.

### 6.3.4 *No distorted incentives from grid tariffs and taxes*

It appears that with the current grid tariffs in the Netherlands for end-users with a connection up to 3 x 80 Ampère (i.e. *kleinverbruikers*), participating in DR does not impact the grid charges. That is because grid charges are based on an assumed capacity per connection type and not on the actual capacity used. The grid charges only increase when to enable DR the size of the connection has to increase such that it leads to a higher assumed capacity. However, it is likely that in the near future instead of the assumed capacity some measure of the actual capacity will be used. Even then, the effect of DR on the capacity is ambiguous. Capacity based grid charges will disincentivise short peak consumption, which might be needed to absorb VRE production.

Energy taxation in the Netherlands doesn’t disincentivise DR from EVs but it also doesn’t support DR. The electricity tax (including surcharge) is based on total electricity consumption (kWh), which ignores the electricity price. Load shifting will not impact the electricity tax as the overall consumption doesn't change. Reforming the electricity tax to a percentage on the electricity costs (like the VAT) would incentivise DR because consuming electricity with a lower average price would result in lower taxes.

#### *6.3.5 Access to markets*

We are unaware of any other technology specific barriers related to the access to markets in addition to the general barriers discussed in chapter 2. The participation of DR from EVs will require aggregation. Thus, the barriers resulting from issues with the market role of independent aggregators is a relevant barrier for DR from EVs.

#### *6.3.6 Measurement and enforcement of demand response*

Smart meters are required to measure the consumption per ISP. For implicit DR there seems to be no barriers to the measurement and enforcement of a program.

For explicit DR, the baseline consumption issue discussed in 2.2.6 is a barrier to DR by EVs. End-users can easily manipulate their EV electricity consumption, because of their moral hazard problem. Furthermore, the complexity of the conflict of interest between a BRP and independent aggregator is a barrier to their aggregation and access to markets.

### 6.4 Costs and benefits of demand response

#### *6.4.1 Costs of flexible operation of the asset*

There appear to be no costs associated with the flexible operation of the asset. However, degradation of the battery is associated with V2G DR, but in this chapter we focus only on G2V DR.

#### *6.4.2 Costs of grid capacity*

As previously discussed in 6.3.2 the effect of EV DR on the required grid capacity compared to EVs without DR is ambiguous. DR could both lead to an increase or a decrease of the required grid capacity. Thus, the effect of DR on the costs of grid capacity from a social perspective are hard to determine. From a private perspective the costs of grid capacity are determined by the grid tariffs. Given the diversity of charging ports (at home, public charging station) with different types of connections it is difficult to discuss the effect of DR on the grid charges.

#### *6.4.3 Costs of taxation*

The energy tax (including surcharge) isn't impacted by DR as the tax is levied per kWh of electricity consumption and annual electricity consumption isn't changed by DR through load shifting. A reduced average electricity price does lead to a reduced VAT.

### *6.4.4 Costs of reduced value of outputs*

There are costs of reduced value of the outputs, because there is a risk that due to participation in DR the battery will be insufficiently charged. These costs usually occur in automated DR programs where a situation may occur where the end-user feels there is insufficient range in its car to complete a journey and the end-user begins to feel like he or she has no control over the charging.

### *6.4.5 Costs of unlocking demand response*

There are many different types of costs to unlock DR. These costs include:

- The installation of smart meters;
- The overdimensioning of charging ports;
- The technology for an automated response or the ICT systems and end-user effort for a behavioural response;
- The loss of privacy due to the sharing of consumption data;
- The costs of an increased price risk in case of implicit DR; and
- The costs of the aggregator or energy supplier that need to be covered.

### *6.4.6 Benefit of demand response*

From a private perspective the main benefit of DR by EVs is the reduction of electricity costs. DR has the potential to reduce the costs of electricity needed to charge the battery because the average electricity price is reduced (implicit DR) and/or revenues are obtained by explicitly selling its flexibility in the market (explicit DR). This benefit from a private perspective reflects the fact that DR by EVs has the potential to reduce the costs of electricity generation, by reducing VRE curtailment and reducing the need for dispatchable power plants.

## 6.5 Deciding on participation in demand response

As discussed in 2.4 there can be barriers that prevent participation in DR even when there is a positive business case for DR. Those barriers can, for example, be related to financial constraints, inertia, consumer values and the form of information. These barriers are all, to some extent, relevant for DR by residential heat pumps.

