

Toward Computing Accurate Free Energies in Heterogeneous Catalysis: a Case Study for Adsorbed Isobutene in H-ZSM-5

Kristof De Wispelaere,* Philipp N. Plessow,* and Felix Studt*

Cite This: *ACS Phys. Chem Au* 2022, 2, 399–406

Read Online

ACCESS |



Metrics & More



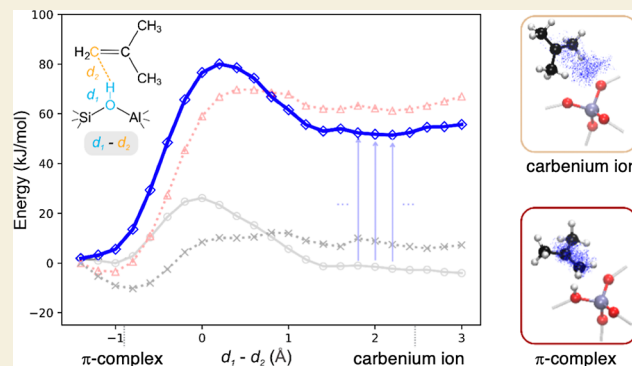
Article Recommendations



Supporting Information

ABSTRACT: Herein, we propose a novel computational protocol that enables calculating free energies with improved accuracy by combining the best available techniques for enthalpy and entropy calculation. While the entropy is described by enhanced sampling molecular dynamics techniques, the energy is calculated using ab initio methods. We apply the method to assess the stability of isobutene adsorption intermediates in the zeolite H-SSZ-13, a prototypical problem that is computationally extremely challenging in terms of calculating enthalpy and entropy. We find that at typical operating conditions for zeolite catalysis (400 °C), the physisorbed π -complex, and not the tertiary carbenium ion as often reported, is the most stable intermediate. This method paves the way for sampling-based techniques to calculate the accurate free energies in a broad range of chemistry-related disciplines, thus presenting a big step forward toward predictive modeling.

KEYWORDS: molecular dynamics, electronic structure, zeolites, free energies, heterogeneous catalysis, H-ZSM-5



INTRODUCTION

The widespread use of heterogeneous catalysts forms the backbone of the chemical industry and in particular acidic zeolites, catalyzing a wide variety of conversions, are thought to play an important role in future bio-refineries and CO₂ utilization processes.^{1,2} The knowledge-based design and optimization of these materials rely on an in-depth understanding of the associated reaction mechanisms on the atomic scale.^{3–5} Quantum chemical calculations are routinely used to study such mechanisms and to obtain reaction energies and barriers.^{3–6} The central quantity for the prediction of chemical reactivity through equilibrium and rate constants is the change in Gibbs free energies, ΔG

$$\Delta G = \Delta H - T\Delta S \quad (1)$$

That depends on the change in enthalpy (ΔH) and entropy (ΔS) along a reaction coordinate. Here “ Δ ” is used to refer the thermodynamic potentials to a reference state, for example, the reactants of a reaction. Besides the properties of the involved system, ΔG generally depends on the temperature and the concentrations or pressures of involved species. To achieve the quantitative predictive modeling, highly accurate free energies, that is with an accuracy of 5–10 kJ/mol, are required. Enthalpies and entropies are most commonly computed using the harmonic approximation to the potential energy surface (PES) around stationary points determined with density functional theory (DFT) calculations. Errors in computed enthalpies are mainly due to inaccuracies in electronic energies obtained with

available, approximate density functionals,^{7,8} while errors in computed entropies are associated with the treatment of the thermal motion of the nuclei, where the harmonic approximation fails to describe flat PESs and highly mobile adsorbates.⁹ Since the entropic contribution to ΔS is multiplied by the temperature, entropic errors become generally more severe with increasing temperature as, for example, relevant for many heterogeneously catalyzed processes.

A prominent example for the computational challenges in zeolite catalysis is posed by the adsorption of isobutene on an acid site with possible physisorption as a π -complex and chemisorption, resulting in a carbenium ion, *t*-butoxide, or isobutoxide (see Figure 1).^{10–12}

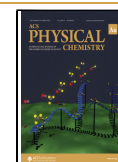
There is an ongoing debate concerning the nature of alkene adsorption intermediates in a zeolite environment. However, precise knowledge of the most stable alkene adsorption state at operating conditions is essential for meaningful modeling of processes such as fluid catalytic cracking,³ methanol-to-hydrocarbons,¹³ and CO₂-to-hydrocarbons.¹⁴ Due to the difficulty of unraveling these issues experimentally,^{15–18} a number of theoretical investigations have targeted this question;^{10,19–23}

Received: April 1, 2022

Revised: April 29, 2022

Accepted: April 29, 2022

Published: August 15, 2022



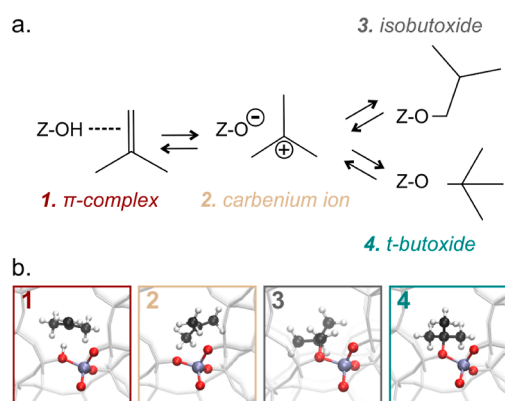


Figure 1. (a) Schematic representation of the various possibilities of isobutene adsorption on a zeolite Brønsted acid site. (b) Corresponding optimized structures of each adsorption intermediate in zeolite H-SSZ-13. Carbon atoms are shown in black, hydrogen atoms are shown in white, the zeolite's Al substitution is shown in purple, and its surrounding oxygens are shown in red. The remainder of the zeolite framework is displayed in gray.

however, no general consensus on the stability of the various intermediates has been reached. The challenges of a theoretical treatment of this problem are due to the erroneous description of carbenium ions with common density functionals and the inability to describe the loosely bound substrate with harmonic potentials. For example, the widely used PBE functional is known to systematically overestimate the stability of carbenium ions by as much as 12–62 kJ/mol.^{10,24} Likewise, the harmonic oscillator approximation that treats the motion of the nuclei as localized vibrations largely underestimates the entropy of these fragments as has been shown by extensive molecular dynamics (MD) simulations.^{23,25} We therefore chose this example as it is similarly challenging to compute accurate enthalpies and entropies.