### *6.5.1 Financial constraints*

Unlocking DR from EVs requires additional investments in smart meters, ICT-systems and automation. Although these investments are limited compared to the investments in the EV, they are added to that investment. Furthermore, smart meters are already installed in a majority of households. Thus, only for some residential end-users there might be financial constraints, which is a barrier for DR.

### *6.5.2 Inertia*

It can be expected that many residential end-users will not take any decision about participation in DR, because residential end-users are inert. Furthermore, end-users might be unaware of the value of DR. Advertising might be needed to inform end-users of this value, but at the expense of advertising costs. Parrish et al. (2019) note that in many residential DR trials and programmes enrolment varies widely between trials and programmes but is typically much lower than assumed in many electricity market models.

### *6.5.3 Consumer values*

For the EV drivers that do consider participating in a DR program, their values and the trust they have in the aggregator/supplier/technology will likely determine whether they will join.

Given the fact that participation in DR basically requires to hand over the control over the battery charging, high trust combined with environmental and economic values will be needed. Low trust or “anti DR” values (such a privacy) will be a significant barrier for DR. For example, EV drivers may feel as if the savings received from participating are too small, especially when their fuel costs are already significantly reduced when switching from petrol or diesel to an EV. They may not like the discomfort of not having a full battery after charging or may not understand the benefits of DR for the power system. They may not like the fact that driving patterns can be derived from charging data that needs to be shared with the energy supplier or independent aggregator.

Furthermore, bounded rationality could mean that end-users over- or underestimate the risk of DR. They could, for example, overestimate the effect of participating in DR on the driving range because of range anxiety. Range anxiety is a specific type of anxiety that EV drivers can have where they fear they will not have enough range in their battery to complete their next trip. The anxiety, however, is often unwarranted and this leads to unnecessary charging of the EV. Not only does this anxiety lead to large increases in grid infrastructure (Mashhoodi & van der Blij, 2021) but it also affects the success of DR.

As a result of all these different consumer values that are affected by DR, many EV-drivers who do consider joining a DR programme may conclude that for them the benefits don’t outweigh the costs.

### *6.5.4 Form of information*

The user experience is important and a well-designed program will lead to greater DR participation rates and less drop out. It is important that the user interface is clear and simple to use to reduce end-user frustration and ensure a smooth operation of the DR program. As automation of DR still requires information of the EV-driver about the timing and range of the next trip, the user experience of the interface to retrieve this information is especially relevant for EVs.

# 7 Conclusion

In this report we discussed many different barriers for DR in general and for the four technologies specifically (i.e. P2H2, hybrid industrial boilers, all-electric residential heat pumps and EVs). The barriers are of a technical, economic or behavioural nature and are often interrelated. We structured the discussion of the barriers by discussing (i) barriers to electrification, (ii) preconditions for DR, (iii) costs and benefits of DR and (iv) deciding on participation in DR. In this chapter we present the conclusions using the same structure.

## 7.1 Barriers to electrification

To participate in DR there first needs to be a demand. Thus barriers to electrification will need to be overcome for DR to play a relevant role. We conclude that there are still many general and technology specific barriers to electrification:

- In many cases the fossil-fuel alternative is still the cheapest option;
- There is competition from other, non-electric, options to reduce emissions;
- Electrification requires significant expansions of the electricity grid.

The market penetration of the technologies discussed in this report will depend on the extent to which these barriers are overcome.

## 7.2 Preconditions for demand response

When there is a demand asset connected to the grid, then in principle it is possible to participate in DR when certain preconditions are met. These preconditions are:

1 Ability to flexibly operate the asset(s)
2 Grid capacity to flexibly operate asset(s)
3 Proper incentives to reduce electricity costs by participating in DR
4 No distorted incentives from grid tariffs and taxation
5 Access to markets
6 Accurate measurement and enforcement of DR

Of these preconditions several aren’t met which implies there are barriers to DR. We conclude the following:

1 Ability to flexibly operate the asset(s): For all the four technologies discussed in this report there is some ability to flexibly operate the assets. That flexibility can be constrained by (i) saturation and load recovery, (ii) the ramping ability of the asset, (iii) the availability of the asset to provide DR and (iv) the reliability of the response as a result of control mechanism for DR. It appears that there are more constraints to DR for the residential technologies (all-electric residential boilers and EVs) than for the large-scale technologies (hybrid industrial boilers and P2H2). For the residential technologies striking the right balance between enabling DR without reducing the comfort of the end-user is a challenge.

2 Grid capacity to flexibly operate asset(s): DR can both increase and decrease the required grid capacity. Although the effect of DR on the individual end-users grid capacity required can sometimes be determined (i.e. load shifting can increase individual peak consumption whereas curtailment reduces the required grid

capacity), the effect on the total grid capacity required for the electricity system is ambiguous as it depends on the flexibility source that would be used in the counterfactual situation without DR and its location. In general we can conclude that DR has the potential to reduce the need for grid capacity when closely located with VRE. However, there is a lack of locational incentives in the current market design.

3 Proper incentives to reduce electricity costs by participating in DR: In principle the wholesale market design ensures that demand flexibility is valuable to BRPs and BSP and, thus, incentivises DR. However, there are some important barriers. First, the incentives for DR need to be passed on to end-users via intermediaries (BRPs, BSPs, energy supplier and independent aggregators). Incentives can be passed through via implicit or explicit contracts. Implicit DR incentivises DR by time-varying prices to which the end-user responds. Explicit DR incentivises DR by an explicit contract where the end-user promises to respond to an instruction to adjust the load. This pass-through of incentives via implicit or explicit DR often leads to diluted incentives, in part because end-user may want to limit the exposure to risk. In addition, the net-metering of residential VRE production disincentivises self-consumption.

4 No distorted incentives from grid tariffs and taxation: Grid tariffs for large industrial end-users (i.e. hybrid industrial boilers and P2H2) distort incentives to provide DR, because (i) the tariff driver is the yearly and monthly individual peak consumption and (ii) the volumetric discount for large industrial end-users depends on the operating time. This strongly incentivises baseload consumption even when the effect of DR on the required grid capacity is ambiguous. Abolishing the volumetric discount for large industrial end-users and reforming the tariff driver can enable DR. Furthermore, the electricity tax is levied on the basis of the annual consumption (kWh), which excludes the price of electricity. Although it is not always the case that this “distorts” the incentives for DR[16], it also doesn’t support DR. Reforming the electricity tax to a percentage on electricity costs ensures that a reduction of the electricity price as a result of DR also leads to lower electricity taxes, thus enabling DR. Furthermore, making the electricity taxes less regressive can limit distorted incentives to participate in DR in specific cases.

5 Access to markets: Significant improvements have been made in recent years to improve the access to markets. A remaining barrier is the symmetric procurement of FCR capacity by TenneT. Furthermore, the access to markets for residential end-users requires aggregation. Thus, barriers to aggregation are barriers to market access for residential end-users. There are important barriers for independent aggregators (i.e. aggregation by a third party and not by the energy supplier) that are related to the measurement and enforcement of DR which we discuss next.

6 Accurate measurement and enforcement of DR: To accurately incentivise DR it is important that the response can be measured and the contractual arrangements from both implicit and explicit DR can be settled. For implicit DR that requires that a smart meter is installed, which is currently not the case in the

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[16] In case of load shifting, the annual consumption doesn’t change and so the electricity taxes aren’t affected by load shifting.

Netherlands for 15% of residential end-users. For explicit DR, in addition, the counterfactual consumption without DR has to be determined. There are several issues with the baseline methods (Ziras et al., 2021) and the use of baselines leads to adverse selection and moral hazard problems (Chao, 2011). When energy supply and aggregation are split over different agents (i.e. independent aggregation), any load adjustment resulting from DR by an independent aggregator will result in an imbalance for the BRP (Vallés et al., 2016). This requires contractual arrangements between energy supplier, independent aggregator and their respective BRPs to determine the effect of DR relative to a baseline consumption level. Given the issues with the use of baselines, this leads to issues for the measurement and enforcement of DR incentivised by independent aggregators.

## 7.3 Costs and benefits of demand response

When the preconditions for DR are met, the next question is whether for a specific technology and in a specific market context there is a positive business case for DR. The business case for DR depends on the costs and benefits of DR, which we discussed from both a private and social perspective.