Systematic improvements to the PES accuracy, and thus computed enthalpies, are possible through more accurate functionals, such as hybrid functionals or wave function methods such as MP2 and CCSD(T).^{7,8,24} However, due to their high computational cost, higher-level methods are often only applicable through single-point (SP) energy calculations. Therefore, one first needs to determine the stationary points on the PES using DFT calculations and apply thermal corrections to compute the free energy at operating conditions (Figure 2a, steps 1 and 2). Then, the enthalpy contribution to the free energy is modified a posteriori by recomputing the energy for the stationary point through SP MP2 or CCSD(T) calculations (Figure 2a, step 3). For the latter, a hierarchical cluster approach is commonly used^{8,24} that has been shown to decrease the errors tremendously to 4–10 kJ/mol (near chemical accuracy).²⁶

On the other hand, there are no established approaches that systematically improve the accuracy of the entropy contribution using the harmonic approximation, although research in this direction is ongoing,^{8,27–31} giving agreement as good as 5–10 kJ/mol in selected cases.^{8,29} Sampling large portions of the PES at operating conditions with classical MD simulations (see Figure 2b) yields more accurate entropies but dramatically increases the computational cost relative to the harmonic approach. Indeed, one typically needs to perform tens of thousands of MD steps, each one requiring an expensive energy gradient calculation. The accuracy of MD crucially depends on the method used to calculate the energy and its gradient, where directly using higher level methods such as MP2 or CCSD(T) will be unfeasible for the foreseeable future. The free energy of a given MD trajectory can be improved using free-energy perturbation theory, which, however typically requires a significant number of additional computationally demanding calculations.³² Unfortunately, in contrast to the harmonic approximation, there is no existing approach a posteriori improve the quality of the free energy from an MD simulation

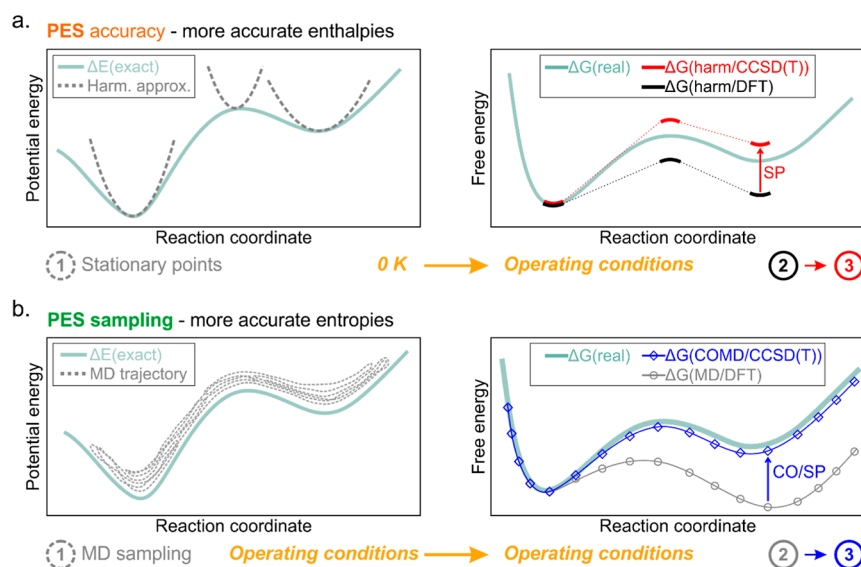


Figure 2. Schematic depiction of protocols to calculate the accurate free energies with the harmonic oscillator (harm) approach and MD. (a) Stationary points are located on the PES at 0 K (step 1), and thermal corrections are applied with the harmonic approximation to compute the free energy at operating conditions with DFT [step 2, $\Delta G(\text{harm/DFT})$]. Then, SP energy calculations at high level of theory [CCSD(T)] improve the accuracy of the free energy [step 3, $\Delta G(\text{harm/CCSD(T)})$]. (b) MD sampling with DFT of large portions of the PES directly yields the free energy at operating conditions [steps 1 and 2, $\Delta G(\text{MD/DFT})$]. Constrained optimizations (CO) at the DFT level followed by SP energy calculations at the CCSD(T) level yield more accurate free energies [$\Delta G(\text{COMD/CCSD(T)})$].

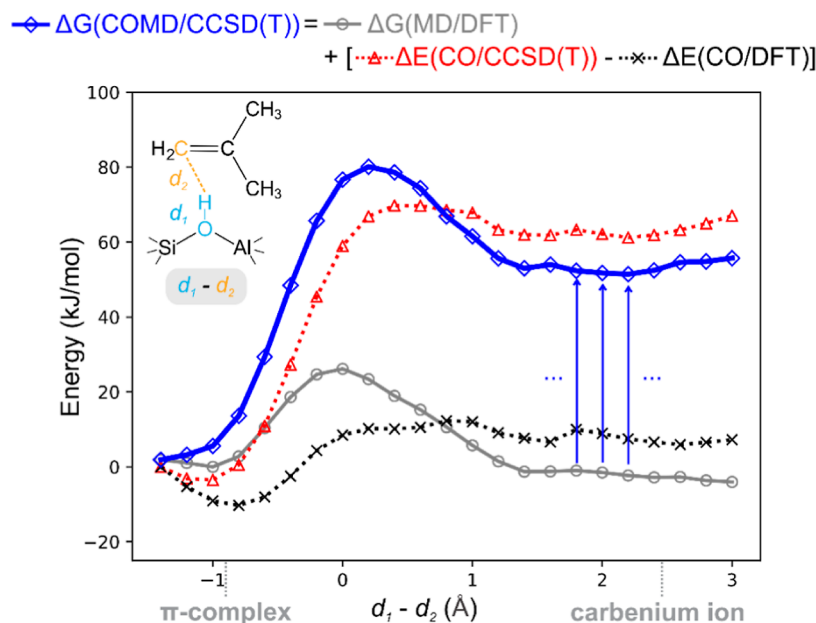


Figure 3. Construction of the COMD free-energy profile for isobutene protonation in H-SSZ-13. Inset: selected collective variable for the π -complex protonation. Free-energy curves at 400 °C from DFT-MD [$\Delta G(\text{MD}/\text{DFT})$, gray circles], electronic energies at the DFT level [$\Delta E(\text{CO}/\text{DFT})$, black x] and CCSD(T) level [$\Delta E[\text{CO}/\text{CCSD}(\text{T})]$, red triangles] and COMD free energies at the CCSD(T) level at 400 °C [$\Delta G[\text{COMD}/\text{CCSD}(\text{T})]$, blue diamonds] for π -complex protonation. The legend in the top shows how the COMD free energies were approximated. All energies are shown in kJ/mol. All DFT energies are computed with the PBE-D3 functional.

with one single calculation since each MD step depends on the energy gradient of the previous step. It should be noted that a SP correction can of course generally not capture the full free-energy difference since it measures only the energy difference for one specific structures.