- Benefit of DR: From a social perspective DR reduces the need to curtail VRE, leads to a higher share of VRE in the system and reduces the need for dispatchable power plants as back-up. Thus, DR can reduce the overall costs and emissions of electricity production. These benefits to the electricity system are passed-through to end-users via implicit or explicit DR contracts, resulting in a reduction of the electricity costs. Participation in DR generally leads to lower energy costs from a private perspective, because the average electricity price is reduced (implicit DR) or additional revenues are obtained (explicit DR).

- Costs of DR: There are several different types of costs associated with participation in DR. We distinguish (i) costs of flexible operation of the asset, (ii) costs of grid capacity, (iii) costs of taxation, (iv) costs of reduced value of outputs and (v) costs of unlocking DR. As discussed previously, the costs of grid capacity and taxation can have a large impact on the private business case even when there is a positive business case for DR from a social perspective (i.e. distorted incentives for DR resulting from grid tariffs and taxation). Furthermore, there is clear difference between the residential (all-electric residential heat pumps and EVs) and industrial technologies (hybrid industrial heat pumps and P2H2). For the industrial technologies there are clear monetary costs of flexible operation or reduced value of the outputs that can be quantified. In addition, these technologies require significant additional investments to be able to participate in DR (i.e. expansion of electrolyser capacity or combining a gas and E-boiler). The costs of unlocking DR appear to be of limited relevance for these technologies. In contrast, for the most relevant costs are related to the reduced value of outputs and costs related to unlocking DR. These are hard to quantify costs like a loss of comfort, a loss of control and a loss of privacy. These “costs” are also not fixed, but can be influenced as we discuss in the next section. In addition, for the residential technologies the costs of participating in DR require limited additional investments (smart meter, ICT-systems) in addition to the investments in the assets (i.e. EV and heat pump).

## 7.4 Deciding on participation in demand response

Even when there is positive business case for DR (from both a private and social perspective), there can be barriers that prevent the end-user from participating in DR. These barriers are related to (i) financial constraints, (ii) inertia, (iii) consumer values and (iv) the form of information. These barriers are especially relevant for residential end-users and appear of limited relevance for industrial end-users.

- Financial constraints: When there is a positive business case for DR but DR requires some investments, financial constraints can be a barrier to DR. The investments needed to enable DR for the residential end-users (i.e. all-electric heat pumps and EVs) appear to be limited but they are added to the high investments needed in the all-electric heat pump or EV. Many residential end-users will not be creditworthy enough to access capital markets and have limited savings, thus preventing them from participating in DR.

- Consumer inertia: is another factor that will limit the participation in DR from residential end-users, as many residential end-users simply won’t consider participating in DR.

- Consumer values: The weight end-users place on hard to quantify costs like a loss of comfort or privacy but also on the wider benefits of DR (such as emission reduction) can be informed by consumer values (Good et al., 2017), such as autonomy, ownership, power and control. These consumer values can prevent end-users giving up control over some of their devices to participate in an automated response and sharing data that is required for the measurement of the response. Other consumer values such as environmental values could stimulate the participation in DR. This also suggests that it matters by whom the DR programme is sold to residential end-users and which values are signalled. Thus, these “costs” are probably not fixed, but they can be influenced by aligning DR with the consumers values. For example, trust between the aggregator or energy supplier and end-user is an important factor that will influence the end-users decision to participate in DR (Good et al., 2017).

- Form of information: The form of information that is exchanged between the end-user and the aggregator or energy supplier is another factor that can influence the decision to participate in DR. For example, implicit DR requires timely information about prices that the end-user can respond to. Explicit DR requires some instruction from the energy supplier or aggregator to adjust the load. Especially in case of a behavioural response poor design of the user interface can be a barrier to DR (Good et al., 2017), but also in case of an automated response it is important that the end-user is informed about the adjustment of the load in a proper way.

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# A Network tariffs

## A.1 Tariff setting process and principles

Gas and electricity system operators are regulated natural monopolists. Grid operators are by law required to be independent from generation, trade and supply. Grid operators have to grant grid users access to their grids and charge reasonable tariffs. The grid tariffs are regulated by the national regulatory authority who sets or approves the grid tariffs.

For the regulation of the grid tariffs a distinction can be made between (i) setting the allowed or target revenue for the grid operator and (ii) setting the tariff structures that determine how the allowed or target revenues are obtained from different grid users. The first gives incentives to the grid operator whereas the second gives incentives to grid users. We focus on the tariff structures, since the tariff structures determine the incentives for DR.

When setting the tariff structures, the national regulatory authority has to balance different competing principles (Council of European Energy Regulators, 2020):
- Cost-reflectivity: For efficient use and development of the network, as far as practicable, tariffs paid by network users should reflect the cost they impose on the system and give appropriate incentives to avoid future costs;
- Non-distortionary: Costs should be recovered in ways that avoid distorting decisions around access to and use of the network, and market offers;
- Cost recovery: Grid operators should be able to recover efficiently incurred costs. As well as tariffs for use of the electricity system, grid operators may also recover costs through connection charges and regulated services;
- Non-discriminatory: There should be no undue discrimination between network users;
- Transparency: Grid tariffs and the methodologies to calculate them should be transparent and accessible to all stakeholders;
- Predictability: It is important that network users can effectively estimate the costs of their use of the electricity system, facilitating efficient long-term investment by network users. However, the changing nature of the energy system means network tariffs will need to evolve over time;
- Simplicity: As far as possible, tariffs should be easy to understand and implement. The simpler they are, the easier they are for network users to respond to.

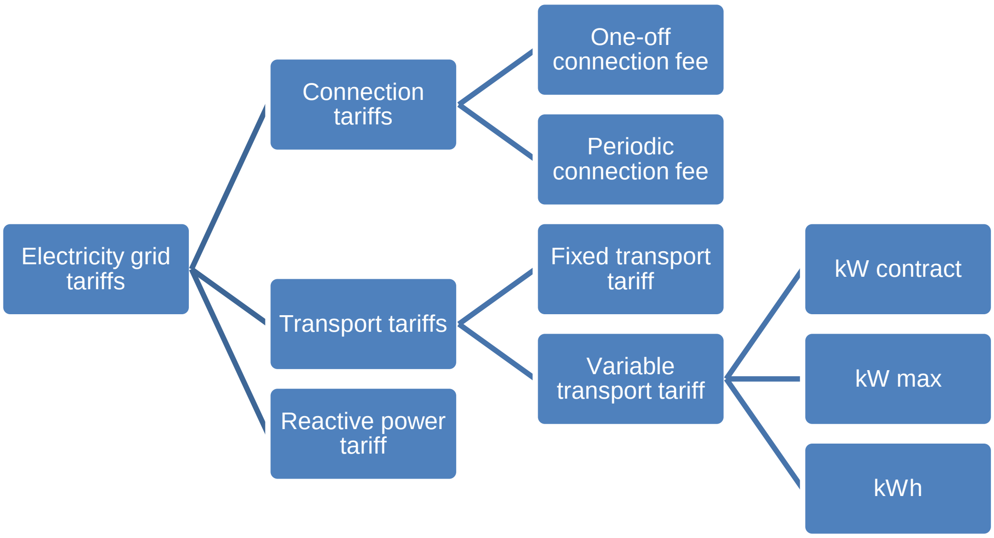
Because many competing principles have to be taken into account, there will generally be a trade-off between providing the right incentives for DR and other tariff principles.

Some of the key design choices for the tariff structure are (Council of European Energy Regulators, 2020):
- Whether and to what extent different types of tariffs are applied that cover a specific part of the cost of the electricity grid. For example, a distinction between connection charges and transport charges is quite common.
- Whether tariffs differ between voltage levels;
- Whether tariffs are charged to generation, load or both;

- What tariff drivers are used. A capacity (kW), energy (kWh) or fixed fee (per connection) are most commonly used. In case of a capacity charge, the way the capacity is determined matters as well (contracted capacity, actual capacity or maximum capacity of the connection). In case of actual capacity: the duration of the period over which the actual capacity is calculated.
- In case a capacity or energy tariff driver is used: whether temporal or spatial differentiation of the grid tariffs will be applied. Some level of temporal differentiation (time-of-use tariffs) is quite common, especially for kWh-tariffs. Spatial differentiation is uncommon.

## A.2 Electricity network tariffs in the Netherlands

For the use of the electricity grid in the Netherlands, different grid tariffs are charged. A schematic overview of the grid tariffs is presented in the figure below (Overlegtafel energievoorziening, 2018).