Herein, we present a novel method to calculate highly accurate free energies through a hybrid method which we call Constrained Optimizations improved Molecular Dynamics (COMD). The COMD method combines accurate enthalpies at the CCSD(T) level of theory with entropies determined from MD simulations according to the workflow shown in Figure 2b. To the best of our knowledge, only few examples exist of highly accurate MD-based free energies. Piccini and Parrinello recently proposed a combination of low-level metadynamics with free-energy perturbation at higher levels to achieve the accurate quantum chemical free energies at an affordable cost; however, the technique has not been demonstrated for complex reaction environments like zeolite catalysis.³³ Computational investigations of heterogeneous catalysts typically employ DFT within the harmonic oscillator approximation. Efforts to go beyond this largely use either DFT-MD or ab initio methods in the harmonic oscillator approximation. Here, we show for the first time for industrially relevant catalytic reactions that the combination of DFT-MD and wave function methods is indeed feasible, arriving at more accurate energies and entropies.

RESULTS AND DISCUSSION

We demonstrate the use of COMD in the case of isobutene protonation within the acidic zeolite H-SSZ-13. First, the free-energy profile at realistic operating conditions is computed with enhanced sampling DFT-MD, in our case umbrella sampling (US), yielding $\Delta G(\text{MD}/\text{DFT})$ (gray curve in Figure 3) along a parameter representing the reaction coordinate, the so called collective variable (see inset in Figure 3). The second step consists of improving the accuracy of the energy term in the

obtained free energy. For this task, cluster models of the zeolite for the respective value of the reaction coordinate are generated, and the electronic energy is then computed at the PBE-D3 and CCSD(T) level. Since each MD trajectory consists of tens of thousands of structures, it is not obvious how to select a representative structure for the energy correction.

In our approach, we performed CO along the collective variable to arrive at the minimum energy structure for each value of the reaction coordinate. Using SP energy calculations at the DFT and CCSD(T) levels gives the $\Delta E(\text{CO}/\text{DFT})$ and $\Delta E[\text{CO}/\text{CCSD}(\text{T})]$ curves in Figure 3. The difference between these two curves yields a one-dimensional correction term that can be applied to correct DFT free-energy calculations to the CCSD(T) accuracy level, finally yielding the blue $\Delta G[\text{COMD}/\text{CCSD}(\text{T})]$ curve in Figure 3. Note that the energy correction only occurs along the degrees of freedom corresponding to the reaction. From Figure 3, it becomes clear that the correction term becomes significant for charged compounds, in line with earlier work employing calculations at the MP2 level of theory.^{24,26} In a similar fashion, as outlined in Figure 3, COMD free-energy profiles can be constructed for all reaction steps shown in Figure 1 (see Supporting Information Section 1.1). For a given value of the collective variable, the correction does therefore not depend on temperature. This is because it captures only the energy difference between the constrained minima and not differences in the shape of the nearby PES. This is expected to work best for the well-defined minima and for cases where there is a clear and systematic chemical reason for the correction. This is the case for the problem that we study, where the organic structures are well-known and well-defined and where it is furthermore known that the main error lies in the formation of the carbocations.^{6,10,26,34} The approach outlined here can therefore not be expected to work well, when the error of the lower-level method is not mainly a function of the collective variable but depends also strongly on other degrees of

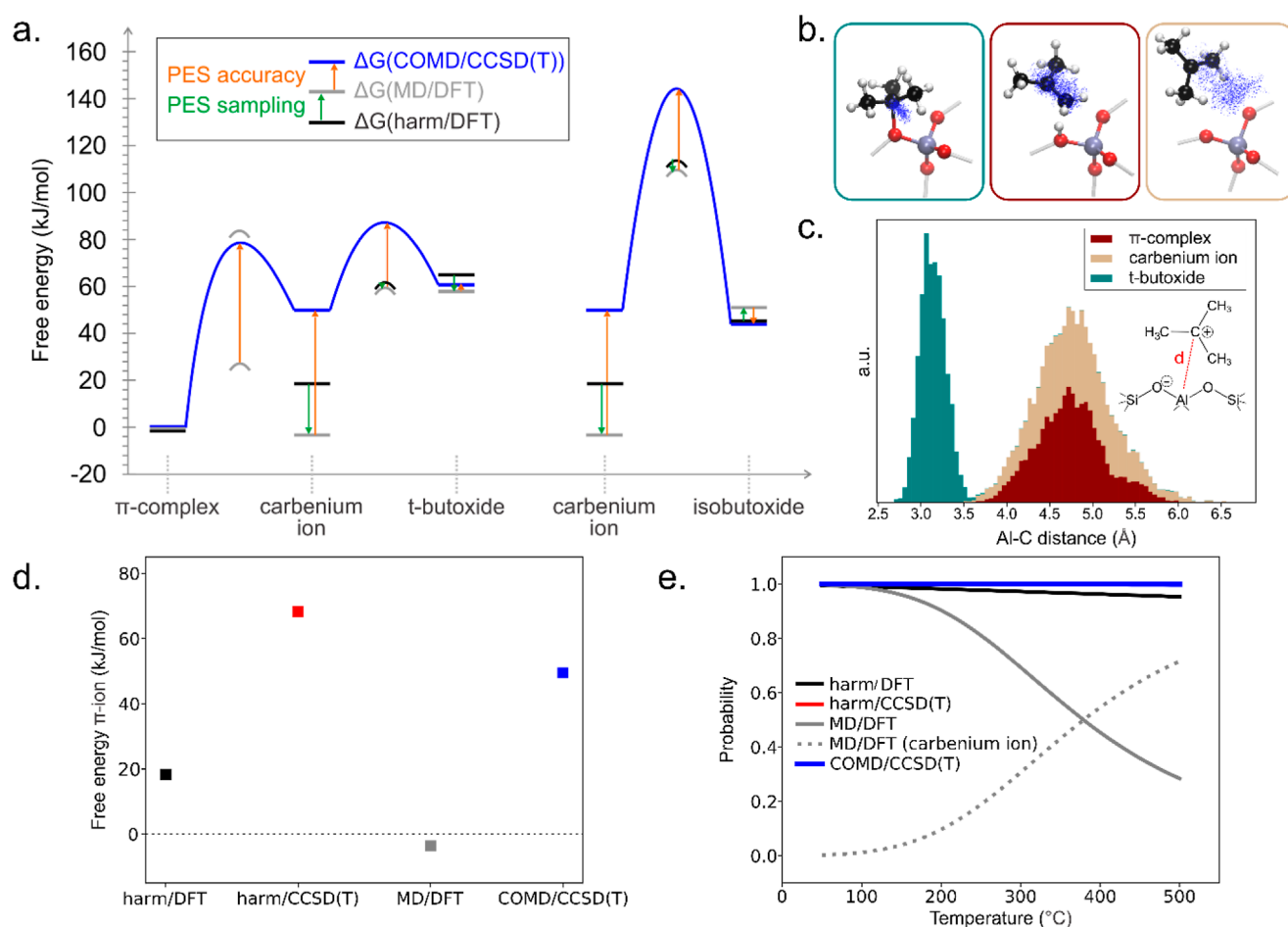


Figure 4. Relative stability of isobutene adsorption intermediates in H-SSZ-13 (a) free-energy diagram for isobutene adsorption in H-SSZ-13 showing the free energy at 400 °C calculated by the harmonic oscillator approximation [$\Delta G(\text{harm/DFT})$, black], DFT-based MD [$\Delta G(\text{MD/DFT})$, gray], and the COMD method [$\Delta G[\text{COMD/CCSD(T)}]$, blue]. The green and orange arrows indicate the deviations induced by PES sampling and PES accuracy, respectively. (b) Snapshots of the US simulations of the *t*-butoxide, π -complex, and carbenium ions with blue dots, indicating the position of the central carbon atom throughout the simulation at 400 °C (25–50 ps). (c) Histograms of the Al-central carbon atom distance (in Å) for the *t*-butoxide, π -complex, and carbenium ions. (d) Free energy of the tertiary carbenium ion with respect to the π -complex at 400 °C with the various applied methods. (e) Probability vs temperature computed with various methods for finding the π -complex (full lines) or carbenium ions (dotted lines) as most stable adsorption intermediate. The red harm/CCSD(T) curve coincides with the blue COMD/CCSD(T) curve. All energies are expressed in kJ/mol and referenced to the π -complex. All DFT energies are calculated with the PBE-D3 functional.

freedom. It is important to note that in the final free-energy profile, as in the underlying free-energy profile from DFT-MD, the motion of nuclei is treated classically.

To allow making conclusions on the relative stability of the isobutene adsorption intermediates in H-SSZ-13, Figure 4a (Supporting Information Section 1.2) provides a full free-energy profile at 400 °C. Next to the COMD free energies [$\Delta G[\text{COMD/CCSD(T)}]$], also values calculated with the traditional static approach applying the harmonic oscillator approximation [$\Delta G(\text{harm/DFT})$] and with DFT-based MD [$\Delta G(\text{MD/DFT})$] are shown. It becomes clear that the COMD free-energy profiles are substantially different from the static and dynamic DFT-based free energies, and the COMD results reveal that at 400 °C, the π -complex is the most stable adsorption intermediate, followed by the isobutoxide, carbenium ion, and *t*-butoxide. π -Complex protonation and *t*-butoxide formation require overcoming only moderate free-energy barriers, while the barrier for isobutoxide formation is significantly higher. Note that we chose the π -complex as the reference state for all methods since it is the most stable structure, and referencing to gas-phase isobutene is not straightforwardly possible with MD

simulations. This choice is somewhat arbitrary but slightly affects the differences in the methodology observed for the other states, as shown in Figure 4a.

Clearly, two factors can be distinguished. First, the effect of sampling the PES through MD seems to be substantial, as indicated by the green arrows in Figure 4a. Indeed, the largest differences between the MD/DFT and harm/DFT results are situated in the description of the carbenium ion. At 400 °C, the carbenium ion is a loosely bound, relatively mobile substrate, as evidenced in Figure 4b. The blue dots indicate the position of the central carbon atom of the isobutene intermediate with respect to the active site of the H-SSZ-13 zeolite throughout the US simulations at 400 °C. As expected, the mobility of the *t*-butoxide intermediate is very limited, as also indicated by the narrow distribution of the Al-central carbon atom distance (Figure 4c). The π -complex and carbenium ion are clearly more mobile species, with the carbenium ion exhibiting the highest mobility. This behavior cannot be fully captured with static methods, advocating the need for a dynamical description. This leads to an erroneous prediction of the relative stability at the DFT level of the carbenium ion with respect to the π -complex in

a wide temperature range. Second, the effect of increasing the PES accuracy through applying accurate ab initio methods seems to be even more substantial, as illustrated by the orange arrows in Figure 4a. Comparing the COMD/CCSD(T) and MD/DFT results shows that the major differences are obtained for the phases of the reaction where charged moieties are formed. Deviations range up to roughly 50 kJ/mol, values that have been reported before for similar zeolite chemistry problems.^{24,26} Note that efficient PES sampling and increasing the PES accuracy have an opposite effect on the stability of the carbenium ion with respect to the π -complex (Figure 4d), underlining the risk of fortuitous error cancellation with certain modeling approaches. Figure 4e shows the stability of the isobutene π -complex (full lines) and carbenium ion (dotted line) as a function of temperature. The temperature dependence of the free energies from DFT was obtained through interpolation of free energies obtained with MD runs at different temperatures (see the Supporting Information). Only at the MD/DFT level, a shift in most stable adsorption intermediate can be observed. From the most accurate free energies at the COMD/CCSD(T) level, it can be concluded that in the 50–500 °C temperature range, the π -complex is always the most stable intermediate. Our findings are in line with the recent report of Sauer and co-workers, in which estimations of the free energy of isobutene adsorption intermediates at high temperature in zeolite H-FER were made.³⁴ By combining static free energies computed with wavefunction-based methods with DFT-MD free energies reported by Cnudde et al.,²³ the π -complex was also found to be the most stable intermediate at typical operating conditions for zeolite catalysis (see discussion in Supporting Information Section 2).

CONCLUSIONS

The results in Figure 4a show that the errors of the enthalpy and entropy introduced by DFT and the harmonic oscillator approximation are of the same order of magnitude for reactions containing loosely bound intermediates occurring at elevated temperatures. This highlights the necessity to move beyond the commonly available methods to compute enthalpies and entropies in heterogeneous catalysis in the future. This quest becomes urgently clear when considering that an error of 10 kJ/mol associated with the transition state of reaction leads to an error of approximately 1 order of magnitude of the corresponding rate constant at a temperature of 250 °C. It is important to note that the proposed correction scheme based on a single CO per state can only work if the relevant structural change between the states in question is contained in the collective variable that describes the reaction coordinate. We expect that this is the case for many chemical reactions occurring along a well-defined reaction path, as described in the present work. However, there are clear exceptions in other areas. Examples include disordered systems, which occur in the melting of silicon, where the state of liquid silicon cannot be reasonably described by a single (temperature-independent) structure. These cases require considering an ensemble, for example, through free-energy perturbation theory,³⁵ which is also the most general approach to compute free-energy differences using MD. The disadvantage of free-energy perturbation theory is that one would need to compute many snapshots with a high level of theory, whereas the COMD method only needs one. This also means that one can do this at a very high level of electronic structure theory [e.g., CCSD(T)]. Overall, the COMD method can therefore be viewed as an