*Connection tariffs*

An industry connected to the electricity grid will need a connection, for which connection tariffs are charged. There is a one-off connection fee that covers the costs of the initial investment to establish the connection. There is also a periodic connection fee that covers the costs of maintenance of the connection. The connection tariffs apply to both generation and load connected to the electricity grid.

*Transport tariffs*

The transport tariffs cover the costs of the actual electricity grid (excluding the connections), by far the largest part of the electricity grid charges. Of the transport tariffs, the fixed transport tariff covers only some small cost items, such as costs of invoicing, customer service and other administrative costs.[17] The fixed transport tariff is charged to both generation and load.

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[17] Tarievencode elektriciteit, article 3.2.2.b

Practically, the variable transport tariff covers the major part of the costs of the electricity grid. The variable transport tariff is charged only to the load. The variable transport tariffs are set per voltage level of the grid and per grid operator. The voltage levels are:

- EHV (extra high voltage) 280/220 kV;
- HV (high voltage) 150/110 kV;
- Transformator HV-TV/MV;
- TV ("tussenspanning") 50/25 kV;
- MV (medium voltage) 1-20 kV;
- Transformator MV-LV;
- LV (low voltage) 0,4 kV.

The costs of the electricity grid are allocated to the users connected to different voltage levels based on the "cascading" principle. Then, the costs allocated to the voltage level are charged to the users connected to the voltage level based on tariff drivers.

Cascading means that a part of the costs of the EHV-grid is charged to the load connected to the EHV-grid and a share of the costs of the EHV-grid is passed through to the HV-grid. The share is based on the load of direct connections to the EHV-grid relative to the transport from the EHV-grid to the HV-grid. This principle is repeated for all voltage levels. Thus, a load connected to the LV-grid is charged for the costs of the LV-grid and some share of the costs of all grids with a higher voltage. The reasoning behind the cascading principle is that historically all generation was connected to the EHV-grid and thus lower voltage grids are only used to transport to users connected to lower voltage grids. With more distributed energy production connected to lower voltage levels, that has changed. However, the cascade is designed in such a way that more generation on lower voltage grids means that a smaller share of the higher voltage grids is allocated to the lower voltage grids.

The costs to be recovered from the load connected to a specific voltage level are charged to the different grid users connected to that voltage level on the basis of tariff drivers. The tariff drivers are some combination of (i) contracted capacity (kW contract), (ii) maximum capacity (kW max) and (iii) energy consumption (kWh). The contracted capacity is the maximum capacity that a grid user uses in the entire year.[18] Grid users have to submit their contracted capacity before the start of the next year. The maximum capacity is the actual maximum capacity used over the period of a month or a week. The energy consumption needs no further explanation.

The actual tariff drivers differ per voltage level. For the EHV and HV, the tariff drivers are the contracted capacity (50%) and the maximum monthly capacity (50%).[19] The lower the voltage level, the higher the share of energy consumption becomes. An exemption to this rule are the tariff drivers for residential end-users (i.e. *kleinverbruikers*) with a connection capacity of maximum 3*80 Ampère. For these connections the charges are independent of the actual use of the grid. Instead they

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[18] Connected load has to submit its expected maximum capacity in advance, but the estimated value is adjusted afterwards to the actual maximum yearly peak.

[19] When the operating time for the connection is smaller than 600 hours, the tariff drivers are 50% * kW contract + kW max per week. The tariff for the kWmax per week is equal to 18/52 * kW max per month. So in case of an installation with a relatively low capacity factor, the share of the contracted capacity decreases and instead of the monthly peak load the weekly peak load is used.

are based on an assumed capacity (in Dutch: *rekencapaciteit*) for different types of connections (Overlegtafel energievoorziening, 2018).

Clearly, the tariff driver will have a significant impact on the incentives for DR. However, the fact that there are different tariff drivers for each voltage level makes an analysis of the effect of the tariff drivers on the incentives for DR quite complex. In general, the grid tariffs for load connected to high voltage grids (EHV and HV) are capacity-based tariffs, where the capacity is calculated based on the yearly and monthly individual peak. This tariff structure incentivizes avoiding individual peak consumption. For load connected to the low voltage grid, the actual use of the grid isn't taken into account as an assumed capacity is used. This tariff structure doesn't provide any specific incentives for the use of the grid, apart from the incentive to limit capacity within the capacity band for the assumed capacity. Requesting a larger connection capacity could increase the assumed capacity, which significantly increases the grid costs.