approximation to free-energy perturbation theory, where, instead of averaging over an ensemble of structures obtained from MD, only a single structure from a CO is considered. At the stationary points (minima and transition states), the correction is strictly identical to the SP approximation commonly applied in static calculations. In terms of applicability, it has to be noted that the COMD method can, like regular MD methods, only be used to integrate the free-energy difference along closed reaction paths. Therefore, the direct determination of adsorption free energies is not simple, which is also an active field of research.^{28,29,36,37} Additionally, quantum effects of nuclear motion, in particular zero-point vibrational energies are not included but are usually added when comparing two stationary points. Challenges that have to be overcome before the COMD method presented here can be commonly used in theoretical heterogeneous catalysis encompass the high cost of MP2 or CCSD(T) and DFT-MD calculations and the advancement of MD-type methods that efficiently allow referencing free energies to the gas phase state of guest molecules.²⁹ Machine-learning methods are becoming more popular and might be able to solve some of the problems.³⁸ While the presented hierarchical approach and the use of MD are applicable for solid acid catalysis, their employment in the field of transition-metal catalysis is not straightforward yet. To this end, we will still be relying on error estimation techniques³⁹ and the fact that trends are usually well described by DFT.⁴⁰

METHOD SECTION

Structure Model of H-SSZ-13

A 50 ps NPT MD simulation at 400 °C and 1 bar has been performed on the empty zeolite structure (details of MD simulations are listed below). The initial structure containing 36 Si atoms was taken from the IZA zeolite database.⁴¹ One Al substitution was included, and a charge-balancing proton was added (see Supporting Information Section 3.1). The cell parameters for all other simulations were obtained through computing time-averaged values, resulting in $a = 13.867$ Å, $b = 13.860$ Å, $c = 14.858$ Å, $\alpha = 90.02^\circ$, $\beta = 90.02^\circ$, and $\gamma = 119.77^\circ$. These cell parameters were used in all MD and static calculations. Based on periodic structures, 46T cluster models were cut (also see ref 24) to contain an entire pore, and terminating, dangling Si–O bonds were replaced by Si–H bonds with predefined Si–H distance (148.9 pm). We note that the choice of both the size of the super cell and the associated Si/Al ratio as well as the size of the cluster models is not unique. On the cluster models, only SP calculations were performed. All optimizations or MD simulations made use of the periodic zeolite models.

Technical Aspects and Software Used

As shown in Figure 3, the free energy is obtained simply by adding an energy correction evaluated on structures obtained through CO to the free-energy profile obtained from MD simulations. The different contributions required for DFT-MDs, constrained minimizations, and ab initio calculations on cluster models employ several different program packages. However, largely, only standard functionality of these programs is required. For DFT-MD, we employ CP2K, with US driven by PLUMED. For CO with DFT, we employ VASP, using the ASE interface. Lastly, for the SP energy calculations on cluster models, we employ ORCA. With the exception of DLPNO-CCSD(T) calculations with ORCA, we expect that all other calculations can equally well be carried out with other DFT-

programs. The choice of methodology and programs of course influences the overall computation, which will in most cases be dominated by the MD simulations, simply due to the number of calculations. Of course, accurate *ab initio* calculations also become increasingly expensive with system and basis set size. We note that while we used cluster models to be able to apply electronic structure methods such as DLPNO-CCDS(T) for nonperiodic systems, it is expected that in the future such methods may also become routinely available for periodic systems, and currently RPA and MP calculations could be performed in this way.^{42–44}

Static Calculations

Periodic DFT calculations were performed using the atomic simulation environment (ASE) and Vienna Ab Initio Simulation Package (VASP 5.4.1) with the PBE functional.^{45–48} To account for attractive London dispersion interactions, Grimme's D3 corrections were added.⁴⁹ During the calculations, the projector augmented wave method was used.^{50,51} A plane-wave cutoff of 400 eV was adopted, and the self-consistent field convergence criterion was set to 10^{-8} eV. The Brillouin zone sampling was restricted to the Γ -point. For the normal mode analysis, the guest molecules and a small part of the zeolite framework (the involved oxygen atom, and the adjacent Al and Si atoms) were allowed to vibrate, as described in ref 24. All transition states have been verified to contain an imaginary harmonic frequency corresponding to the transition vector of the reaction.

SP energy calculations on cluster models were carried out with ORCA for the DLPNO-CCSD(T)/def2-TZVPP results based on structures obtained from CO. SP PBE-D3 calculations were carried out with CP2K. We have also tested a protocol, where cluster models are generated directly from snapshots of the MD. The energy correction is then obtained by averaging over multiple snapshots. DLPNO-MP2/def2-TZVPP calculations were employed in this case due to high computational cost required for calculating on the order of 1000 SPs. It has previously been shown that MP2 calculations are in good agreement with CCSD(T) for acidic zeolites,⁷ and MP2 is therefore sufficient to study the convergence behavior. Computing the energy correction directly from the MD trajectory is generally more challenging due to the framework vibrations that lead to large variations in the energies. However, when selecting a sufficient number of snapshots (>50), we find that the mean energy correction is in excellent agreement (deviation ≈ 5 – 10 kJ/mol), with the computationally much more efficient CO approach outlined above that only requires a single cluster correction (see Supporting Information Section 1.1.1). The approach of computing the energy correction by averaging over snapshots from the trajectory can also be understood as a first-order approximation to free-energy perturbation theory.

Molecular Dynamics Simulations

MD simulations were carried out with the CP2K simulation package (version 5.1)^{52,53} using DFT with a combination of Gaussian and plane-wave basis sets.^{54,55} For the MD simulations, the PBE-D3 functional⁵⁶ with a TZVP-GTH basis set and pseudopotentials were selected.⁵⁷ To obtain the cell parameters, an initial NPT simulation of the empty zeolite lattice was performed (*vide infra*). All other MD-based simulations were performed in the NVT ensemble at 50, 300, 400, and 500 °C. The temperature and pressure (if applicable) were controlled via a chain of 5 Nosé-Hoover thermostats and an

MTK barostat, respectively.^{58,59} An integration time step of 0.5 fs was applied.

During 140 ps regular MD simulations at high temperature, only very few protonation reactions could be sampled (Supporting Information Section 3.2). To obtain the sufficient sampling of the reactions, as shown in Figure 1, US was used.⁶⁰

All US simulations have been performed with CP2K version 5.1 as MD engine, interfaced with the PLUMED module (version 2.4.0)⁶¹ with the same settings as for the regular MD simulations. All umbrellas were sampled for 10 ps with a time integration step of 0.5 fs. With this technique, the phase space is subdivided into a number of windows along a chosen collective variable that represents the reaction coordinate. For each window, a separate restrained MD simulation is performed by constructing a bias potential (umbrella). The definition of the collective variables is displayed in Supporting Information Section 1.1. The initial configuration for each window is generated with a moving bias potential simulation, describing the entire collective variable range of the reaction. In each window, the applied quadratic bias potential centered around value q_0 has the following shape

$$U_b(q) = \frac{\kappa}{2}(q - q_0)^2 \quad (2)$$

The number of windows and the value of the respective κ values are tuned to ensure sufficient overlap between neighboring windows. An overview of the used collective variables, the umbrella positions, and bias strengths in the US simulations can be found in Supporting Information Section 3.3. From the US, the free-energy profiles are reconstructed by using the umbrella integration methods with the code developed by the Kästner group.^{62,63} This method has several advantages over the commonly applied WHAM method as it significantly reduces the statistical error. In the limit of a strong bias, the method is equivalent to thermodynamic integration. The umbrella integration method also yields an estimate of the statistical error made, as described in ref 63. The statistical error bars on all reported free energy values from US simulations are smaller than 5 kJ/mol (see Section 1.2 of Supporting Information). The free-energy profiles were reconstructed using 50 bins divided over the range of the collective variables as specified below. The first 1000 frames of the sampling in each umbrella were skipped in analysis. The umbrella integration code automatically computes the location of extrema in the free-energy profile. Due to limited sampling, it often occurred that several minima with nearly equal free energies could be localized in reactant or product states. In that case, the minimum corresponding to the lowest free energy was chosen to calculate free-energy barriers and reaction free energies. As sampling is performed in the NVT ensemble, the obtained free energies are formally Helmholtz instead of Gibbs free energies. However, the difference between Gibbs and Helmholtz free energy is usually very small in crystalline materials such as zeolites. In catalysis, it is more common to describe chemical transformations based on Gibbs free energies, and therefore, we denote free energies as Gibbs free energies in this work.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsphyschemau.2c00020>.

Construction of COMD free-energy profiles, MD and US, and additional data and analysis (PDF)

AUTHOR INFORMATION

Corresponding Authors

Kristof De Wispelaere – Center for Molecular Modeling, Ghent University, B-9052 Ghent, Belgium; orcid.org/0000-0003-1147-7050; Email: kristof.dewispelaere@gmail.com

Philipp N. Plessow – Institute of Catalysis Research and Technology, Karlsruhe Institute of Technology, D-76344 Eggenstein-Leopoldshafen, Germany; orcid.org/0000-0001-9913-4049; Email: plessow@kit.edu

Felix Studt – Institute of Catalysis Research and Technology, Karlsruhe Institute of Technology, D-76344 Eggenstein-Leopoldshafen, Germany; Institute for Chemical Technology and Polymer Chemistry, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany; orcid.org/0000-0001-6841-4232; Email: felix.studt@kit.edu

Complete contact information is available at: <https://pubs.acs.org/10.1021/acsphyschemau.2c00020>

Author Contributions

K.D.W. and P.N.P. contributed equally. The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

K.D.W. thanks the research foundation-Flanders (FWO). The computational resources and services used in this work were provided by the VSC (Flemish Supercomputer Center), funded by FWO and the Flemish Government—Department EWI. P.N.P. and F.S. acknowledge the support by the state of Baden-Württemberg through bwHPC (bwunicluster and JUSTUS, RV bw17D011) and financial support from the Helmholtz Association. We acknowledge support by the KIT-Publication Fund of the Karlsruhe Institute of Technology.