*Reactive power tariff*

Grid operators also charge a tariff for reactive power. This tariff is only charged to customers in case the ratio between consumption (in kWh) and reactive power (in KVarh) exceeds a certain limit. The share of grid costs covered by the reactive power is very limited. Some grid operators have chosen not to charge a reactive power tariff (Overlegtafel energievoorziening, 2018).

*Exemption: volumetric discount for large industrial end-users*

The volumetric discount for large industrial end-users (in Dutch: *volumekorting energie-intensieve industrie)* was introduced in the Electricity Act by the Ministry of Economic Affairs and Climate.[20] The discount applies only to grid users with a yearly electricity demand larger than 50 GWh. The discount is determined by first determining the operating time, which is closely related to the capacity factor, since it expresses the ratio between yearly consumption and the peak consumption during the year. A maximum of 85% for the operating time is applied for the calculation of the discount. The discount is then calculated as follows:

> Discount (in %) = (operating time – 65%)/(85%–65%) * (yearly consumption – 50 GWh)/(250 GWh – 50 GWh) * 100

A maximum of 250 GWh is used to calculate the yearly consumption The discount kicks-in at an operating time of 65% and increases as the operating time further increases. Furthermore, the overall discount is limited to 90%.

The discount was publicly sold as a measure to better reflect the fact that the grid costs caused by large industrial end-user with a flat consumption profile is small. However, the discount was actually an attempt to avoid a bankruptcy of Aldel. A similar discount already existed in Germany. The argument that large end-users with a flat profile cause less costs doesn't make much sense, given the fact that for large industrial end-users the tariff drivers are based on contracted and maximum capacity.

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[20] Elektriciteitswet 1998, zevende tot en met elfde lid.

Clearly, the discount incentivizes a flat consumption profile, since that could lead to significant discounts on the grid tariffs. DR might require a short increase of the load, which reduces the operating time and reduces the discount.

*Exemption: subsidy covers costs of offshore grid*

For the connection of offshore wind, the Ministry of Economic Affairs and Climate introduced the role of the “offshore grid operator”, and assigned TenneT as offshore grid operator. Even though TenneT also operates the onshore transmission grid, legally these are two separated grids with each an own grid operator.
The connections of the first offshore wind farms were not covered through grid charges, but through SDE-subsidies. This policy will likely change in the near future, but it is not clear yet how.

The decision to subsidize the offshore grid costs basically results in a transfer of these costs to the connections on the lower voltage grids, since the ODE is charged mostly to residential end-users and small businesses.

## A.3 Gas network tariffs

The description of the gas tariff structure here is limited to the TSO tariff structures, because that is relevant for industrial power-to-heat DR. DSO tariffs are excluded, because they are not relevant for this report.

For the gas grid, the shipper has to book exit capacity at the exit point (e.g. the connection of the industry). Contracted exit capacity gives the shipper the right to withdraw the contracted amount of gas per hour from the grid at the specified exit point. The shipper can contract yearly-, quarterly-, monthly-, daily- and within-day capacity products.[21] The yearly capacity product will give the shipper the right to withdraw a given amount of gas from the grid for the entire year. A daily capacity product will give the shipper the right to withdraw a given amount of gas only for the relevant day.[22] The grid tariffs differ for these capacity products, such that booking consecutive short-term products is more expensive than booking long-term products.[23] Furthermore, the tariffs of short-term capacity products are higher for the winter than for the summer.[24] The overall gas grid charges are minimised if the shipper optimises the capacity bookings given the expected profile.

# B Taxation

## B.1 Electricity

In the Netherlands three different taxes are applied to electricity consumption:
- The electricity tax (e.g. “belasting op elektriciteit”);
- The renewable energy and climate transition surcharge (e.g. “opslag duurzame energie en klimaattransitie”; and
- The value added tax (e.g. “belasting toegevoegde waarde”).

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[21] Transportcode gas, article 2.1.2
[22] A within-day capacity product gives the shipper the right to withdraw gas for the remaining part of the gas day.
[23] Tarievencode gas, article 3.2.3.5
[24] Tarievencode gas, article 3.2.3.6

Furthermore, the net metering ("saldering") is a relevant element for the taxation.

### *B.1.1 Electricity tax*

The electricity tax is applied to the consumption of electricity for each connection to the electricity grid. The electricity tax is a tax per kWh of electricity consumed. There are tariffs for different tax brackets. The marginal tariff decreases as the consumption increases, which makes the tax regressive. Table B.1 shows the applicable electricity tax tariffs per tax bracket for 2021. A reduced tariff is applied to electricity consumed by EV-charging stations. For the highest tax bracket a different tariff is applied to private and business consumption.

Table B.1 Electricity tax

| Year | 0 to 10.000 kWh | 10.001 to 50.000 kWh | 50.001 to 10 million kWh | More than 10 million kWh private | More than 10 million kWh business |
|---|---|---|---|---|---|
| 2021 | € 0,09428 | € 0,05164 | € 0,01375 | € 0,00113 | € 0,00056 |

Source: Belastingdienst

For connections to a residence function (e.g. "verblijfsfunctie" meaning households and offices) a lump-sum reduction on the energy tax is applied. In 2021 the lump-sum tax reduction was € 461,62 per connection. This tax reduction makes the electricity tax progressive for household consumption.

### *B.1.2 Renewable energy and climate transition surcharge on the electricity tax*

There is a renewable energy and climate transition surcharge on the electricity tax. The surcharge is used to fund SDE++ subsidies for renewable energy and other emission reducing technologies. The surcharges are shown in Table B.2. A similar surcharge exists for gas, but the tariffs differ.

Table B.2 Renewable energy and climate transition surcharge

| Year | 0 to 10.000 kWh | 10.001 to 50.000 kWh | 50.001 to 10 million kWh | More than 10 million kWh private | More than 10 million kWh business |
|---|---|---|---|---|---|
| 2021 | € 0,0300 | € 0,0411 | € 0,0225 | € 0,0004 | € 0,0004 |

Source: Belastingdienst

### *B.1.3 Value added tax*

The value added tax in the Netherlands is 21%. For electricity consumption the VAT is calculated over the electricity costs, including the energy tax and renewable energy and climate transition surcharge.

## B.2 Gas

In the Netherlands three different taxes are applied to electricity consumption:
- The gas tax (e.g. “belasting op aardgas”);
- The renewable energy and climate transition surcharge (e.g. “opslag duurzame energie en klimaattransitie”; and
- The value added tax (e.g. “belasting toegevoegde waarde”).

### *B.2.1 Gas tax*

The gas tax is applied to the consumption for each connection to the gas grid. The gas tax is a tax per m³ of gas consumed. Tariffs are determined for different tax brackets. The marginal tariff decreases as the consumption increases, resulting in a regressive tax. Table B.3 shows the applicable gas tax tariffs per tax bracket in 2021. A reduced tariff is applied to gas consumption by greenhouse horticulture. For gas consumption, there is no lump-sum tax reduction for connection to a residence function as there is for electricity.

Table B.3 Gas tax (regular tariff)

| Year | 0 to 10.000 m³ | 10.001 to 50.000 m³ | 50.001 to 10 million m³ | More than 10 million m³ |
|---|---|---|---|---|
| 2021 | € 0,34856 | € 0,06547 | € 0,02386 | € 0,01281 |

Source: Belastingdienst

### *B.2.2 Renewable energy and climate transition surcharge on the gas tax*

The renewable energy and climate transition surcharge is a surcharge on the energy tax. The surcharge is used to fund SDE++ subsidies for renewable energy and other emission reducing technologies. A reduced surcharge is applied to gas consumption by greenhouse horticulture.

Table B.4 Renewable energy and climate transition surcharge on the gas tax (regulator tariff)

| Year | 0 to 10.000 m³ | 10.001 to 50.000 m³ | 50.001 to 10 million m³ | More than 10 million m³ |
|---|---|---|---|---|
| 2021 | € 0,0851 | € 0,0235 | € 0,0232 | € 0,0232 |

Source: Belastingdienst

### *B.2.3 Value added tax*

The value added tax in the Netherlands is 21%. For gas consumption the VAT is calculated over the electricity costs, including the energy tax and renewable energy and climate transition surcharge.