REFERENCES

- (1) Jacobs, P. A.; Dusselier, M.; Sels, B. F. Will zeolite-based catalysis be as relevant in future biorefineries as in crude oil refineries? *Angew. Chem., Int. Ed.* **2014**, *53*, 8621–8626.
- (2) Gao, P.; Li, S.; Bu, X.; Dang, S.; Liu, Z.; Wang, H.; Zhong, L.; Qiu, M.; Yang, C.; Cai, J.; Wei, W.; Sun, Y. Direct conversion of CO₂ into liquid fuels with high selectivity over a bifunctional catalyst. *Nat. Chem.* **2017**, *9*, 1019–1024.
- (3) Van Speybroeck, V.; Hemelsoet, K.; Joos, L.; Waroquier, M.; Bell, R. G.; Catlow, C. R. A. Advances in theory and their application within the field of zeolite chemistry. *Chem. Soc. Rev.* **2015**, *44*, 7044–7111.
- (4) Grajciar, L.; Heard, C. J.; Bondarenko, A. A.; Polynski, M. V.; Meeprasert, J.; Pidko, E. A.; Nachtigall, P. Towards operando computational modeling in heterogeneous catalysis. *Chem. Soc. Rev.* **2018**, *47*, 8307–8348.
- (5) Bruix, A.; Margraf, J. T.; Andersen, M.; Reuter, K. First-principles-based multiscale modeling of heterogeneous catalysis. *Nat. Catal.* **2019**, *2*, 659–670.
- (6) Sauer, J. Ab Initio Calculations for Molecule-Surface Interactions with Chemical Accuracy. *Acc. Chem. Res.* **2019**, *52*, 3502–3510.
- (7) Goncalves, T. J.; Plessow, P. N.; Studt, F. On the accuracy of density functional theory in zeolite catalysis. *ChemCatChem* **2019**, *11*, 4368–4376.
- (8) Piccini, G.; Alessio, M.; Sauer, J. Ab Initio calculation of rate constants for molecule-surface reactions with chemical accuracy. *Angew. Chem., Int. Ed.* **2016**, *55*, 5235–5237.
- (9) Benco, L.; Bucko, T.; Hafner, J. Dehydrogenation of propane over ZnMOR. Static and dynamic reaction energy diagram. *J. Catal.* **2011**, *277*, 104–116.
- (10) Tuma, C.; Kerber, T.; Sauer, J. The tert-Butyl Cation in H-Zeolites: Deprotonation to Isobutene and Conversion into Surface Alkoxides. *Angew. Chem., Int. Ed.* **2010**, *49*, 4678–4680.
- (11) Dai, W.; Wang, C.; Yi, X.; Zheng, A.; Li, L.; Wu, G.; Guan, N.; Xie, Z.; Dyballa, M.; Hunger, M. Identification of tert-Butyl Cations in Zeolite H-ZSM-5: Evidence from NMR Spectroscopy and DFT Calculations. *Angew. Chem., Int. Ed.* **2015**, *54*, 8783–8786.
- (12) Boronat, M.; Viruela, P. M.; Corma, A. Reaction Intermediates in Acid Catalysis by Zeolites: Prediction of the Relative Tendency to Form Alkoxides or Carbocations as a Function of Hydrocarbon Nature and Active Site Structure. *J. Am. Chem. Soc.* **2004**, *126*, 3300–3309.
- (13) Plessow, P. N.; Studt, F. Olefin methylation and cracking reactions in H-SSZ-13 investigated with ab initio and DFT calculations. *Catal. Sci. Technol.* **2018**, *8*, 4420–4429.
- (14) Ramirez, A.; Chowdhury, A. D.; Dokania, A.; Cnudde, P.; Caglayan, M.; Yarulina, I.; Abou-Hamad, E.; Gevers, L.; Ould-Chikh, S.; De Wispelaere, K.; Van Speybroeck, V.; Gascon, J. Effect of Zeolite Topology and Reactor Configuration on the Direct Conversion of CO₂ to Light Olefins and Aromatics. *ACS Catal.* **2019**, *9*, 6320–6334.
- (15) Haw, J. F.; Nicholas, J. B.; Xu, T.; Beck, L. W.; Ferguson, D. B. Physical Organic Chemistry of Solid Acids: Lessons from In Situ NMR and Theoretical Chemistry. *Acc. Chem. Res.* **1996**, *29*, 259–267.
- (16) Stepanov, A. G.; Zamaraev, K. I. 13C Solid State NMR Evidence for the Existence of Isobutyl Carbenium Ion in the Reaction of Isobutyl Alcohol Dehydration in H-ZSM-5 Zeolite. *Catal. Lett.* **1993**, *19*, 153–158.
- (17) Schallmoser, S.; Haller, G. L.; Sanchez-Sanchez, M.; Lercher, J. A. Role of Spatial Constraints of Brønsted Acid Sites for Adsorption and Surface Reactions of Linear Pentenes. *J. Am. Chem. Soc.* **2017**, *139*, 8646–8652.
- (18) Kondo, J. N.; Liqun, S.; Wakabayashi, F.; Domen, K. IR Study of Adsorption and Reaction of 1-Butene on H-ZSM-5. *Catal. Lett.* **1997**, *47*, 129–133.
- (19) Frash, M. V.; van Santen, R. A. Quantum-Chemical Modeling of the Hydrocarbon Transformations in Acid Zeolite Catalysts. *Top. Catal.* **1999**, *9*, 191–205.
- (20) Sarazen, M. L.; Iglesia, E. Stability of Bound Species During Alkene Reactions on Solid Acids. *Proc. Natl. Acad. Sci. U.S.A.* **2017**, *114*, E3900–E3908.
- (21) Wang, W.; Hunger, M. Reactivity of Surface Alkoxy Species on Acidic Zeolite Catalysts. *Acc. Chem. Res.* **2008**, *41*, 895–904.
- (22) Fang, H.; Zheng, A.; Xu, J.; Li, S.; Chu, Y.; Chen, L.; Deng, F. Theoretical Investigation of the Effects of the Zeolite Framework on the Stability of Carbenium Ions. *J. Phys. Chem. C* **2011**, *115*, 7429–7439.
- (23) Cnudde, P.; De Wispelaere, K.; Van der Mynsbrugge, J.; Waroquier, M.; Van Speybroeck, V. Effect of Temperature and Branching on the Nature and Stability of Alkene Cracking Intermediates in H-ZSM-5. *J. Catal.* **2017**, *345*, 53–69.
- (24) Plessow, P. N.; Studt, F. Unraveling the Mechanism of the Initiation Reaction of the Methanol to Olefins Process Using ab Initio and DFT Calculations. *ACS Catal.* **2017**, *7*, 7987–7994.
- (25) Bučko, T.; Hafner, J. The Role of Spatial Constraints and Entropy in the Adsorption and Transformation of Hydrocarbons Catalyzed by Zeolites. *J. Catal.* **2015**, *329*, 32–48.
- (26) Tuma, C.; Sauer, J. Treating dispersion effects in extended systems by hybrid MP2:DFT calculations – protonation of isobutene in zeolite ferrierite. *Phys. Chem. Chem. Phys.* **2006**, *8*, 3955–3965.
- (27) De Moor, B. A.; Ghysels, A.; Reyniers, M.-F.; Van Speybroeck, V.; Waroquier, M.; Marin, G. B. Normal Mode Analysis in Zeolites: Toward an Efficient Calculation of Adsorption Entropies. *J. Chem. Theory Comput.* **2011**, *7*, 1090–1101.

- (28) Jørgensen, M.; Chen, L.; Grönbeck, H. Monte Carlo Potential Energy Sampling for Molecular Entropy in Zeolites. *J. Phys. Chem. C* **2018**, *122*, 20351–20357.
- (29) Amsler, J.; Plessow, P. N.; Studt, F.; Bučko, T. Anharmonic Correction to Adsorption Free Energy from DFT-Based MD Using Thermodynamic Integration. *J. Chem. Theory Comput.* **2021**, *17*, 1155–1169.
- (30) Collinge, G.; Yuk, S. F.; Nguyen, M.-T.; Lee, M.-S.; Glezakou, V.-A.; Rousseau, R. Effect of Collective Dynamics and Anharmonicity on Entropy in Heterogeneous Catalysis: Building the Case for Advanced Molecular Simulations. *ACS Catal.* **2020**, *10*, 9236–9260.
- (31) Galimberti, D. R.; Sauer, J. Chemically Accurate Vibrational Free Energies of Adsorption from Density Functional Theory Molecular Dynamics: Alkanes in Zeolites. *J. Chem. Theory Comput.* **2021**, *17*, 5849–5862.
- (32) Rocca, D.; Dixit, A.; Badawi, M.; Lebègue, S.; Gould, T.; Bučko, T. Bridging Molecular Dynamics and Correlated Wave-Function Methods for Accurate Finite-Temperature Properties. *Phys. Rev. Mater.* **2019**, *3*, 040801.
- (33) Piccini, G.; Parrinello, M. Accurate Quantum Chemical Free Energies at Affordable Cost. *J. Phys. Chem. Lett.* **2019**, *10*, 3727–3731.
- (34) Ren, Q.; Rybicki, M.; Sauer, J. Interaction of C3-C5 Alkenes with Zeolitic Bronsted Sites: π -Complexes, Alkoxides, and Carbenium Ions in H-FER. *J. Phys. Chem. C* **2020**, *124*, 10067–10078.
- (35) Dorner, F.; Sukurma, Z.; Dellago, C.; Kresse, G. Melting Si: Beyond Density Functional Theory. *Phys. Rev. Lett.* **2018**, *121*, 195701.
- (36) Bajpai, A.; Mehta, P.; Frey, K.; Lehmer, A. M.; Schneider, W. F. Benchmark First-Principles Calculations of Adsorbate Free Energies. *ACS Catal.* **2018**, *8*, 1945–1954.
- (37) Waitt, C.; Miles, A. R.; Schneider, W. F. Adsorbate Free Energies from DFT-Derived Translational Energy Landscapes. *J. Phys. Chem. C* **2021**, *125*, 20331–20342.
- (38) Bučko, T.; Gesvandtnerová, M.; Rocca, D. Ab Initio Calculations of Free Energy of Activation at Multiple Electronic Structure Levels Made Affordable: An Effective Combination of Perturbation Theory and Machine Learning. *J. Chem. Theory Comput.* **2020**, *16*, 6049–6060.
- (39) Medford, A. J.; Wellendorff, J.; Vojvodic, A.; Studt, F.; Abild-Pedersen, F.; Jacobsen, K. W.; Bligaard, T.; Nørskov, J. K. Assessing the reliability of calculated catalytic ammonia synthesis rates. *Science* **2014**, *345*, 197–200.
- (40) Plessow, P. N.; Studt, F. How Accurately Do Approximate Density Functionals Predict Trends in Acidic Zeolite Catalysis. *J. Phys. Chem. Lett.* **2020**, *11*, 4305–4310.
- (41) Baerlocher, C.; McCusker, L. B. *Database of Zeolite Structures*. <http://www.iza-structure.org/databases/>.
- (42) Booth, G. H.; Grüneis, A.; Kresse, G.; Alavi, A. Towards an exact description of electronic wavefunctions in real solids. *Nature* **2013**, *493*, 365–370.
- (43) Harl, J.; Kresse, G. Accurate Bulk Properties from Approximate Many-Body Techniques. *Phys. Rev. Lett.* **2009**, *103*, 056401.
- (44) Pisani, C.; Maschio, L.; Casassa, S.; Halo, M.; Schütz, M.; Usvyat, D. Periodic local MP2 method for the study of electronic correlation in crystals: Theory and preliminary applications. *J. Comput. Chem.* **2008**, *29*, 2113–2124.
- (45) Kresse, G.; Furthmüller, J. Efficient Iterative Schemes for Ab initio Total-Energy Calculations using a Plane-Wave Basis Set. *Phys. Rev. B: Condens. Matter Mater. Phys.* **1996**, *54*, 11169–11186.
- (46) Kresse, G.; Furthmüller, J. Efficiency of Ab-Initio Total Energy Calculations for Metals and Semiconductors Using a Plane-Wave Basis Set. *Comput. Mater. Sci.* **1996**, *6*, 15–50.
- (47) Kresse, G.; Hafner, J. Ab initio Molecular-Dynamics Simulation of the Liquid-Metal-Amorphous-Semiconductor Transition in Germanium. *Phys. Rev. B: Condens. Matter Mater. Phys.* **1994**, *49*, 14251–14269.
- (48) Kresse, G.; Hafner, J. Ab initio Molecular Dynamics for Liquid Metals. *Phys. Rev. B: Condens. Matter Mater. Phys.* **1993**, *47*, 558–561.
- (49) Grimme, S.; Antony, J.; Ehrlich, S.; Krieg, H. A Consistent and Accurate Ab Initio Parametrization of Density Functional Dispersion Correction (DFT-D) for the 94 Elements H-Pu. *J. Chem. Phys.* **2010**, *132*, 154104.
- (50) Blöchl, P. E. Projector Augmented-Wave Method. *Phys. Rev. B: Condens. Matter Mater. Phys.* **1994**, *50*, 17953–17979.
- (51) Kresse, G.; Joubert, D. From Ultrasoft Pseudopotentials to the Projector Augmented-wave Method. *Phys. Rev. B: Condens. Matter Mater. Phys.* **1999**, *59*, 1758–1775.
- (52) VandeVondele, J.; Krack, M.; Mohamed, F.; Parrinello, M.; Chassaing, T.; Hutter, J. QUICKSTEP: Fast and Accurate Density Functional Calculations Using a Mixed Gaussian and Plane Waves Approach. *Comput. Phys. Commun.* **2005**, *167*, 103–128.
- (53) Hutter, J.; Iannuzzi, M.; Schiffrmann, F.; Vandevondele, J. CP2K: atomistic simulations of condensed matter systems. *Wiley Interdiscip. Rev.: Comput. Mol. Sci.* **2014**, *4*, 15–25.
- (54) Lippert, G.; Hutter, J. x. r.; Parrinello, M. The Gaussian and augmented-plane-wave density functional method for ab initio molecular dynamics simulations. *Theor. Chem. Acc.* **1999**, *103*, 124–140.
- (55) Lippert, G.; Hutter, J.; Parrinello, M. A hybrid Gaussian and plane wave density functional scheme. *Mol. Phys.* **1997**, *92*, 477–487.
- (56) Yang, K.; Zheng, J.; Zhao, Y.; Truhlar, D. G. Tests of the RPBE, revPBE, t-HCTHyb, o-B97X-D, and MOHLYP density functional approximations and 29 others against representative databases for diverse bond energies and barrier heights in catalysis. *J. Chem. Phys.* **2010**, *132*, 164117.
- (57) Goedecker, S.; Teter, M.; Hutter, J. Separable dual-space Gaussian pseudopotentials. *Phys. Rev. B: Condens. Matter Mater. Phys.* **1996**, *54*, 1703–1710.
- (58) Martyna, G. J.; Tobias, D. J.; Klein, M. L. Constant pressure molecular dynamics algorithms. *J. Chem. Phys.* **1994**, *101*, 4177–4189.
- (59) Frenkel, D.; Smit, B. *Understanding Molecular Simulation*, 2nd ed.; Academic Press, 2002.
- (60) Kästner, J. Umbrella Sampling. *Wiley Interdiscip. Rev.: Comput. Mol. Sci.* **2011**, *1*, 932–942.
- (61) Tribello, G. A.; Bonomi, M.; Branduardi, D.; Camilloni, C.; Bussi, G. PLUMED 2: New feathers for an old bird. *Comput. Phys. Commun.* **2014**, *185*, 604–613.
- (62) Kästner, J.; Thiel, W. Bridging the gap between thermodynamic integration and umbrella sampling provides a novel analysis method: “Umbrella integration”. *J. Chem. Phys.* **2005**, *123*, 144104.
- (63) Kästner, J.; Thiel, W. Analysis of the statistical error in umbrella sampling simulations by umbrella integration. *J. Chem. Phys.* **2006**, *124*, 234106.